EFFECT OF CORE BALANCE CURRENT TRANSFORMER ERRORS ON SENSITIVE EARTH-FAULT PROTECTION IN COMPENSATED MV-NETWORKS

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ABSTRACT

The protection functions applied for sensitive directional earth-fault protection in compensated MV-networks are based on measurement of residual current and voltage, and derivation of the resistive operation quantity thereof. In this paper, the importance of residual current measurement accuracy on earth-fault protection performance in compensated MV-networks is analysed. First the fundamental theory of directional earth-fault protection is recalled. Then the factors affecting the measuring errors of a Core Balance Current Transformer (CBCT) are described. Finally a selection guideline of CBCTs for residual current and neutral admittance-based directional earth-fault protection taking into account the measurement errors is given.

INTRODUCTION

Directional earth-fault protection in compensated networks

A simplified three-phase equivalent circuit of a compensated network during a single phase earth fault is presented in ***Fig. 1***. From it, general equations required for basic earth-fault protection analysis can be derived [1]: phasor of the residual voltage or the neutral point voltage of the network $\overline{U}_o = (\overline{U}_A + \overline{U}_B + \overline{U}_C)/3$, and phasor of the residual current or the sum current $\overline{I}_o = (\overline{I}_A + \overline{I}_B + \overline{I}_C)$ measured at the beginning of the protected feeder during an earth fault. In the following equations, ideal symmetry of the network is assumed.

$$\overline{U}_{op} = -\frac{U_{PE}}{\overline{a}_{RF}} \tag{1a}$$

$$\overline{I}_{op}^{OutsideEF} = -\frac{I_{EFFd}\cdot(d_{Net} + j\cdot 1)}{\overline{a}_{RF}} \tag{1b}$$

$$\overline{I}_{op}^{InsideEF} = \frac{I_{Par} + I_{Coil}\cdot(d_{Coil} - j\cdot 1) + I_{EFNet}\cdot(d_{Net} + j\cdot 1)}{\overline{a}_{RF}} + \overline{I}_{op}^{OutsideEF} \tag{1c}$$

where $\overline{a}_{RF} =$

$$\frac{R_F\cdot(I_{Par} + I_{Coil}\cdot(d_{Coil} - j\cdot 1) + I_{EFNet}\cdot(d_{Net} + j\cdot 1)) + U_{PE}}{U_{PE}} \tag{1d}$$

The factor $\overline{a}_{RF}$ takes into account the effect of fault resistance, which attenuates the voltage and current by the same amount. During a solid (R_F =0Ω) earth fault $\overline{a}_{RF}$ = 1. In ***Eq. 1a-1d*** the following parameters are used, which are the basic earth fault related parameters of the network:

U_{PE} is the operating phase-to-earth voltage [V]. I_{EFFd} is the capacitive uncompensated earth-fault current of the protected feeder [A]. d_{Net} is a factor [pu] to approximate the natural losses of the feeder/network, typical value is between 0.01…0.10. I_{Par} is the additional resistive current [A] at primary voltage level produced by the parallel resistor of the Arc Suppression Coil (ASC, Petersen coil). I_{Coil} is the inductive current produced by the ASC [A] determined by the set tuning degree. d_{Coil} is a factor [pu] to approximate the losses of the ASC, typical value is between 0.01…0.05. I_{EFNet} is the capacitive uncompensated earth-fault current of the network [A]. Subscript *p* refers to primary voltage level.

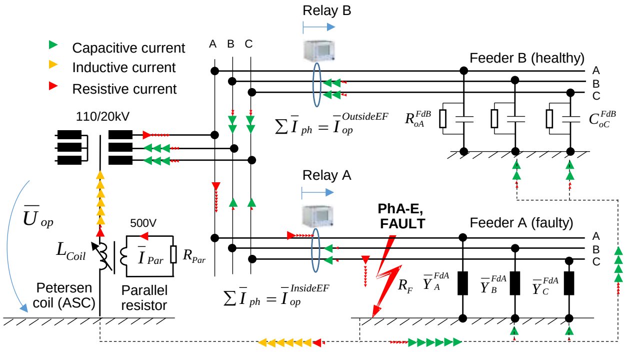

Fig. 1. *Three-phase simplified equivalent circuit of a compensated network with earth fault in phase A of the Feeder A.*

In the following a numerical example using ***Eq. 1a-1d*** is given. Assume a 20kV network with 200A of uncompensated earth-fault current, the network is operated with 5A overcompensation (coil current is 200+5 = 205A) and with 7A parallel resistor continuously connected. The earth-fault current of the protected feeder is 25A. Natural losses of the feeder/network are estimated to be 4%. The losses of the ASC are 2.5%. The parameters required for ***Eq. 1a-1d*** are then at primary voltage level:

$$U_{PE} = 20000V/\sqrt{3} = 11547\,V,\ d_{Net} = 0.04\,pu,\ I_{Par} = 7A$$
$$I_{Coil} = (200+5)A,\ d_{Coil} = 0.025\,pu,\ I_{EFNet} = 200A,\ I_{EFFd} = 25A$$

In ***Table 1***, the phasors of $\overline{U}_{op}$ and $\overline{I}_{op}$ calculated with ***Eq. 1a-1d*** are given during an earth fault inside and outside the protected feeder with fault resistances 0, 500 and 5000Ω. Note that phase angle difference φ is calculated as $-\overline{U}_{op}$ being the reference phasor: $\varphi = \angle -\overline{U}_{op}$ - $\angle \overline{I}_{op}$.

Table 1. $\overline{U}_{op}$ and $\overline{I}_{op}$ phasors during an earth fault in the network.

R_F	$-\overline{U}_{op}$		$\overline{I}_{op}^{InsideEF}$			$\overline{I}_{op}^{OutsideEF}$		
Ω	Abs V	Ang. deg.	Abs A	Ang. deg.	φ deg.	Abs A	Ang. deg.	φ deg.
0	11547	0.0	35.6	-57.5	57.5	25.0	-92.3	92.3
500	6129.2	6.6	18.9	-50.9	57.5	13.3	-85.7	92.3
5000	1160.2	12.6	3.6	-44.9	57.5	2.5	-79.7	92.3

There are two important observations that can be made:

a) The magnitudes of $\bar{U}_{op}$ and $\bar{I}_{op}$ decrease proportionally with increasing value of R_F,

b) The phase angle difference φ between $-\bar{U}_{op}$ and $\bar{I}_{op}$ is constant, i.e. it is not affected by the fault resistance!

This means that the ratio of phasors $\bar{Y}_{op} = \bar{I}_{op}/-\bar{U}_{op}$, the admittance phasor, remains constant! The results of ***Table 1*** are illustrated in ***Fig. 2***.

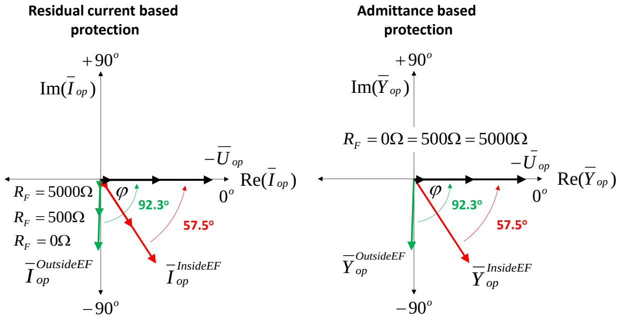

Fig. 2. *Illustration of earth-fault quantities,* $-\bar{U}_{op}$, $\bar{I}_{op}$ *and* $\bar{Y}_{op}$.

In compensated networks, the traditionally applied directional earth-fault protection is based on the fundamental frequency resistive component of residual current, known as the *Iocos*-component:

$$Iocos = abs(\bar{I}_{op}) \cdot \cos(\varphi) \quad (2)$$

The operation of *neutral admittance*-based directional earth-fault protection in compensated networks, is based on the real-part of the measured admittance, known as the *conductance* (G_o) which can be calculated as:

$$G_o = Re(\bar{I}_{op}/-\bar{U}_{op}) \quad (3)$$

The operation quantities of earth-fault protection derived from phasors of ***Table 1*** are presented in ***Table 2***.

Table 2. Operation quantities of directional earth-fault protection in primary calculated from phasors of ***Table 1***. Conductance value G_o is converted into equivalent current value by multiplying it with U_{PE}.

R_F [Ω]	Inside fault	Outside fault	Inside fault	Outside fault
	Iocos [A]	*Iocos [A]*	*G_o [A]*	*G_o [A]*
0	19.1	-1.0	19.1	-1.0
500	10.2	-0.5	19.1	-1.0
5000	1.9	-0.1	19.1	-1.0

From ***Table 2***, the following observations can be made:

1. The resistive component in the faulty and healthy feeder have theoretically opposite signs: it is positive in the faulty feeder and negative in the healthy feeder (assuming $-\bar{U}_{op}$ as the reference phasor). Note that the conductance value G_o is not affected by fault resistance and it always equals the value obtained from current based method with $R_F = 0\Omega$!

2. The resistive component measured in the faulty feeder depends in practice dominantly on the parallel resistor of the ASC (parameter I_{Par}). In modern networks, the value of natural losses (parameter d_{Net}) is very low due to increased share of cables with good insulation properties. Thus the dependability of protection becomes more and more dependent on the existence of the "forced" resistive component from the parallel resistor of the ASC.

3. The resistive component measured in the healthy feeder is due to the natural losses of the feeder itself. In case, there is distributed compensation coils installed along the feeder, the losses of the coils typically increase the value of resistive component.

As seen from ***Table 2***, the resistive component especially in the healthy feeder may be very small and thus subject to measurement inaccuracies. If the measurement chain introduces a high value of phase displacement, then a large apparent resistive component may be introduced to the operation quantities measured by earth-fault protection. This may lead to unwanted, unselective operation of the protection in the healthy feeder, especially if very sensitive protection settings are used. Therefore, it is important to recognize the measurement errors especially in residual current, and understand their effect. Next, the errors of residual current measurement are studied in detail.

Measurement error introduced by the CBCT

In compensated networks the residual current measured at the beginning of the protected feeder is typically very small during a single phase earth fault, only a few tens of amperes at maximum. The measurement of such low current is recommended to be done with a Core Balance Current Transformer (CBCT). The equivalent circuit of a CBCT is shown in ***Fig. 3***. It can be seen that the total primary current referred to secondary does not flow through the secondary burden: a small part of the secondary current is consumed for core excitation, which introduces a measuring error both in terms of magnitude and phase angle. These errors increase, the lower current in relation to the rated primary current is measured.

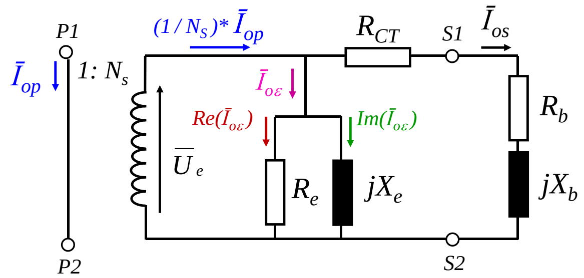

Fig 3. *Equivalent circuit of CBCT.*

In ***Fig. 3***, the following notations are used:

Primary terminals = P1, P2, $\bar{I}_{op}$ = Primary current, N_s = Number of turns of secondary winding, $\bar{U}_e$ = Magnetizing voltage, $\bar{I}_{o\varepsilon}$ = Magnetizing current, $Re(\bar{I}_{o\varepsilon})$ = Resistive part of magnetizing current due to core losses, $Im(\bar{I}_{o\varepsilon})$ = Reactive part of magnetizing current due to excitation, R_e = Magnetizing resistance, X_m = Magnetizing reactance, R_{CT} = Secondary winding resistance, Secondary terminals = S1, S2, $\bar{I}_{os}$ = Secondary current, R_b, X_b = Resistance and reactance of the burden.

The following phasor diagrams referred to primary can be derived from the equivalent circuit of ***Fig. 3***.

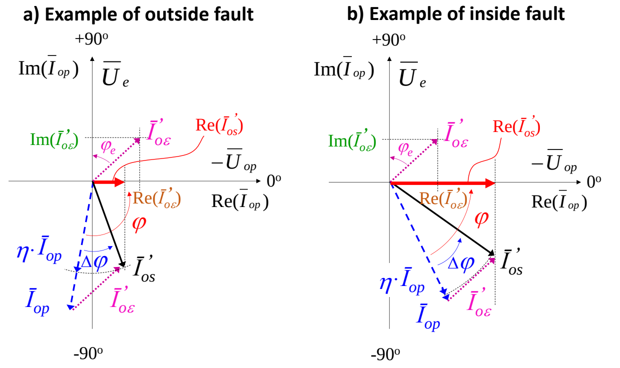

Fig. 4. *Phasor diagrams of CBCT.* $\bar{I}'_{os}$ *is the secondary residual current measured by protection relay referred to primary. The error phasor introduced by the magnetizing impedance is* $\bar{I}'_{o\varepsilon}$.

For the magnetizing impedance, the following applies:

$$\bar{Z}_e = R_e + j \cdot X_e = \frac{\bar{U}_e}{\bar{I}_{o\varepsilon}} \cong j \cdot \omega \cdot \bar{\mu} \cdot \frac{N_s^2 \cdot A_{Fe}}{l_{Fe}} \qquad (4)$$

where $\bar{\mu}$ = Permeability of magnetic material i.e. the measure of the ability of a material to support the formation of a magnetic field within itself (in practice permeability is strongly non-linear and depends on the magnetic flux density). A_{Fe} = Cross-section of the iron core. l_{Fe}= Average length of the magnetic path.

From ***Eq. 4*** it can be seen that minimization of the measurement errors of a CBCT can be made by minimizing the magnetizing current. This can be achieved by increasing the value of the magnetizing impedance by:

- ✓ Increasing the iron core cross-section (A_{Fe}):
  - "The bigger core, the better"
- ✓ Decreasing the core lengt (l_{Fe}):
  - "Ring type better than window type"
- ✓ Increasing A-turns value (N_S):
  - "The higher turns, the better"
- ✓ Using higher quality magnetic materials ($\bar{\mu}$):
  - To improve the accuracy of current transformers, special magnetic materials may be used (e.g. "myy"-metal instead of standard M5-iron), which have better magnetic properties. From economical perspective, such materials are more expensive.

The errors for current transformers are defined in IEC-standard 61869-2 [2] as follows:

Current error (ratio error) ε [%]

$$\varepsilon = \frac{I'_{os} - I_p}{I_p} \cdot 100\% \qquad (5a)$$

The current error may be either positive or negative depending e.g. on the actual burden. If current error is positive, then actual secondary current is higher due to measurement error. Current error can also be expressed as *efficiency* (of measurement), η:

$$\eta = 1 + \varepsilon \qquad (5b)$$

With efficiency, the magnitude of secondary current can be written as (refer to ***Fig. 4***):

$$abs(\bar{I}'_{os}) = \eta \cdot abs(\bar{I}_{op}) \qquad (5c)$$

Phase displacement (phase angle error) $\Delta\varphi$ [min]

Phase displacement is the difference in phase between the primary and secondary current phasors (refer to ***Fig. 4***). The phase displacement for CBCT is always positive, the secondary current leads the primary.

It is important to realize, that standard IEC 61869-2 does not specify CT errors at low residual current magnitudes for protection class (5P or 10P) current transformers. For example, if CBCT of class 5P with ratio 100/1A is used, the standard only defines the errors at one operation point, at the rated primary current 100A. From application perspective, such value is very high during an earth fault in compensated network. Typically the sensitivity requirements of protection set by legislation results in setting values in the range of 1…5A in compensated networks.

Measurement class current transformers have defined accuracy also at lower values than the rated current – for special class (0.5S, 0.2S), even down to 1% of rated current. Application of measuring class CTs to earth-fault protection applications, especially if tripping protection is used, must be carefully considered. So called *Instrument Security Factor (FS)* defines the overcurrent magnitude as a multiple of the rated current at which the metering core will saturate. It is thus limiting the secondary current to *FS* times the rated current beyond which CT core becomes saturated. During saturation the measuring errors are highly increased. If a measuring class CBCT is applied for sensitive directional earth-fault protection, then additional earth-fault protection stages operating with calculated residual current or measured sum current ("Holmgreen connection") must be implemented in the protection scheme. High residual currents, which may saturate a measuring class CBCT, may be measured for example during earth faults, when the detuning of the ASC highly deviates from its normal value, or when the ASC is disconnected. Also cross-country faults can produce very high residual currents.

It is also possible to specify a CBCT with both requirements on accuracy at low primary currents and on capability to reproduce a high primary current without saturation. This means a CBCT with combined measuring and protection class properties. Such CBCT has a class designation, for example as: 0.2S/5P25, 100/1A, 1.2VA. Practically it means that for primary currents 1A-120A, accuracy of class 0.2S is guaranteed and for high primary current up to 25*100A = 2500A, the composite error is equal or lower than 5% (class 5P). Alternatively it is possible to complement the standard protection class specification with a special requirement for phase displacement at low current values, e.g.: $\Delta\varphi$<5° at 1%.

REQUIREMENTS FOR RESIDUAL CURRENT MEASUREMENT ACCURACY

Next the requirements for residual current measurement accuracy are defined for sensitive earth-fault protection considering residual current- or admittance-based methods. Taking into account the errors introduced by the CBCT, the secondary current measured by a protection relay can be written from the basis of ***Fig. 4*** as (secondary quantities referred to primary):

$$\bar{I}'_{os} = \bar{I}_{op} + \bar{I}'_{o\varepsilon} \qquad (6)$$

Where $\bar{I}'_{o\varepsilon}$ represents the total current error in phasor format which results from combined effect of current error ε and phase displacement $\Delta\varphi$. The resistive component of the measured residual current considering the measurement errors is thus:

$$real(\bar{I}'_{os}) = \eta \cdot abs(\bar{I}_{op}) \cdot \cos(\varphi - \Delta\varphi) \qquad (7)$$

Eq. 8 can be re-written by solving the phase displacement:

$$\Delta\varphi = \varphi - a\cos\left(\frac{\mathrm{Re}(\bar{I}'_{os})}{\eta \cdot abs(\bar{I}_{op})}\right) \qquad (8a)$$

If *Iocos*-criterion is applied in protection, the requirements for the residual current measurement accuracy can be derived by replacing the term $Re(\bar{I}'_{os})$ with the resistive current threshold setting I_{ocos}^{set}. Therefore, to avoid unselective operation of protection during an earth fault outside the protected feeder, the (maximum) phase displacement must not exceed:

$$\Delta\varphi \le \varphi - a\cos\left(\frac{I_{o\cos}^{set}}{\eta \cdot abs(\bar{I}_{op})}\right) \qquad (8b)$$

The interpretation of ***Eq. 9b*** is that the maximum allowed phase displacement is a function of measured residual current magnitude. The requirement becomes stricter when measured residual current magnitude increases, and milder when measured residual current magnitude decreases. The strictest requirement is valid when maximum value of residual current is measured. Such condition is encountered in practice with long cable feeders with high capacitive earth-fault current contribution during low-ohmic outside faults.

If *conductance*-criterion is applied in protection, the requirement for phase displacement must be defined differently. Theoretically (refer to ***Fig. 2***) the residual current and voltage phasors are both attenuated by the same factor $\bar{a}_{RF}$ due to fault resistance, and their ratio i.e. the admittance phasor remains constant. Thus, for the admittance based protection, requirement for phase displacement must be written as:

$$\Delta\varphi \le \varphi - a\cos\left(\frac{U_{PE}[kV] \cdot G_o^{set}[mS]}{\eta \cdot I_{EFFd}[A]}\right) \qquad (8c)$$

The interpretation of ***Eq. 8c*** is that the maximum allowed phase displacement is defined with maximum residual current value measured for admittance calculation. In practice, this requirement depends on the I_{EFFd}-value of the feeder and becomes stricter when the I_{EFFd}-value increases. The requirement becomes a constant value, valid down to a minimum residual current value used for admittance calculation (typically ~1A)! Similarly as in current based protection, the strictest requirement is valid with long cable feeders with high I_{EFFd}-value. Comparing ***Eq. 8b*** with ***Eq. 8c***, it can be concluded that the admittance based protection has stricter requirement for phase displacement as the requirement is constant down till the lowest current value to be measured.

The phase displacement requirement depends also on the assumed phase difference defined by the parameters of the primary network. In ***Eq. 8a-8c***, the phase difference φ depends on the natural losses of the protected feeder, and it can be calculated as:

$$\varphi \cong 90^\circ + a\tan\left(\frac{1}{I_{\mathrm{Res}}/(I_W - I_{Par})}\right) \qquad (9)$$

where I_{Res} the total uncompensated earth-fault current of the network, I_W is the total wattmetric (resistive) component current of the network including the losses of the network, the coil and the parallel resistor. By subtracting the resistive current of the parallel resistor from the total network losses ($I_W - I_{Par}$), estimate of the resistive losses valid for the feeders is obtained.

From ***Eq. 8b-8c*** it can be concluded that the phase displacement requirement for CBCT depends on:

a) *Setting value*. The lower setting, the higher phase displacement requirement becomes. When the sensitivity of protection is increased, the requirement for the phase displacement becomes stricter.

b) *Measured residual current or earth-fault current produced by the protected feeder (I_{EFFd})*. This means that the requirement must be defined as a function of residual current magnitude, not only in a single operate point. Note that I_{EFFd}-value depends on the topology of the feeder. *M*aximum realistic I_{EFFd} -value should be considered in the calculations. In this paper, I_{EFFd} = 25A.

I. In the *Iocos*-criterion the apparent resistive current component is proportional to the actual measured current magnitude: The higher the measured current, the higher the apparent resistive current component becomes.

II. In the *conductance*-criterion the apparent conductance is proportional to the earth-fault current value produced by the feeder when $R_F = 0\Omega$, not to the actual measured residual current. The higher the I_{EFFd} -value is, the higher the apparent resistive component (conductance) becomes.

In order to visualize the requirement for phase displacement, the requirement for *Iocos*-criterion, ***Eq. 8b,*** is plotted as a function measured residual current magnitude with I_{ocos}^{set} = 1A and η =1.1 in ***Fig. 5***. The setting 1A is very typical in substations in Scandinavia, where residual current based protection is commonly applied.

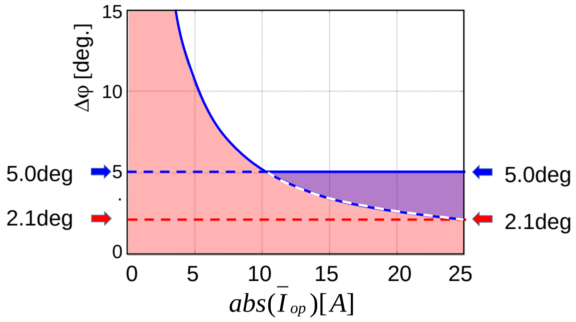

Fig. 5. *Requirement for phase displacement (area shaded in red) for Iocos-criterion,* I_{ocos}^{set} *= 1A,* η *=1.1.*

From ***Fig. 5*** it can be concluded that the phase displacement requirement for *Iocos*-criterion becomes stricter as the measured residual current increases. The maximum allowed phase displacement is 2.1deg. at 25A. As the magnitude of residual current decreases the requirement becomes lower, it is only 15deg. at 3.5A.

The requirement for *conductance*-criterion, ***Eq. 8c***, is illustrated in ***Fig. 6*** as a function of measured residual current with I_{EFFd} =25A, G_o^{set} = 3A = (0.26mS@20kV) and η =1.1. Selected setting value 3A is the minimum recommended setting value in practical networks.

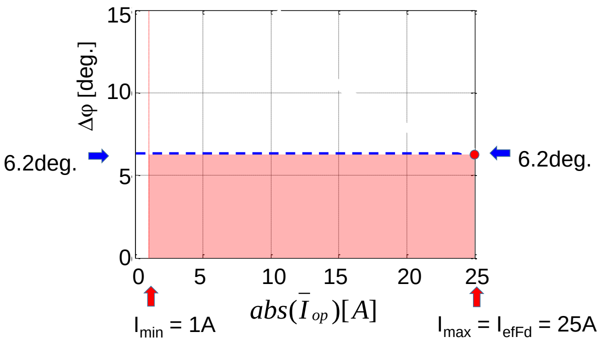

Figure 6. *Requirement for phase displacement (area shaded in red) for conductance-criterion,* I_{EFFd} *=25A,* G_o^{set} *= 3A =(0.26mS@20kV),* η *=1.1.*

The result of ***Fig. 6*** is that for *conductance*-criterion, phase displacement must not exceed 6.2deg. in current range 1A-25A.

It should be noted that in previous examples, the phase angle difference φ of 90deg. was used, i.e. losses of the protected feeder were neglected. This gives the most conservative phase displacement requirement.

As seen from ***Eq. 8b-8c*** one way to reduce requirements for phase displacement is to increase the setting values. However, in order to maintain adequate sensitivity of protection, this would require increasing the rated current value of the parallel resistor I_{Par}. Note that in admittance-based earth-fault protection, this additional resistive component seen by protection is not affected by the fault resistance value. Thus, the higher the value of I_{Par} is, the higher tolerance against measurement errors can be achieved. Increasing the value of I_{Par} must be considered carefully as it may decrease the sensitivity of protection by increased attenuation of the residual voltage especially with higher fault resistance values.

Another alternative to reduce the requirements for phase displacement is to narrow the applied operate sector by tilting the boundary line of operate area. In ***Fig. 5*** it is shown that a tilt angle of 5deg. (blue dashed line) reduces the requirement for phase displacement at 25A from 2.1deg. to 5.0deg. The tilt angle must not be set to too high value, as it may reduce the dependability of protection.

CONCLUSIONS

This paper describes the effect of Core Balance Current Transformer (CBCT) errors on sensitive earth-fault protection in compensated MV-networks. Other error sources in a practical measurement chain such as relay and voltage measurement were not considered. The analysis in this paper was limited to study the influence of measurement errors from security perspective, so that false protection operations during outside faults due to measurement errors are prevented.

It is important to notice that the suitability of protection class CBCTs cannot be guaranteed by default for sensitive earth-fault protection in compensated MV-networks! This is because their accuracy is not specified at typical residual current levels measured during practical faults. Therefore, the accuracy of any CBCT, especially the phase displacement, should always be specified at the design phase of a substation project. This paper gives a simple method for determining the requirement for phase displacement. The final requirement depends on the feeder/network parameters, type of protection relays, applied functions and their settings. Based on the practical experience by the authors, the preferred CBCT combines the measuring class and protection class requirements. Such CBCT is able to measure low residual currents accurately, and is also capable of reproducing high residual currents without saturation.

It can be foreseen that the sensitivity requirements for earth-fault protection are increasing in the future. Therefore, a properly specified "combi-class" CBCT with universal applicability would be a future proof solution to fulfill these new requirements considering the long expected life time of primary measuring equipment.

REFERENCES

[1] A. Wahlroos, J. Altonen, *Performance of novel neutral admittance criterion in MV-feeder earth-fault protection, CIRED2009 Prague.*

[2] IEC 61869-2:2012, Instrument transformers - Part 2: Additional requirements for current transformers.