IMPROVING PERSONAL SAFETY IN MV-NETWORKS THROUGH NOVEL EARTH-FAULT CURRENT BASED FEEDER PROTECTION

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ABSTRACT

In this paper a novel method for earth-fault (EF) protection applicable in high-impedance earthed networks, especially in resonant earthed networks, is described. The innovative method is not based on traditional zero-sequence quantities (Uo, Io), but on accurate estimation of EF-current (I_F) flowing at the fault location. Estimation of EF-current is done utilizing changes in phase currents measured at the beginning of the feeder due to an earth fault. Thanks to its novel operation principle, the method has several advantages over the traditional state-of-art EF-protection methods such as the wattmetric method. The method enables automatic adaptation of protection operation speed according to the estimated EF-current magnitude, including the harmonic content, which further enhances the accuracy and practicality of the novel protection method. The estimated EF-current magnitude can be converted into corresponding touch voltage magnitude, which enables direct compliance of protection operation to the electrical safety codes, such as EN50522.

In this paper, first the theory and operation principle of the new method is described. Then the performance of the suggested protection algorithm is validated using data from a field test in practical 20kV resonant earthed network. The results show that the novel method enables significant improvement on safety and overall dependability of the protection schemes used today.

INTRODUCTION

In resonant earthed systems, the maximum value for the 'compensated' EF-current flowing at the fault location can be written as:

$$I_F(RMS) = \sqrt{I_d^2 + I_v^2 + \sum_{n=2}^{m} I_{harm\_n}^2} \quad (1)$$

where I_d is the 'damping' or resistive component of fault current due to losses of coil(s), network admittances and parallel resistor. $I_v = I_{coil} - I_c$ is the detuning of the network or reactive component of fault current. I_v is zero, when network is operated at resonance, positive value indicates over-compensated network. I_{coil} is the total inductive current of the compensation coil(s) in the network. I_c is the capacitive EF-current contribution of the network. I_{harm_n} is the n^{th} harmonic component of the EF-current.

Traditional EF-protection functions applied today in resonant earthed networks, such as the *multi-frequency admittance protection* [1] or *Iocosphi-method*, are based on measurement of zero-sequence voltage or neutral point voltage $\underline{U}_o$ and residual current or sum current $\underline{I}_o$.

In the *healthy feeder*, the measured residual current during the fault equals the current of the total admittances of the healthy feeder itself (with minus sign), and it is the EF-current contribution from the protected feeder in question:

$$\underline{I}_o = -\underline{I}_{oFd} \quad (2a)$$

$\underline{I}_{oFd}$ is capacitive unless the feeder is overcompensated by distributed coils. In the *faulted feeder*, the relation between $\underline{I}_o$ and $\underline{I}_F$ can be written as:

$$\underline{I}_o = \underline{I}_F - \underline{I}_{oFd} \quad (2b)$$

The real- and imaginary-part of the measured residual current can thus be written as (neglecting harmonics):

$$Re(\underline{I}_o)=Re(\underline{I}_F) - Re(\underline{I}_{oFd}) = I_d - Re(\underline{I}_{oFd}) \quad (3a)$$
$$Im(\underline{I}_o)=Im(\underline{I}_F) - Im(\underline{I}_{oFd}) = I_v - Im(\underline{I}_{oFd}) \quad (3b)$$

It can be concluded from ***Eq.1-3*** that the magnitude of $\underline{I}_o$ is not a valid indicator of a faulted feeder – also in the healthy feeder similar magnitude of $\underline{I}_o$ can be measured as in the faulted feeder. The imaginary-part seen by the *Io*-based EF-protection is not the same as the imaginary-part of the fault current (=detuning), but it is affected by the amount of EF-current contribution of the protected feeder itself. This feeder specific value can be very high due to increased use of underground cables in modern MV-networks. As result the *Io*-current used as operation quantity by traditional EF-protection is thus becoming more invalid representation of the fault current flowing at the fault location! There is also a new identified protection challenge introduced by the fact that cabling increases significantly the imaginary-part of the measured *Io*-phasor and thus its phase angle φ_o in relation to *Uo*-phasor during an inside fault:

$$\varphi_o = atan((I_v + Im(\underline{I}_{oFd})) / I_d) \quad (4)$$

As can be seen from ***Eq.4*** especially when system damping is low and if simultaneously either detuning or EF-current contribution of the protected feeder is high, then the phase angle φ_o may increase considerably (>80°). Such high phase angle value may turn the *Io*-phasor outside the operate sector of traditional EF-protection risking thus dependable operation of protection.

Generally, all traditional EF-protection methods applied in resonant earthed networks have fixed, pre-determined operation delay time settings. If for any reason the EF-current becomes higher than expected, the traditional protection may not be able to clear the fault according to the required speed stated in the safety regulations. Such condition may occur when network topology is suddenly changed. Due to inherent delays in coil tuning procedure, the coil current I_{coil} cannot be immediately re-tuned to a new, desired detuning value. Thus, during the coil tuning procedure, the imaginary-part and thus the phase angle φ_o, and especially the magnitude of the fault current may temporarily have very high values. This may endanger both the dependability and adequate speed of protection operation. Similarly changes in the harmonic content of fault current may increase its RMS-value considerably. Higher fault current would require faster operation of protection. Harmonics may have high variation within time as they are due to non-linear loads and depend on the loading levels of the network. Consideration of harmonics in fulfilling the operate speed requirements is yet another shortcoming of the traditional EF-protection methods.

In order to solve the previously mentioned problems, *the fault current based earth fault-protection*, or *I_F-protection* applicable in resonant earthed networks is proposed. The method has many unique and favorable features, which cannot be achieved with the traditional EF-protection functions, as explained in the following.

THEORY OF I_F-PROTECTION

Fault current estimate

Next it is shown that the fault current $\underline{I}_F$ flowing in the fault location can be estimated based on phase currents measured in the beginning of the faulted feeder. For the derivation of necessary equations, a simplified equivalent circuit of a compensated 3-phase distribution network illustrated in ***Fig.1*** is applied. The derived equations are valid for the phase A-to-earth fault, but similar equations can be derived for other phases.

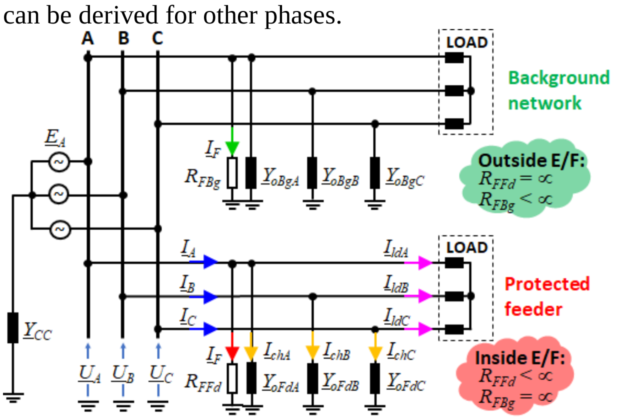

Fig.1 *Simplified equivalent circuit of compensated 3-phase distribution network with a single-phase earth fault in phase A.*

The network consists of two feeders, one representing the protected feeder (*Fd*) and the other the rest of the feeders in the substation (background network, *Bg*). The line series impedances are neglected as their values are very small compared with the shunt admittances. However, loads must be included as the novel method utilizes phase currents. Notations used in ***Fig.1***:

$\underline{E}_A$	= Source voltage, phase A (e.g. 20/√3 kV∠0º)
$\underline{U}_X$	= Phase voltage of phase A, B or C at the substation
$\underline{I}_X$	= Phase current of phase A, B or C of the protected feeder
$\underline{I}_{chX}$	= Charge current of phase A, B or C of the protected feeder
$\underline{I}_{ldX}$	= Load current of phase A, B or C of the protected feeder
$\underline{Y}_{oFdX}$	= Admittance of phase A, B or C of the protected feeder
$\underline{Y}_{oBgX}$	= Admittance of phase A, B or C of the background network
$\underline{Y}_{CC}$	= Admittance of the compensation coil (incl. parallel resistor)
R_{FFd}	= Fault resistance when the fault is in the protected feeder
R_{FBg}	= Fault resistance when the fault is in the background network
$\underline{I}_F$	= Earth-fault current at the fault location

The equivalent circuit is equally valid during healthy and faulty states. During the healthy state the fault resistances equal infinity, $R_F = \propto$ ohm. In case of an earth fault inside the protected feeder, then $R_{FFd} < \propto$ ohm and $R_{FBg} = \propto$ ohm. Further, if an earth fault occurs outside the protected feeder, $R_{FFd} = \propto$ ohm and $R_{FBg} < \propto$ ohm. Utilizing the equivalent circuit of ***Fig.1*** and assuming full symmetry of the phase-admittances in the whole network ($\underline{Y}_{oA}=\underline{Y}_{oB}=\underline{Y}_{oC}=\underline{Y}_o$) the equation for the EF-current can be written as:

$$\underline{I}_F = U_{PE}\cdot(\underline{Y}_{otot})/\ (R_{FFd}\cdot\underline{Y}_{otot}+1) \tag{5}$$

Where

$\underline{Y}_{otot} = (\underline{Y}_{oFdA}+\underline{Y}_{oBgA})+(\underline{Y}_{oFdB}+\underline{Y}_{oBgB})+(\underline{Y}_{oFdC}+\underline{Y}_{oBgC})+\underline{Y}_{CC}$ = Total network admittance, U_{PE}=Nominal phase voltage.

In case of inside galvanic fault, R_{FFd} =0 ohm, the result equals $\underline{I}_F = U_{PE}\cdot\underline{Y}_{otot}$, which is the generic equation for the earth-fault current in the compensated network.

In the following it is studied, how the EF-current flowing at the fault location can be estimated utilizing phase current measurements from the beginning of the feeder at the substation. Applying the superposition theorem, the measured phase currents can be divided into components as described in ***Table 1***. Prior to fault, phase currents consist of load currents and charge currents. During an earth fault, fault current component is added to the faulted phase current at the faulted feeder. Also charge currents in all phases are affected due to voltage imbalance created by the fault. Load currents are not affected as loads are connected between phases.

Table 1. *Measured phase current components at the protected feeder.*

Ph. curr.	Pre-fault	During inside flt	Change due to inside flt	During outside flt	Change due to outside flt
$\underline{I}_A$	$\underline{I}_{preA}=\underline{I}_{ldA}+\underline{I}_{chA}$	$\underline{I}_{preA}+\Delta\underline{I}_{chA}+\underline{I}_F$	$\Delta\underline{I}_A=\Delta\underline{I}_{chA}+\underline{I}_F$	$\underline{I}_{preA}+\Delta\underline{I}_{chA}$	$\Delta\underline{I}_A=\Delta\underline{I}_{chA}$
$\underline{I}_B$	$\underline{I}_{preB}=\underline{I}_{ldB}+\underline{I}_{chB}$	$\underline{I}_{preB}+\Delta\underline{I}_{chB}$	$\Delta\underline{I}_B=\Delta\underline{I}_{chB}$	$\underline{I}_{preB}+\Delta\underline{I}_{chB}$	$\Delta\underline{I}_B=\Delta\underline{I}_{chB}$
$\underline{I}_C$	$\underline{I}_{preC}=\underline{I}_{ldC}+\underline{I}_{chC}$	$\underline{I}_{preC}+\Delta\underline{I}_{chC}$	$\Delta\underline{I}_C=\Delta\underline{I}_{chC}$	$\underline{I}_{preC}+\Delta\underline{I}_{chC}$	$\Delta\underline{I}_C=\Delta\underline{I}_{chC}$

In order to understand the meaning of the changes of phase currents due to earth fault, symbolic equations are derived from the equivalent circuit of ***Fig.1*** and shown in ***Table 2***.

Table 2. *Equations describing the measured changes of phase currents due to phase-A-to-earth fault.*

Change due to fault	Faulted feeder, symbolic equation	Healthy feeder, symbolic equation
$\Delta\underline{I}_A$	$U_{PE}\cdot(\underline{Y}_{otot}-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$	$U_{PE}\cdot(-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$
$\Delta\underline{I}_B$	$U_{PE}\cdot(-\underline{Y}_{oFdB})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$	$U_{PE}\cdot(-\underline{Y}_{oFdB})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$
$\Delta\underline{I}_C$	$U_{PE}\cdot(-\underline{Y}_{oFdC})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$	$U_{PE}\cdot(-\underline{Y}_{oFdC})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$

*$dm1 = (R_{FFd}\cdot\underline{Y}_{otot}+1)\cdot\underline{Y}_{otot}$, $dm2 = (R_{FBg}\cdot\underline{Y}_{otot}+1)\cdot\underline{Y}_{otot}$

Where

$\underline{Y}_{utot} = (\underline{Y}_{oFdA}+\underline{Y}_{oBgA})+\underline{a}^2\cdot(\underline{Y}_{oFdB}+\underline{Y}_{oBgB})+\underline{a}\cdot(\underline{Y}_{oFdC}+\underline{Y}_{oBgC})$ = Asymmetry admittance of the total network, $\underline{Y}_{uFd} = \underline{Y}_{oFdA}+\underline{a}^2\cdot\underline{Y}_{oFdB}+\underline{a}\cdot\underline{Y}_{oFdC}$ = Asymmetry admittance of the protected feeder.

From ***Table 2***, it can be seen that changes in phase currents as such do not represent the true fault current flowing at the fault location. Thus, the changes must be combined to derive correct equations for the EF-current estimate. In ***Table 3***, three alternative equations ($\underline{I}_{F1\ldots F3}$) are presented.

Table 3. Fault current estimate equations and their meaning.

Fault curr. estimate	Faulted feeder, symbolic equation
$\underline{I}_{F1} = \Delta\underline{I}_A - \Delta\underline{I}_B$	$U_{PE}\cdot(\underline{Y}_{otot}+\underline{Y}_{oFdB}-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$
$\underline{I}_{F2} = \Delta\underline{I}_A - \Delta\underline{I}_C$	$U_{PE}\cdot(\underline{Y}_{otot}+\underline{Y}_{oFdC}-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$
$\underline{I}_{F3} = \Delta\underline{I}_A-(\Delta\underline{I}_B+\Delta\underline{I}_C)/2$	$U_{PE}\cdot(\underline{Y}_{otot}+(\underline{Y}_{oFdB}+\underline{Y}_{oFdC})/2-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$
Fault curr. estimate	**Healthy feeder, symbolic equation**
$\underline{I}_{F1} = \Delta\underline{I}_A - \Delta\underline{I}_B$	$U_{PE}\cdot(\underline{Y}_{oFdB}-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$
$\underline{I}_{F2} = \Delta\underline{I}_A - \Delta\underline{I}_C$	$U_{PE}\cdot(\underline{Y}_{oFdC}-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$
$\underline{I}_{F3} = \Delta\underline{I}_A-(\Delta\underline{I}_B+\Delta\underline{I}_C)/2$	$U_{PE}\cdot((\underline{Y}_{oFdB}+\underline{Y}_{oFdC})/2-\underline{Y}_{oFdA})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm2$

Assuming full symmetry towards earth i.e. $\underline{Y}_{oFdA}=\underline{Y}_{oFdB}=\underline{Y}_{oFdC}=\underline{Y}_{oFd}$ and $\underline{Y}_{utot}= \underline{Y}_{uFd} = 0$, equations are simplified into format given in ***Table 4***.

Table 4. Fault current estimate equations and their meaning.

Fault current estimate	Faulted feeder, symbolic equation	Healthy feeder, symbolic equation
$\underline{I}_{F1} = \Delta\underline{I}_A - \Delta\underline{I}_B$	$U_{PE}\cdot(\underline{Y}_{otot})/ (R_{FFd}\cdot\underline{Y}_{otot}+1)$	0
$\underline{I}_{F2} = \Delta\underline{I}_A - \Delta\underline{I}_C$	$U_{PE}\cdot(\underline{Y}_{otot})/ (R_{FFd}\cdot\underline{Y}_{otot}+1)$	0
$\underline{I}_{F3} = \Delta\underline{I}_A-(\Delta\underline{I}_B+\Delta\underline{I}_C)/2$	$U_{PE}\cdot(\underline{Y}_{otot})/ (R_{FFd}\cdot\underline{Y}_{otot}+1)$	0

From equations in ***Tables 3-4*** one can see that in case of inside galvanic fault, R_{FFd} =0 ohm, the result is $U_{PE}\cdot\underline{Y}_{otot}$ which equals the EF-current of the compensated network! Additionally, the EF-current estimate is theoretically zero in a healthy feeder ($R_{FFd} =\propto$ ohm, $R_{FBg} < \propto$ ohm).

These important observations mean that the proposed equations enable calculation of an estimate for the EF-current $\underline{I}_F$. There is however a practical challenge in determining the phase current changes due to fault: for the presented theory and equations to be valid, the load current component in phase currents should be known prior to fault and it should not be changed during the fault. If these pre-conditions are valid, the load current is fully eliminated when 'delta' phase currents are calculated. In practice, due to time dependent nature of loads, such assumption is generally not valid, especially if fault duration is long. Other identified challenges are during feeder energization and switching on to fault, when load currents are not known prior to circuit breaker closing.

Solution to the previously mentioned problems is obtained by utilizing negative-sequence current component ($\underline{I}_2$), which is present prior to fault only due to imbalance in load currents ($\underline{I}_{2ld}$) and charge currents ($\underline{I}_{2ch}$). Due to this fact, its pre-fault value is typically rather low and constant, which enables better accuracy regardless of load variations, or in case of uncertainty in the pre-fault value. To estimate the EF-current, threefold negative-sequence component or change in threefold negative-sequence component due to earth fault must be calculated (phase A as reference, $\underline{a}=cos(120^o)+j\cdot sin(120^o)$):

$$\underline{I}_F = 3\cdot\underline{I}_2 = \underline{I}_A + \underline{a}^2\cdot \underline{I}_B + \underline{a}\cdot\underline{I}_C \qquad (6a)$$

$$\underline{I}_F =3\cdot\Delta\underline{I}_2 = \Delta\underline{I}_A + \underline{a}^2\cdot\Delta\underline{I}_B + \underline{a}\cdot\Delta\underline{I}_C \qquad (6b)$$

Applying the superposition theorem, the measured threefold negative-sequence component can be divided into components as described in ***Table 5***. During an earth fault, additional negative-sequence component ($\underline{I}_{2F}$) is introduced which is only measurable at the faulted feeder.

Table 5. Measured threefold negative-sequence current components at the protected feeder.

Curr.	Pre-fault	During inside flt	Change due to flt	During outside flt	Change due to flt
$3\cdot\underline{I}_2$	$3\cdot\underline{I}_{2pre}=$ $3\cdot(\underline{I}_{2ld}+\underline{I}_{2ch})$	$3\cdot\underline{I}_{2pre}$ $+3\cdot(\Delta\underline{I}_{2ch}+ \underline{I}_{2F})$	$3\cdot\Delta\underline{I}_2=$ $3\cdot(\Delta\underline{I}_{2ch}+ \underline{I}_{2F})$	$3\cdot\underline{I}_{2pre}$ $+3\cdot\Delta\underline{I}_{2ch}$	$3\cdot\Delta\underline{I}_2=$ $3\cdot\Delta\underline{I}_{2ch}$

Next, the symbolic equations are derived from the equivalent circuit of ***Fig.1*** to understand the meaning of the changes in threefold negative-sequence current due to earth fault, ***Table 6***. The symbolic equation valid for the faulted feeder provides yet another alternative method for estimating the fault current: $\underline{I}_{F4} =3\cdot\Delta\underline{I}_2$.

Table 6. Equations describing the changes of measured threefold negative-sequence current due to phase-A-to-earth fault.

Curr.	Faulted feeder, symbolic eq.	Healthy feeder, symbolic eq.
$3\cdot\Delta\underline{I}_2$	$U_{PE}\cdot(\underline{Y}_{otot}-\underline{Y}_{uFd})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/dm1$	$U_{PE}\cdot(-\underline{Y}_{uFd})\cdot(\underline{Y}_{otot}-\underline{Y}_{utot})/ dm2$

Assuming full symmetry towards earth i.e. $\underline{Y}_{oFdA}=\underline{Y}_{oFdB}=\underline{Y}_{oFdC}=\underline{Y}_{oFd}$ and $\underline{Y}_{utot}= \underline{Y}_{uFd} = 0$, equations are simplified into format given in ***Table 7***.

Table 7. Fault current estimate equations and their meaning.

Fault current estimate	Faulted feeder, symbolic equation	Healthy feeder, symbolic equation
$\underline{I}_{F4} =3\cdot\Delta\underline{I}_2$	$U_{PE}\cdot(\underline{Y}_{otot})/ (R_{FFd}\cdot\underline{Y}_{otot}+1)$	0

From equations in ***Tables 6-7*** one can see that in case of inside galvanic fault, R_{FFd} =0 ohm, the result is $U_{PE}\cdot\underline{Y}_{otot}$ which equals the EF-current of the compensated network! Additionally, the EF-current estimate is theoretically zero in a healthy feeder ($R_{FFd} =\propto$ ohm, $R_{FBg} < \propto$ ohm).

Operation characteristic

By utilizing the EF-current estimate as an operate quantity of EF-protection in compensated networks a novel fault current based protection is introduced. This new I_F-*protection* provides discrimination between faulty and healthy feeders based on current amplitude selectivity, which is not possible with traditional zero-sequence quantities. There is also an important practical advantage in the new method: the harmonic components can be taken into account in real time by simply calculating phase current phasors at frequency $n\cdot f_n$, where $n=1,2,\ldots,m$ and then calculating their change due to earth fault. For example, for the EF-current estimate utilizing the change in threefold negative-sequence current can be written:

$$I_F(RMS) = \sqrt{\sum_{n=1}^{m}(3\cdot abs(\Delta\underline{I}_2^n))^2} \qquad (7)$$

Where $abs(\Delta\underline{I}_2^n)$ is the change in magnitude of the n^{th} harmonic negative-sequence current component due to earth fault.

Adequate sensitivity of protection can be achieved by utilizing traditional *Uo*-based condition to detect the presence of an earth fault. This condition ensures also the security of protection during non-fault condition, which may create negative-sequence current, such as transformer inrush conditions, or in situations where phase and/or threefold negative-sequence current can change considerably during normal operation, e.g. during feeder energization. Combining *Uo*-voltage measurement into fault current estimation enables also the division of the estimated EF-current into its real- and imaginary-parts, which can be applied for further ensuring the dependability and security of the method.

Example of operation characteristic of the I_F-protection function is illustrated in ***Fig.2***. The start value '*Min Flt Curr*'-setting would be based on the known or estimated fundamental parameters of the compensated network: damping (I_d) and detuning (I_v , set detuning degree = I_{v_set}).

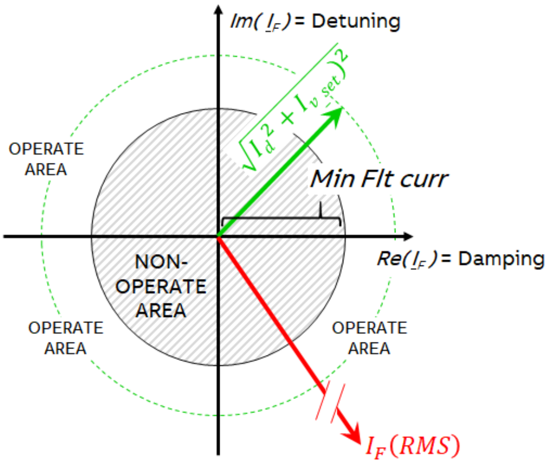

Fig.2 *Example of operation characteristic of the novel I_F-protection.*

Operate timer based on touch voltage estimate

Real time estimation of the actual fault current in the fault location enables automatic adaptation of operate time of the I_F-protection. Fundamental frequency component or RMS-value of the fault current estimate can be utilized for this purpose, ***Eq.7***, and the operate time curve implemented with any user defined IDMT-characteristics. An example of IDMT-type operate time curve is shown in ***Fig. 3***, which is derived based on the Finnish standard SFS6001 'High-voltage electrical installations' and is therefore compatible with EN50522.

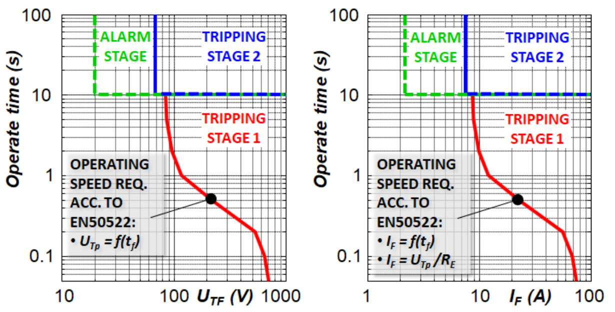

Fig.3 *Examples of operate time characteristics of I_F -protection: based on estimated touch voltage (left) and on estimated fault current (right).*

The most favourable application would be to convert the fault current estimate to corresponding touch voltage estimate. Then the required operate speed is directly derived based on the national electrical safety codes and standards.

Conversion of fault current estimate I_F into touch voltage estimate U_{TF} can be calculated using ***Eq. 8***:

$$U_{TF} = k \cdot r \cdot R_E \cdot I_F \qquad (8)$$

Where

k is a user defined coefficient (e.g. 0.25-1.0), describing the share of touch voltage from the total Earth Potential Rise (EPR) at fault location. r is a user defined reduction factor considering that not all of the EF-current will flow back through "remote" earth. A portion of the EF-current may have alternative return paths, e.g. cable sheaths. A reduction factor 1.0 means that 100% of EF-current flows back through "remote" earth. R_E is a user defined maximum earthing resistance value encountered in the protected feeder. I_F is the magnitude of the EF-current estimate calculated according to the proposed method.

VALIDATION BY PRACTICAL FIELD TEST

In recent years, ABB Oy, Distribution Solutions, Finland has undertaken intensive field testing in co-operation with some Finnish power utilities to develop new EF-protection algorithms. Next, a few field test recordings are studied in more details. Special interest is to validate the accuracy of the novel algorithm to estimate the EF-current including its harmonic components. These tests were made in a 20kV distribution network with data as presented in ***Table 8***.

Table 8. *Network data of the studied network.*

Network parameter	Value at 20kV
Uncompensated EF-current of the network	100A
Rated current of the parallel resistor	4.2A
Resistive losses of the system	3.3A
Compensation degree	-3A or unearthed
EF-current produced by the test feeder	15A
Maximum earthing resistance	9.5ohm
Phase CT class and ratio	5P10, 200/5A

The actual EF-current at the fault location was measured using a core balance CT and REF541 feeder terminal. Also actual prospective touch voltage (U_{vT}) was measured using TOPAS1000 power quality analyzer: between the metallic frame of a LV-distribution board and the metal plate on the ground. The measurement arrangement at the fault location is illustrated ***Fig.4***. At the supplying 20kV primary substation all current and voltage signals of the faulted feeder were also recorded.

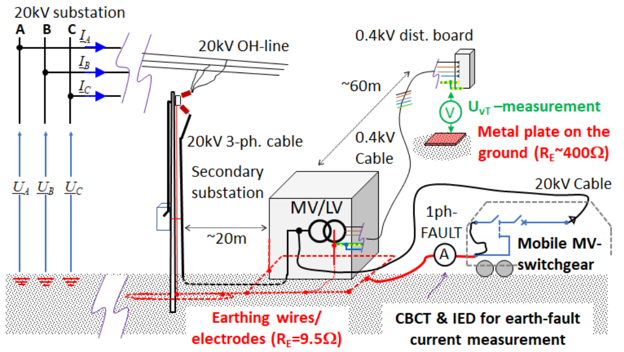

Fig.4 Illustration of the field test measurement arrangement. MV-side protective earthing and LV-neutral earthing are connected.

Next, in ***Fig.5-8*** results from the EF-current estimation are presented during different fault cases. Values of estimated and measured fault currents and touch voltages together with the expected operate delay times of the I_F-*protection* are summarized in ***Table 9***. All current and voltage values are maximum RMS-values from the total duration of the earth-fault test in question.

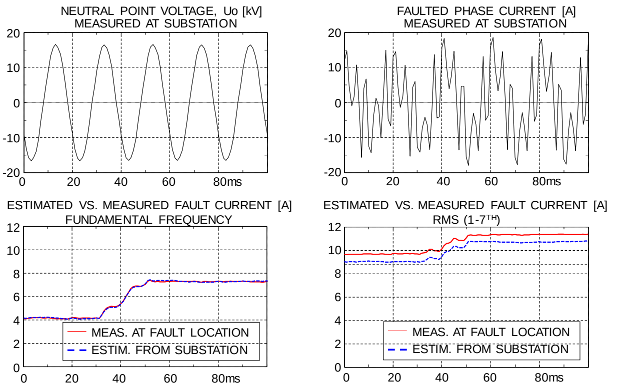

Fig. 5. Case #1 (zoomed in the moment of parallel resistor connection): galvanic fault with I_{v_set} = -2A.

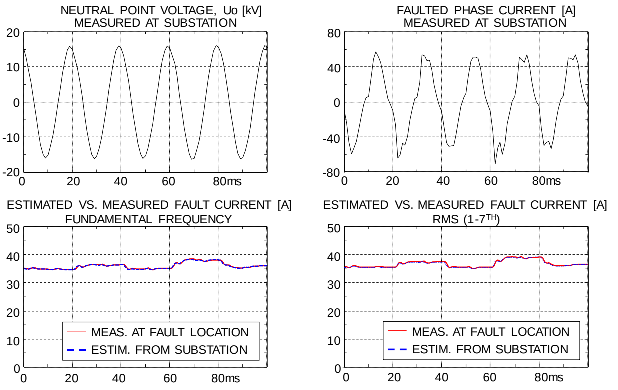

Fig. 6. Case #2: galvanic fault with I_{v_set} = +40A.

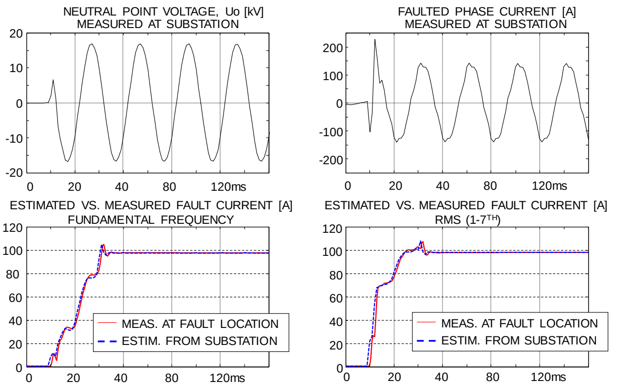

Fig. 7. Case #3: galvanic fault with unearthed neutral point.

From ***Fig.5-8*** the following conclusions can be made: first, the estimated EF-current and touch voltage matches very well with the measured one, which enables proposed inverse time mode of operation. Secondly, the estimated EF-current is valid for both fundamental frequency component and the RMS-value. There is a distinct harmonic content in the actual EF-current during the galvanic faults in cases #1 and #4. The effect of this can also be seen in the estimate, which matches the actual measurement with good accuracy.

CONCLUSIONS

In this paper a novel method for EF-protection applicable in resonant earthed networks was described.

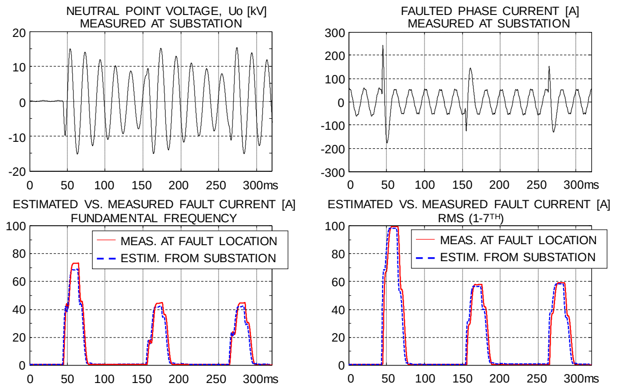

Fig. 8. Case #4: galvanic re-striking fault with I_{v_set} = -2A. Note, that the fault current estimate is not affected by post-fault oscillation.

***Table 9**. Summary of estimation and measurement results, R_E = 9.5ohm.*

Case	Meas. I_F [A]	Estim. I_F [A]	Meas. U_{vT} [V]	Estim. U_{TF} [V]= $R_E \cdot I_F$	Estim. op. time [s] (1
1	~11.3	~10.7	~92	~102	~1.7
2	~36.5	~36.5	~314	~345	~0.38
3	~98	~98	~767	~931	<0.05
4	~99	~98	-	-	-

1) Based on exemplary operate time curve, ***Fig. 3.***

Table 10 summarizes the main features of the new method.

***Table 10.** Summary and comparison of features between traditional protection methods and the novel method in resonant earthed network.*

Feature	*Traditional methods*	*Novel I_F-protection*
Fault current as operation quantity is measured at the faulted feeder	No	Yes
Operation quantity is zero at the healthy feeder	No	Yes
Operation possible without Petersen coil status information	No	Yes
Operation possible without definite Iocos component (parallel resistor)	No	Yes
Effect of harmonics included	No	Yes
Dependable and timely operation during unplanned operating conditions	No	Yes
Enables optimal time for self-extinguishment of fault arc	No	Yes
Immunity to post-fault oscillations	No	Yes
Easy setting principles	No	Yes
Timer characteristics	Definite time, DT	Inverse time, IDMT
Measurement	*Io* (CBCT), *Uo*	I_A, I_B, I_C (CTs), *Uo*

The results show that the novel algorithm estimates the earth-fault current very accurately regardless of fault type or network parameters. It has potential to improve the dependability and safety provided by traditional EF-protection schemes. With the novel method timely and precise protection operation can be ensured in compliance with applied legislation during all possible operating conditions. The algorithm will be implemented in the next generation of feeder terminals targeted to global power distribution and sub-transmission markets.

REFERENCES

[1] A. Wahlroos, J. Altonen, et al, "*Application of novel cumulative phasor sum measurement into earth-fault protection in compensated MV-networks*", CIRED 2013, Stockholm, Sweden.