IMPROVEMENT OF THE POWER QUALITY BY RELIABLE EARTH FAULT PROTECTION IN RESONANT-EARTHED GRIDS

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Summary: Power quality is in practice severely afflicted by voltage dips or supply interruptions. These depend to a high degree on the treatment of the system neutral of the local m.v. networks. In resonant earthed systems the infeed of energy into the afflicted feeder can be continued during earth fault location. After an overview over the classical methods of earth fault location a new method is introduced which evaluates the maximum harmonics content of the earth fault currents on a busbar and shows high sensitivity. Test results and experience show satisfactory behaviour.

INTRODUCTION

Presently the European Community experiences the development of a liberalised market of electrical energy. Most discussions are dominated by economic and juridical questions and the technical aspects are dealt with to a lesser degree. In many national regulations so far the notion of power quality is not treated with the due importance. Nevertheless power quality is an important factor in the relationship between supplier and customer, because it describes the technical quality of the delivered product “electrical power”.

Statistics show that earth faults constitute a large portion of the grid faults. If they are cleared by automatically tripping out the afflicted feeder, every earth fault will lead to a severe deterioration of the power quality for the afflicted consumers. As will be shown there is no general need in resonant earthed grids for automatic tripping of the faulty element. With good earth fault engineering there exist interesting solutions to sustain the supply of electrical power even in the event of earth faults, but this area of protection engineering necessitates the co-ordination of both protection measures and network operation procedures. Earth fault location while fully maintaining the electricity supply necessitates careful engineering by applying thorough understanding of the physical background. The suitable method of earth fault location has to be matched to both the physical properties of the network and the operation strategies of the network operator.

POWER QUALITY PARAMETERS

Power Quality definitions

Power quality is defined by a set of technical parameters which describe the different aspects of the power delivered to a customer. This is done mainly in terms of the voltage quality for which an IEC working group (IEC77A / WG09) is at present setting up the exact description and the methods of how to exactly obtain reproducible results. These parameters can be grouped into 2 categories: The first one deals with parameters that are related to the partial or total loss of supply. The second category describes phenomena originating from non-constant load behaviour. The power quality parameters foreseen for international standardisation are given in table 1.

Table 1 Classification of Power Quality Parameters

Category 1	**Category 2**
Supply voltage dip	**Voltage variation** **Rapid voltage change** **Flicker**
Interruption (of supply)	**Temporary power frequency overvoltage** **Transient overvoltage** **Voltage unbalance**
Frequency of the supply voltage	**Harmonic voltage** **Interharmonic voltage** **Mains signalling voltage**

It is international experience in liberalised markets that the power quality will be permanently monitored by the contracting parties against regulated or agreed limit values.

For further clarification the definitions of the parameters according to EN50160 that afflict the consumers in the most severe way are given below:

- A supply voltage dip is a sudden reduction of the supply voltage to a value between 90 % and 1 % of the declared voltage Uc, followed by a voltage recovery after a short period of time. Conventionally the duration of a voltage dip is between 10 ms and 1 minute. The depth of a voltage dip is defined as the difference between the minimum r.m.s. voltage during the voltage dip and the declared voltage. Voltage changes which do not reduce the supply voltage to less than 90 % of the declared voltage Uc are not considered to be dips.
- An interruption (of supply) is a condition in which the voltage at the supply-terminals is lower than 1 % of the declared voltage, Uc. A supply interruption can be classified as:

- prearranged, when consumers are informed in advance, to allow the execution of scheduled works on the distribution system, or
- accidental, caused by permanent or transient faults, mostly related to external events, equipment failures or interference.

An accidental interruption is classified as:

- a long interruption (longer than three minutes) caused by a permanent fault,
- a short interruption (up to three minutes) caused by a transient fault.

NOTE 1: The effect of a prearranged interruption can be minimised by the customers by taking appropriate measures.

NOTE 2: Accidental supply interruptions are unpredictable, they are largely random events.

Supply voltage dips

In distribution networks dips are short events which originate in some cases from disturbances emanating from loads but come mainly from remotely located short circuits. These can be located in the same grid as where the dip is experienced, either in the same feeder downstream from the point where the dip is observed, or in other feeders than the faulty one. But dips can also be experienced if there is a short circuit upstream in the higher voltage transportation network. In medium and low voltage grids the first type of dips leads to durations of approximately 0.2 – 1.5 s. This is due to the fact that in these grids short circuit protection is mostly carried out by definite or inverse definite minimum time (IDMT) protection. If a fault occurs in the superseding high voltage grid, the fault clearing times are considerably smaller because they are reduced by the application of high-class unit protection, e.g. distance protection. This leads to fault durations of approximately 0.05 ... 0.5 s.

An analysis of the cause of supply voltage dips in public utility networks shows that their occurrence is mostly determined by the protection and its fault clearing behaviour of the local m.v. and only in a lesser degree by the fault treatment in the higher voltage systems.

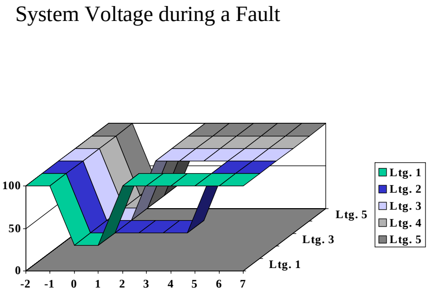

Fig. 1 Voltage behaviour during a fault

Supply Interruptions

Interruptions in distribution networks are often due to network behaviour in consequence of short circuits. In radially structured grids interruptions afflict necessarily all customers that lie downstream from the fault clearing circuit breaker. Interruptions are benchmarked as power quality indices, e.g. by the “Customer Average Interruption Duration Index” (CAIDI)

But there are also interruptions that are not due to short circuits, especially in m.v. resonant-earthed grids. They occur in the case of earth fault locating procedures: If the earth fault protection does not give clear indications of the faulty feeder, it is common practice to determine the faulty line section by the trial-and-error method. Then segment by segment of the suspected grid is taken out of service and – if the earth fault has not been cleared by this – are reconnected if they prove to be healthy and put back into service again. This rough approach is deplorable, but if there is no clear indication of the faulty line section due to poorly performing earth fault protection it becomes nevertheless necessary. That means: whole lines and consequently whole groups of consumers are temporarily taken out of service only in order to determine the earth-fault-afflicted feeder. If the faulty feeder has been determined at last, the same method is applied again in order to find the faulty section.

These operation are perceived by the customers at best as single and in the worst case as repetitive power supply interruptions. Needless to say that such a practice of earth fault location deteriorates the power quality and its relevant benchmark figures unnecessarily. On the other hand it is evident that good earth fault protection and correct earth fault engineering improves the power quality of the customers.

Earth fault location while fully maintaining the electricity supply necessitates careful engineering by applying thorough understanding of the physical background. The suitable method of earth fault location has to be matched to both the physical properties of the network and the operation strategies of the network operator.

The avoidance of dips and disconnection of customers due to safe earth fault locating procedures while fully maintaining the full supply improves the power quality. Under this aspect, earth fault protection and earth fault locating procedures can be regarded as an element to maintain or improve power quality in the competitiveness in the liberalised market.

PHYSICS OF EARTH FAULTS

Earth faults in low resistance-earthed grids

As it is well known, in both low resistance and solidly earthed grids any phase-to-earth fault will lead to a substantially large power frequency fault current in the afflicted feeder. This causes a considerable voltage drop both along the faulty line and also across the transformer(s) feeding energy from the superseding h.v. grid into the m.v. grid. This leads to a voltage drop on the main substation busbar. In consequence in radially operated grids, this reduced voltage in its turn causes a voltage drop of the same size in all other outgoing feeders, and this means a voltage drop for the whole m.v. grid.

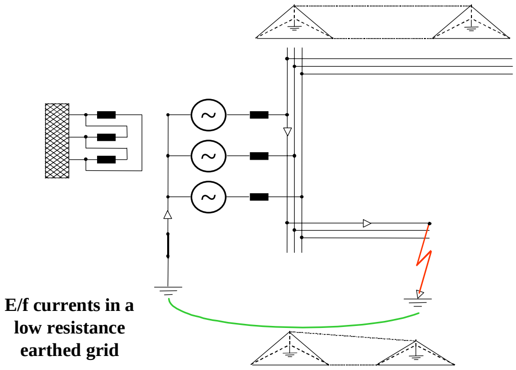

Fig. 2 Voltage distribution during an earth fault in a low resistance earthed grid

Because in low resistance and solidly earthed grids the fault current is too large to prevent any arcing fault to extinguish by itself, any earth fault must be in consequence definitively cleared by the earth fault protection of the system. For customers downstream of the tripped circuit breaker this leads to an interruption of the power supply, and for the other consumers of the same feeder and those of the healthy feeders this leads to a dip. Both events are counted as parameters of the power quality, and therefore any earth fault reduces the power quality in a resistance-earthed grid.

Earth fault currents in resonant-earthed grids

A totally different situation arises in resonant-earthed grids: Here there are two basically different types of current paths which can provide a closed loop for any current which flows from the afflicted feeder into earth. One type of current return path is given by the line-to-earth capacitances of all feeders, including the faulty feeder. By its nature, these currents are purely capacitive. The second type of return path goes through the arc suppression (Petersen) coil, one terminal of which is connected to earth, whereas its other terminal is connected to the transformer neutral or a neutral earthing transformer.

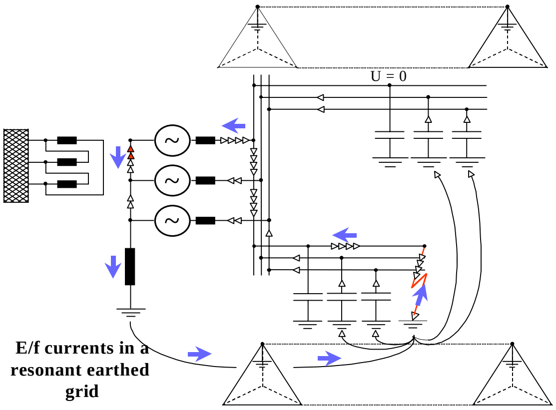

Fig. 3 Voltage distribution during an earth fault in a resonant-earthed grid

By its nature, this current is basically inductive. But it also contains a small resistive component due to the heat losses of the phase-to-ground elements of the grid such the arc suppression coil(s) and to a lesser degree surge diverters or dirty insulators.

Experience has shown that the resistive component is limited by the continuous thermal capacity of the arc suppression coil, i.e. its cooling properties by radiation and convection. Experience has further shown that due to their similar physical dimensions this continuous thermal withstand capacity it roughly the same for a large range of arc suppression coils. It appears that in contrast to common expectations the resistive component of arc suppression coils current does virtually not depend from neither their rated current nor from their rated voltage or frequency.

All earth fault return path currents join at the fault point and are here geometrically superimposed. The inductive component is adjusted by most system operators to values that are slightly higher than the sum of the capacitive components. This measure leads to the same fault current amplitudes for both capacitive and inductive components, which then compensate each other. In consequence arc faults become self-extincting. This is the rationale for the installation of arc suppression coils.

The resistive component cannot be counterbalanced and therefore the fault current will never be exactly zero. This feature restricts the arc suppression capacity of the grid.

According to the concept of superposition there are also harmonic components in the fault current due to the harmonics content of the pre-fault line-to-earth voltages. Their magnitude in the current spectrum is relatively large due to the fact that at higher frequencies the reactance of the line-to-earth capacities is reduced with the harmonic order. This fact is disadvantageous for the self-extinction properties of any arc fault, but on the other side this phenomenon can be used to locate the faulty feeder, as will be shown later on.

OVERVIEW OVER DIFFERENT EARTH FAULT LOCATION METHODS IN RESONANT-EARTHED GRIDS

By intention a resonant-earthed grid is designed to sustain and to be continuously operated under the condition of a steady state earth fault. The earth fault protection shall give an indication about the location of the fault point. Its exact location is carried out by sequentially transferring parts of the faulty feeder without any interruptions to other healthy feeders. Finally the faulty section is determined by the fact that as soon this is transferred to another healthy feeder this one is identified by the earth fault protection as being faulty whereas the original feeder is identified as free from earth faults.

The main difficulty in earth fault protection in resonant-earthed grids is due to the fact that the fault current compared to the nominal feeder currents or even the load currents of the feeder is so small, both at the fault point and also at the measuring point (earth fault protection at the busbar). In order to obtain useful results, this small quantity must nevertheless be carefully measured, filtered and evaluated.

A certain range of methods has been developed and applied so far, the most common of which are presented in the following table (Table 2)

Table 2 Different earth fault location methods and their evaluated quantities (selection)

METHOD OF EARTH FAULT PROTECTION	*EVALUATED QUANTITY*
Transient earth fault protection	**Transient zero sequence currents and neutral displacement voltage**
Harmonic earth fault protection	**Harmonics in steady state zero sequence currents and neutral displacement voltage**
Wattmetrical relay protection	**In-phase component of the steady state zero sequence currents related to the neutral displacement voltage. Sometimes the wattmetrical current is increased by introducing additional resistors.**
Pulsed earth fault current protection	**Periodic rapid changes of the degree of earth fault compensation**
Reactance method	**Evaluation of the zero sequence voltage vs. current changes in accordance with variations of the arc suppression coil**
Earth fault distance protection	**Fourier transform of the transient zero sequence currents and neutral displacement voltage**
Manual switching	**Displacement voltage during manual switching operations**
Automatic reclosure	**Displacement voltage during automatical sequential switching operations**
Short time neutral grounding	**Steady state zero sequence currents**
Short time grounding of a healthy phase	**Short circuit currents**

MAXIMUM HARMONICS CONTENTS EARTH FAULT LOCATION METHOD

Distribution of the harmonic earth fault currents

As is well known, the earth fault currents in a resonant-earthed grid can be classified as capacitive and arc suppression coil currents, according to their return paths. At system frequency by design these two current components compensate each other except for small residual reactive and resistive components. At higher frequencies the earth return path for the capacitive components becomes less resistive, in contrast to the return paths over the arc suppression coil, because the impedance of the arc suppression coil increases in contrast to the capacitances' impedance.

This can be shown in a rough example: If the capacitive earth fault current in a grid is 200 Amps (50 Hz) and the 5. harmonic of the (pre-fault) voltage is 3%, the resulting 250 Hz component of the capacitive earth fault current is expected in the order of

$$I_{cap} = 0.03x200x(250/50) = 30 \text{ Amps}, \quad (1)$$

which is not a negligible quantity. In contrast, the current through the arc suppression coil gets down to approximately of

$$I_{ind} = 0.03x200x(50/250) = 1.2 \text{ Amps} \quad (2)$$

This current can be neglected for practical purposes in respect to the capacitive currents. If for 50 Hz the ratio of the capacitive to the inductive current is assumed as roughly 1:1, this ratio changes for any higher frequency to

$$I_{cap} : I_{ind} = (f/50Hz)^2:1 \quad (3)$$

For the 250 Hz components of the current the ratio takes the value of

$$I_{cap,250HZ} : I_{ind,250Hz} = (250/50)^2:1 = 25 : 1 \quad (4)$$

This fact can be used to give a rough description of the earth fault phenomena at higher frequencies as follows: For harmonics and higher frequencies the earth fault current can be regarded as purely capacitive current. It flows at the fault point into earth and re-enters the h.v. or m.v. system through the line-to-earth capacitances of each feeder.

In radial systems the earth fault current distribution is given by fig. 4.

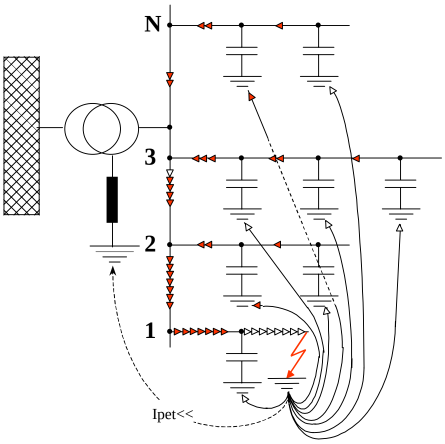

Fig. 4 Physical distribution of the higher harmonic zero sequence currents

As can be seen each feeder contributes to the (capacitive harmonic) earth fault current. The contribution depends from both the physical nature and length of the line and also from the harmonic content of the pre-fault line-to-earth voltage. Neglecting the effect of line inductances on the earth fault current the following table (Table 4) may serve as an indication to the earth fault current contribution to be expected:

The table shows that the contribution of a cable of a given length is in the order of magnitudes higher than that of a corresponding overhead line. Nowadays there are more and more cables being inserted into distribution grids. This results in the increase of capacitive earth fault currents which is disadvantageous to the fault clearing ability of the system on one side. But on the other hand, it is advantageous for earth fault location methods that base on the evaluation of harmonic components in the zero sequence currents: Because their content is increased, the signal level of any method that employs the harmonic current evaluation is raised and therefore such methods become more stable.

In the following a short description of a new principle of earth fault protection is given: Since at 250 Hz or similar frequencies the currents through the arc suppression coil(s) are very small compared to the capacitive earth fault currents, the grid can be regarded for 250 Hz phenomena as a system with insulated neutral. Therefore all 250 Hz earth fault currents “flow together” at the fault point. This general rule (“The healthy lines feed the sick line”) is also applicable for the busbar connected to the faulty feeder. Here the current contribution from the healthy feeders(“$I_{250,healthy}$”) add up to the fault current (“$I_{250,fault}$“).

$$I_{250,fault} = I_{250,healthy,1} + I_{250,healthy,2} + ... + I_{250,healthy,i} \quad (5)$$

For the current amplitudes this means:

$$|I_{250,fault}| = |I_{250,healthy,1} + I_{250,healthy,2} + ... + I_{250,healthy,i}| \quad (6)$$

Since all 250 Hz currents are purely capacitive by their nature and therefore in phase, equation (6) can be written as

$$|I_{250,fault}| = |I_{250,healthy,1}| + |I_{250,healthy,2}| + ... + |I_{250,healthy,i}| \quad (7)$$

This means: The 250 Hz earth fault current of the faulty feeder is the arithmetic sum of the 250 Hz earth fault currents of the healthy feeders and therefore larger than every healthy feeder current contribution.

$$|I_{250,fault}| > |I_{250,healthy,i}| \quad (8)$$

Though this relation has been derived for the earth fault current distribution in a radial system, it is generally applicable.

This fact can be used for the design of new earth fault protection system, based on the maximum harmonic content: In such a system all earth fault (zero sequence) currents are first filtered, then their 250 Hz component extracted and the faulty feeder is finally determined by identifying the largest 250 Hz earth fault current. Care must be taken to measure all feeders at the same time because the harmonic level of the 250 Hz component of the driving voltage varies quickly and therefore a time shifted sampling of the 250 Hz earth

Table 4 Earth Fault Current for different Types of Feeders

Type of feeder	earth fault current for UN = 10 kV	earth fault current for UN = 20 kV
Cable	**0.25 A**	**0.45 A**
Overhead Line	**0.005**	**0.009 A**

fault currents will lead to wrong results when comparing the harmonic content of the earth fault currents.

Experiences

Earth fault protection systems based on the maximum harmonic contents method have been built and tested in laboratory models and later on in realistic earth fault tests. They are in operation in different substations for two years. The experiences are satisfying. Though –in theory – the concept of symmetrical components necessitates a steady state of the power system, it was found in practice that due to the high harmonic content of the transient earth fault currents this method also gives satisfying results even for transient earth faults as short as 20 milliseconds.

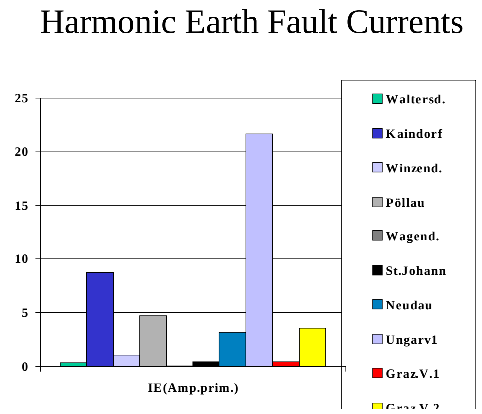

Fig. 5 Measurement values of harmonic zero sequence

During field tests (see fig. 5) in a typical radial m.v. grid the distribution of the 250 Hz earth fault currents was analysed. As can be seen the 250 Hz earth fault current of the faulty feeder is the very largest. The evaluation of the amplitudes shows that the amplitude of the earth fault current of the faulty feeder is the sum of the contribution of the healthy feeders with a relative error of less than 8%. This is the experimental proof of the underlying theory resulting in the key formula (7). Since the method is simple by concept and does not need any additional equipment, it has proven as being reliable.

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