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Performance of Novel Neutral Admittance Criterion in MV-feeder Earth-fault Protection

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This paper describes the fundamentals of the neutral admittance based earth-fault protection. First, the theory is briefly introduced. Secondly, certain improvements to the traditional measuring principle and operation characteristics are suggested. Finally, the performance is evaluated and compared with traditional earth-fault protection schemes using simulated and recorded data. The results show that the neutral admittance criterion has potential to become a standard and widely used earth-fault protection function in high impedance earthed networks.

INTRODUCTION

Earth-fault (EF) protection is traditionally based on directional residual overcurrent criterion with zero-sequence voltage as the polarizing quantity. An example of such is the $I_0cos(\varphi)$-criterion that is commonly used in compensated medium voltage distribution systems. However, e.g. in Poland, the neutral admittance (Y_0) criterion has become popular and is today a standard EF protection function required by the local utilities [1].

THEORY

The following analysis assumes that all the measured quantities are fundamental frequency phasors. The equations are valid for the phase L1-to-earth fault, but similar equations can be derived for phase L2- or L3-to-earth faults.

The theory of the Y_0 criterion can be explained with the aid of a simplified equivalent circuit of a 3-phase distribution network illustrated in *Fig. 1*. The network consists of two feeders, one representing the protected feeder *(Fd)* and the other the background network *(Bg)*. The background network represents the rest of the feeders in the substation. The line series impedances are neglected as their values are very small compared with the shunt admittances. Also the loads and phase-to-phase capacitances are disregarded as they do not contribute to the zero-sequence current.

Notations used in *Fig. 1*:

$\underline{U}_0$ = $(\underline{U}_{L1}+\underline{U}_{L2}+\underline{U}_{L3})/3$ = Zero-sequence voltage of the network
$3\underline{I}_{0Fd}$ = $(\underline{I}_{L1Fd}+\underline{I}_{L2Fd}+\underline{I}_{L3Fd})$ = Residual current of the protected feeder
$3\underline{I}_{0Bg}$ = $(\underline{I}_{L1Bg}+\underline{I}_{L2Bg}+\underline{I}_{L3Bg})$ = Residual current of the background network
$\underline{I}_{CC}$ = Current through the earthing arrangement
$\underline{Y}_{CC}$ = Admittance of the earthing arrangement
$\underline{E}_{L1}$ = Source voltage, phase L1 (e.g. 20/√3 kV∠0º)
$\underline{U}_{Lx}$ = Phase voltage of phase L1, L2 or L3 at the substation
$\underline{I}_{LxFd}$ = Phase current of phase L1, L2 or L3 of the protected feeder
$\underline{I}_{LxBg}$ = Phase current of phase L1, L2 or L3 of the background network
$\underline{Y}_{FFd}$ = Fault admittance when the fault is in the protected feeder
$\underline{Y}_{FBg}$ = Fault admittance when the fault is in the background network
$\underline{Y}_{LxFd}$ = Admittance of phase L1, L2 or L3 of the protected feeder
$\underline{Y}_{LxBg}$ = Admittance of phase L1, L2 or L3 of the background network

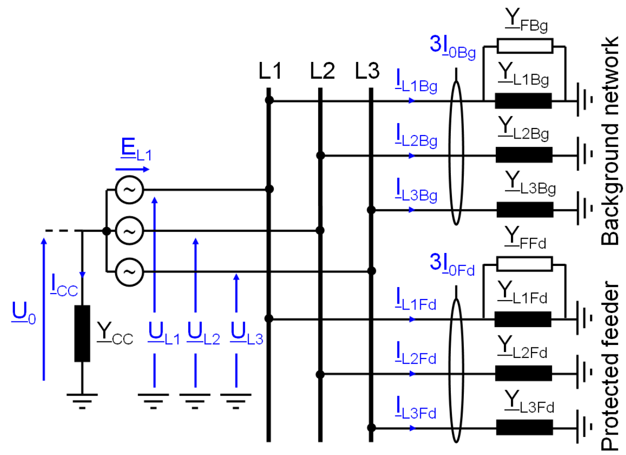

Fig. 1 Simplified equivalent circuit for high impedance earthed three phase distribution network with a single-phase earth fault in phase L1.

The equivalent circuit of *Fig. 1* is equally valid during healthy and faulty states. During the healthy state the fault resistances equal infinity i.e. the fault admittances $\underline{Y}_{FFd}$ and $\underline{Y}_{FBg}$ are zero. In case of an earth fault inside the protected feeder, then $\underline{Y}_{FFd} > 0$ and $\underline{Y}_{FBg} = 0$. Further, if an earth fault occurs outside the protected feeder i.e. somewhere in the background network, $\underline{Y}_{FBg} > 0$ and $\underline{Y}_{FFd} = 0$.

In compensated networks, the admittance of the earthing arrangement equals $\underline{Y}_{CC} = G_{CC} - j{\cdot}B_{CC} = 1/R_{CC} - j{\cdot}K{\cdot}B_{tot}$, where K is the degree of compensation, B_{tot} is the total susceptance of the network and R_{CC} is the resistance of the parallel resistor of the compensation coil. It should be noted that the value of $\underline{Y}_{CC}$ is affected by the connection status of the parallel resistor according to the applied Active Current Forcing (ACF) scheme. Typical ACF schemes are:

I. The resistor is continuously connected during the healthy state, and then momentarily disconnected and again re-connected during the fault. The purpose of disconnecting is to improve the conditions for self-extinguishment of the fault arc.
II. The resistor is disconnected during the healthy state, and then connected during the fault until the protection operates.
III. The resistor is permanently connected. The primary purpose is to limit the healthy state U_0.

In all ACF schemes the feeder EF protection is typically set to operate based on the resistive current increased by the parallel resistor during the fault.

The applied ACF scheme also affects the behavior of the Y_0 protection algorithms as shown in the following. In addition it is important to note that in the schemes *I* and *III* the admittance $\underline{Y}_{CC}$ is the same prior to the fault and when the feeder EF protection operates. In the scheme *II*, the admittance $\underline{Y}_{CC}$ is different prior to the fault and when the feeder EF protection operates.

From *Fig. 1*, general equations for the zero-sequence voltage $\underline{U}_0$ and the residual current of the protected feeder $3\underline{I}_{0Fd}$ can be derived:

$$\boxed{\underline{U}_0 = -\underline{E}_{L1}\cdot\left(\frac{\underline{Y}_{uFd}+\underline{Y}_{uBg}+\underline{Y}_{FFd}+\underline{Y}_{FBg}}{\underline{Y}_{CC}+\underline{Y}_{Fdtot}+\underline{Y}_{Bgtot}+\underline{Y}_{FFd}+\underline{Y}_{FBg}}\right)} \quad (1)$$

$$\boxed{3\underline{I}_{0Fd} = \underline{U}_0\cdot(\underline{Y}_{Fdtot}+\underline{Y}_{FFd})+\underline{E}_{L1}\cdot(\underline{Y}_{uFd}+\underline{Y}_{FFd})} \quad (2)$$

where

$\underline{Y}_{uFd} = \underline{Y}_{L1Fd} + \underline{a}^2\underline{Y}_{L2Fd} + \underline{a}\underline{Y}_{L3Fd}$, $\underline{Y}_{Fdtot} = \underline{Y}_{L1Fd} + \underline{Y}_{L2Fd} + \underline{Y}_{L3Fd}$,

$\underline{Y}_{uBg} = \underline{Y}_{L1Bg} + \underline{a}^2\underline{Y}_{L2Bg} + \underline{a}\underline{Y}_{L3Bg}$, $\underline{Y}_{Bgtot} = \underline{Y}_{L1Bg} + \underline{Y}_{L2Bg} + \underline{Y}_{L3Bg}$,

$\underline{a} = \cos(120^o) + j\cdot\sin(120^o)$

Admittances $\underline{Y}_{uFd}$ and $\underline{Y}_{uBg}$ represent the asymmetrical part of the corresponding total phase admittance, $\underline{Y}_{Fdtot}$ and $\underline{Y}_{Bgtot}$. In an ideally symmetrical network, $\underline{Y}_{uFd}$ and $\underline{Y}_{uBg}$ equal zero. In practice, there is always some difference between the phases, and according to *Eq. 1-2* this asymmetry creates a healthy-state zero-sequence voltage and residual current.

Neutral admittance protection is based on evaluating the quotient between the residual current and zero-sequence voltage. According to the simplest approach the neutral admittance is calculated utilizing the residual current and zero- sequence voltage phasors during the fault (at time *t2*).

$$\boxed{\underline{Y}_0 = 3\underline{I}_{0Fd\_t2}/(-\underline{U}_{0\_t2})} \quad (3a)$$

An equivalent method is the use of phasors $\underline{S}_1$, $\underline{S}_2$, $\underline{S}_3$ and $\underline{S}_4$:

$$\boxed{G_0 = \mathrm{Re}(\underline{Y}_0) = 0.5\cdot(\underline{S}_2-\underline{S}_1)/abs(\underline{U}_{0\_t2})} \quad (3b)$$

$$\boxed{B_0 = \mathrm{Im}(\underline{Y}_0) = 0.5\cdot(\underline{S}_3-\underline{S}_4)/abs(\underline{U}_{0\_t2})} \quad (3c)$$

where

$\underline{S}_1 = abs(\underline{U}_{0\_t2} + 3\underline{I}_{0Fd\_t2})$, $\underline{S}_2 = abs(\underline{U}_{0\_t2} - 3\underline{I}_{0Fd\_t2})$,

$\underline{S}_3 = abs(\underline{U}_{0\_t2} + j\cdot 3\underline{I}_{0Fd\_t2})$, $\underline{S}_4 = abs(\underline{U}_{0\_t2} - j\cdot 3\underline{I}_{0Fd\_t2})$

Inserting *Eq. 1-2* into *Eq. 3a* gives the following:

a) Assuming an earth fault inside the protected feeder, $\underline{Y}_{FFd} > 0$, $\underline{Y}_{FBg} = 0$:

$$\boxed{\underline{Y}_{0in} = (\underline{Y}_{CC\_t2}+\underline{Y}_{Bgtot})\cdot k_1 + k_2} \quad (4)$$

where

$k_1 = (\underline{Y}_{uFd}+\underline{Y}_{FFd})/k_3$, $k_2 = -(\underline{Y}_{Fdtot}+\underline{Y}_{FFd})\cdot\underline{Y}_{uBg}/k_3$

$k_3 = \underline{Y}_{uFd}+\underline{Y}_{uBg}+\underline{Y}_{FFd}$

b) Assuming an earth fault outside the protected feeder, i.e. in the background network, $\underline{Y}_{FFd} = 0$ and $\underline{Y}_{FBg} > 0$:

$$\boxed{\underline{Y}_{0out} = -\underline{Y}_{Fdtot}\cdot k_4 + k_5} \quad (5)$$

where

$k_4 = (\underline{Y}_{uBg}+\underline{Y}_{FBg})/k_6$, $k_5 = \underline{Y}_{uFd}\cdot(Y_{CC\_t2}+\underline{Y}_{Bgtot}+\underline{Y}_{FBg})/k_6$

$k_6 = \underline{Y}_{uFd}+\underline{Y}_{uBg}+\underline{Y}_{FBg}$

From *Eq. 4-5* it can be seen that the calculated neutral admittance utilizing *Eq. 3a* is not single-valued neither during inside nor outside faults, but it is affected by e.g. the degree of asymmetry of the network. Also the fault resistance affects the measured admittance, which is not desirable.

In order to mitigate these effects *Eq. 3a* can be enhanced by utilizing changes in the zero-sequence quantities due to the fault:

$$\boxed{\underline{Y}_{0\Delta} = (3\underline{I}_{0Fd\_t2}-3\underline{I}_{0Fd\_t1})/(-\underline{U}_{0\_t2}-(-\underline{U}_{0\_t1}))} \quad (6)$$

where *t1*, *t2* are time instances prior to and during the fault.
Inserting *Eq. 1-2* into *Eq. 6*, and setting the fault resistances to zero prior to the fault (at time *t1*), the following equations are obtained:

a) Assuming an earth fault inside the protected feeder, $\underline{Y}_{FFd} > 0$, $\underline{Y}_{FBg} = 0$:

$$\boxed{\underline{Y}_{0\Delta in} = \underline{Y}_{CC\_t2}+\underline{Y}_{Bgtot}} \quad (7a)$$

$$\boxed{\underline{Y}_{0\Delta in} = \frac{m_0+\underline{Y}_{Fdtot}\cdot m_1\cdot(\underline{Y}_{CC\_t1}-\underline{Y}_{CC\_t2})}{m_1\cdot(\underline{Y}_{CC\_t2}-\underline{Y}_{CC\_t1})-(\underline{Y}_{CC\_t1}+m_2)\cdot\underline{Y}_{FFd}}} \quad (7b)$$

where

$m_0 = (m_3\cdot\underline{Y}_{CC\_t1} - \underline{Y}_{CC\_t2}\cdot(\underline{Y}_{CC\_t1}+m_5) + (m_4-\underline{Y}_{Bgtot})\cdot\underline{Y}_{Bgtot})\cdot\underline{Y}_{FFd}$

$m_1 = (\underline{Y}_{uFd}+\underline{Y}_{uBg})$, $m_2 = \underline{Y}_{aFd}+\underline{Y}_{aBg}$, $m_3 = \underline{Y}_{uFd}-\underline{Y}_{aBg}$, $m_4 = \underline{Y}_{uBg}-\underline{Y}_{aFd}$,

$m_5 = \underline{Y}_{Fdtot}+\underline{Y}_{Bgtot}$,

$\underline{Y}_{aFd} = \underline{Y}_{Fdtot}-\underline{Y}_{uFd}$, $\underline{Y}_{aBg} = \underline{Y}_{Bgtot}-\underline{Y}_{uBg}$

Admittances $\underline{Y}_{aFd}$ and $\underline{Y}_{aBg}$ represent the symmetrical part of the corresponding total phase admittance, $\underline{Y}_{Fdtot}$ and $\underline{Y}_{Bgtot}$.

The result from *Eq. 7a* is valid when the admittance $\underline{Y}_{CC}$ is the same at time *t1* and *t2*, $\underline{Y}_{CC\_t1} = \underline{Y}_{CC\_t2}$. This is the case when the ACF scheme *III* is used or when ACF scheme *I* is used and *t2* equals time when the resistor is re-connected during the fault. It is also theoretically valid with the ACF scheme *II,* when *t2* equals the time prior to the connection of the resistor during the fault. It is important to notice that the neutral admittance obtained in this way is not affected by the network asymmetry or the fault resistance.

The result from *Eq. 7b* is valid when the admittance $\underline{Y}_{CC}$ is different at time *t1* and *t2*, $\underline{Y}_{CC\_t1} \neq \underline{Y}_{CC\_t2}$. This is the case when the ACF scheme *II* is used, and *t2* equals the time after the connection of the resistor during the fault. The equation is also theoretically valid with the ACF scheme *I,* when *t2* equals the time when the resistor is disconnected during the fault. The obtained neutral admittance is not single-valued, i.e. it is affected by the values of e.g. $\underline{Y}_{CC\_t1}$ and $\underline{Y}_{CC\_t2}$, degree of asymmetry of the network and the fault resistance.

b) Assuming an earth fault outside the protected feeder, $\underline{Y}_{FFd} = 0$, $\underline{Y}_{FBg} > 0$:

$$\boxed{\underline{Y}_{0\Delta out} = -\underline{Y}_{Fdtot}} \quad (8)$$

According to *Eq. 8*, the calculated admittance always equals the total neutral admittance of the protected feeder itself with a negative sign, i.e. –$\underline{Y}_{Fdtot}$. It is important to note that the result is valid regardless of the applied ACF scheme. In addition, the obtained neutral admittance is not affected by the network asymmetry or the fault resistance.

By comparing *Eq. 7a* to *Eq. 4* and *Eq. 8* to *Eq. 5* it can be seen that by calculating the neutral admittance utilizing changes in the zero-sequence quantities due to the fault, the result can be made single-valued by selecting the time instance *t2* during the fault so that $\underline{Y}_{CC}$ has the same value as at time *t1* prior to the fault. From this point of view, ACF schemes with resistor switching should be avoided when *Eq. 6* is applied. In practice this means the parallel resistor should preferably be constantly connected.

COMMON EF PROTECTION FUNCTIONS

As a common start criterion for EF protection functions a U_0 overvoltage criterion is typically used. *Fig. 2* illustrates U_0 as a function of fault resistance R_F in an example network. The shaded areas represent the variation due to the network asymmetry and the faulted phase with different compensation degrees. In resonance condition (K = 1) the healthy state U_0 is 5% or 16% depending on whether or not the parallel resistor of 5 A is connected. From *Fig. 2* it can be concluded that if the parallel resistor is not connected during the healthy state, the considerably high healthy-state U_0 limits the sensitivity of the protection. Therefore the ACF scheme *I* or *III* should be applied in this example.

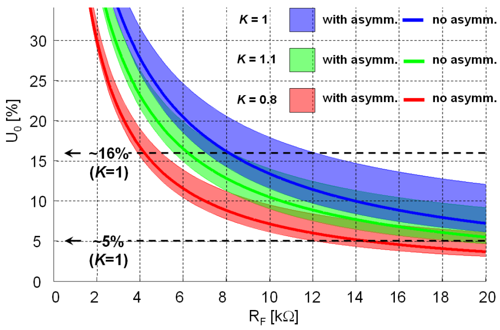

Fig. 2 Behavior of U_0 as a function of R_F in an example network with different compensation degrees when the 5 A parallel resistor is connected.

$I_0cos(\varphi)$ and phase angle criteria

In the $I_0cos(j)$ criterion operation is achieved when the product: *abs(3$\underline{I}_0$)*cos(j)* exceeds the setting value. Alternatively the phase angle criterion can be used, where the operation is achieved, when the amplitude of $3\underline{I}_0$ exceeds the setting value and the phase angle φ between -$\underline{U}_0$ and $3\underline{I}_0$ is within the set limits, i.e. inside the operation sector. The middle point of this sector is defined as the *basic angle*. In compensated networks the basic angle equals 0°, and the operation sector is typically either ±80° or ±88° wide.

Neutral admittance criterion

In the Y_0 criterion, the neutral admittance is calculated using e.g. *Eq. 6*. The result is compared to boundary lines in the admittance plane. Examples of typical characteristics available in modern feeder terminals are illustrated in *Fig. 3*. The shaded area represents the non-operation area i.e. the operation of the protection is achieved, when the calculated admittance moves outside the shaded area.

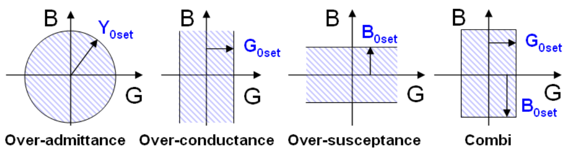

Fig. 3 Examples of Y_0 characteristics.

The key result from analysis of *Eq. 6* was that, when the Y_0 calculation is done utilizing changes in the zero-sequence quantities due to the fault, then in case of an outside fault, the calculated admittance always equals –$\underline{Y}_{Fdtot}$ i.e. the total neutral admittance of the protected feeder itself with a negative sign. This fact is utilized in the novel characteristics presented in *Fig. 4*. The idea is to set the non-operation area around –$\underline{Y}_{Fdtot}$ with a sufficient security margin. The characteristic then becomes off-set and asymmetrical in the admittance plane. Such characteristic improves the sensitivity of the protection and is valid also when the compensation coil is temporarily disconnected.

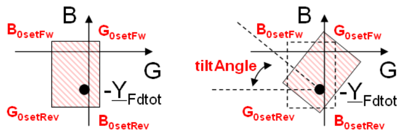

Fig. 4 Examples of the novel Y_0 characteristic.

The value of $\underline{Y}_{Fdtot}$ is the primary setting base for the novel characteristic. The imaginary part of $\underline{Y}_{Fdtot}$ can be easily calculated from the capacitive EF current of the protected feeder itself:

$$Im(\underline{Y}_{Fdtot}) \approx j \cdot 3I_{0Fd}/U_{phase} \qquad (9)$$

The value of $3I_{0Fd}$ can be obtained directly from the utility DMS, and can easily be updated, in case the feeder configuration changes substantially. The real part of $\underline{Y}_{Fdtot}$ can be either determined by measurements or estimated to be typically 20…30 times smaller than the imaginary part.

EARTH-FAULT SIMULATIONS

The meaning of *Eq. 3a* and *Eq. 6* is illustrated in *Fig. 5* using simulated data. The simulated network represents a simplified distribution network as illustrated in *Fig. 1*. A single-phase earth-fault is applied into each phase, and the fault resistance is varied from 0 to 20 kΩ in 1 kΩ steps. Two compensation degrees, K = 0.8 and 1.1 are analyzed. The rated current of the parallel resistor (I_{ACF}) is assumed to be 5 A. All ACF schemes are included in the simulation. The degree of network asymmetry matches the values used in the calculations represented in *Fig. 2*.

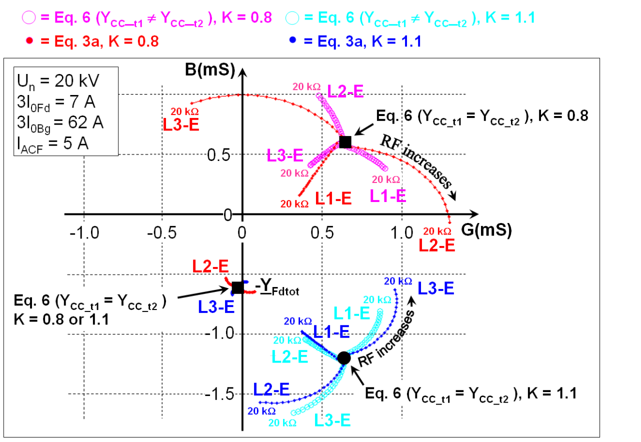

Fig. 5 Simulated behavior of the neutral admittance calculation algorithms.

From *Fig. 5* the effect of fault resistance, network asymmetry and the faulted phase on the different Y_0 calculation methods can clearly be seen:

- The best result is achieved, when the Y_0 calculation is based on *Eq. 6* and when the admittance $\underline{Y}_{CC}$ is the same prior to and during the fault, $\underline{Y}_{CC\_t1}$ = $\underline{Y}_{CC\_t2}$. The result is then single-valued and not affected by the value of R_F, the network asymmetry or the faulted phase. This allows high sensitivity of the protection, especially if the novel characteristic would be applied.
- If the Y_0 calculation is based on *Eq. 3a* or on *Eq. 6* when the admittance $\underline{Y}_{CC}$ is different prior to and during the fault, $\underline{Y}_{CC\_t1} \neq \underline{Y}_{CC\_t2}$, then the result is not single-valued. Depending on the faulted phase, each phase-to-earth fault creates an individual admittance trajectory, the course of which depends on R_F and network asymmetry. This reduces the dependability of the Y_0 criterion, especially if high sensitivity is required.

FIELD TESTING AND EXPERIENCE

In recent years, ABB Oy, Distribution Automation, Finland has undertaken intensive field testing in co-operation with some Finnish power utilities in order to test and develop new EF protection algorithms. Below, one field test series is studied. These tests were made in a 20 kV rural distribution network with overhead lines in Finland. The compensation degree during the tests was K = 1.1 and the ACF scheme *II* was applied. The faulted phase was L3 and R_F was varied from 0 to 10 kΩ. The capacitive EF currents of the network match the values used in the simulation model, see *Fig. 5*.

The performance of traditional $I_0cos(j)$ criterion is evaluated in *Fig. 6*. A two-stage protection is applied using the low-set stage $I_0cos(j)$> for alarming, and the high-set stage $I_0cos(j)$>> for tripping. In this case, the stages are set to 2.5 % and 20 %. This corresponds to 0.5 A and 4.0 A primary currents. Red color represents the results when the parallel resistor is connected and blue color when the parallel resistor is disconnected during the fault.

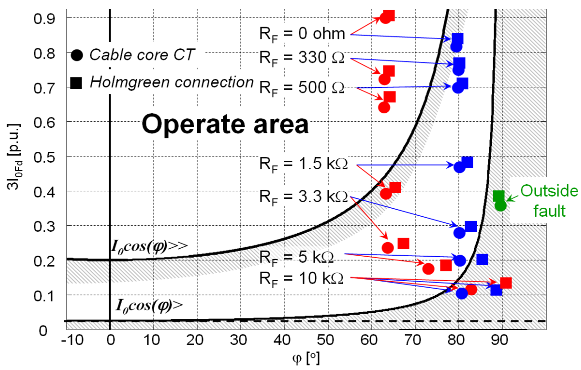

Fig. 6 Evaluation of the I_0cos(j) criterion based on field test data.

From *Fig. 6* it can be concluded that in order for the high-set stage to operate properly, the parallel resistor needs to be connected. Also with the selected settings, the low-set stage cannot detect faults with 10 kΩ fault resistance. More sensitive operation could be achieved by the use of phase angle criterion and ±88° wide operation sector.

As a comparison, the Y_0 calculation methods are evaluated in *Fig. 7*, prior to (left) and after (right) the 5 A parallel resistor was connected during the fault. The results using *Eq. 3a* are shown with red and magenta, whereas results from *Eq. 6* are highlighted in blue and cyan. Red and blue color represents results when a cable core CT was used for residual current measurement, whereas magenta and cyan represent results with a Holmgreen connection.

From *Fig. 7* it can be seen that utilization of changes in the zero-sequence quantities (*Eq. 6*) reduces the deviation in the calculated admittance. With this measuring principle, the maximum tested fault resistance of 10 kΩ can be detected easily, provided that the novel Y_0 characteristic is applied.

Also the applied start criterion must have adequate sensitivity without the risk of false starts, e.g. when the switching state changes in the network. Further, the traditional over-conductance (G_0>) method lacks sensitivity compared with the novel approach, which can operate even without the parallel resistor due to the natural losses of the coil and the network. However, it is recommended to keep the resistor constantly connected, as then the discrimination between inside and outside faults is improved.

In case two-stage protection is required, it can be achieved by two independent Y_0 protection instances (Y_{01}>, Y_{02}>) with differently set start criteria. For example in case of network studied in *Fig. 2*, the Y_{01}>-stage for alarming could have U_0-start set to 10% corresponding to $R_F \approx$ 6 kΩ (K=0.8) and the Y_{02}>-stage for tripping could have U_0-start set to 30% corresponding to $R_F \approx$ 2 kΩ (K=0.8).

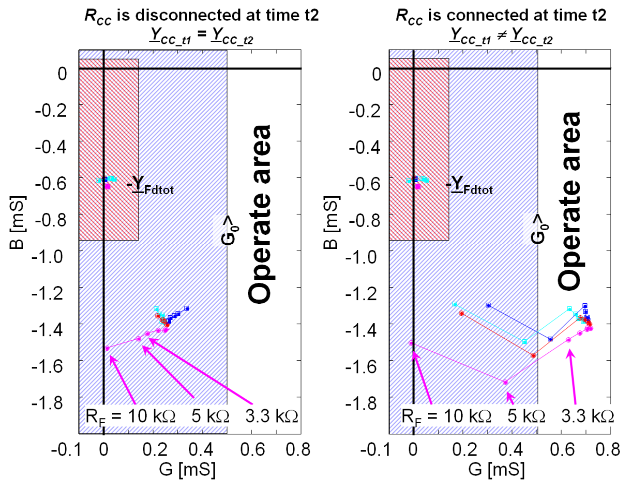

Fig. 7 Comparison of performance of the novel (red) and traditional (blue) Y_0 characteristics and Y_0 calculation methods based on field test data.

For both evaluated EF protection functions the measuring principle of the residual current has a noticeable impact, and cable core CTs should be used if high sensitivity is required.

CONCLUSIONS

The performance of the neutral admittance based EF protection has been studied. The results show that Y_0 protection is a respectable alternative to traditional EF protection functions. Benefits include e.g. good immunity to fault resistance and easy setting principles. Based on the theory and field tests, the admittance calculation should be based on changes in the zero-sequence quantities due to a fault, the novel Y_0 characteristic should be used and the parallel resistor should be permanently connected. This maximizes the performance of the Y_0 protection. The neutral admittance protection function together with the presented algorithm enhancements will be implemented in the next generation feeder terminals applied in distribution and sub-transmission networks.

REFERENCES

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