PRACTICAL APPLICATION AND PERFORMANCE OF NOVEL ADMITTANCE BASED EARTH-FAULT PROTECTION IN COMPENSATED MV-NETWORKS

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ABSTRACT

This paper describes the practical application and performance of a novel neutral admittance based earth-fault protection function for compensated networks. First, the theories of the traditional residual current based and the neutral admittance based earth-fault protection functions are reviewed. For admittance protection a novel method is presented, characterized by exceptionally easy setting and application. Second, a typical earth-fault protection scheme with example settings is composed and then implemented with the traditional and novel functions. Finally, the performance of the two alternative methods is compared by simulation and using actual field test data. The results show that the novel neutral admittance protection principle provides superior performance in many ways and has therefore a high potential to become a widely used protection principle in networks with centralized or distributed compensation.

INTRODUCTION

Feeder earth-fault (E/F) protection in compensated MVnetworks is typically based on traditional residual current measuring principles such as the *Iocosphi* or *phase angle principle*. In recent years, also the neutral admittance protection principle (*Y_o principle*) has been under research and development, and improvements to traditional measurement methods and operation characteristics have been suggested [1]. As a result of this work an enhanced admittance protection function is now available in IEDs of the *ABB Relion®* product family.

THEORY

In the *Iocosphi principle* operation is achieved when the product *abs($\underline{I}_o$)*cos(phi),* i.e. the resistive component of $\underline{I}_o$, exceeds the *start current* setting. Alternatively, the *phase angle principle* can be used, where the operation is achieved, when the amplitude of $\underline{I}_o$ exceeds the *start current* setting and the phase angle difference *phi* between -$\underline{U}_o$ and $\underline{I}_o$ is within the set operation sector. The middle point of the sector is defined by the *base angle*, which equals 0° in compensated networks and -90° in isolated neutral networks. In both methods the sector width may be limited by a *correction angle* in order to allow for e.g. measurement inaccuracies. In both methods, a general U_o based start criterion is typically used, which defines the principal sensitivity of the protection. Typical operation characteristics for the *Iocosphi* (solid line) and *phase angle principle* (dashed line) are presented in *Fig. 1*.

The advantage of the traditional E/F protection methods is that they are commonly known and the setting principles are familiar to protection engineers and utility personnel. The performance of the traditional protection methods is generally considered adequate, but certain practical limitations exist as will be described in the following.

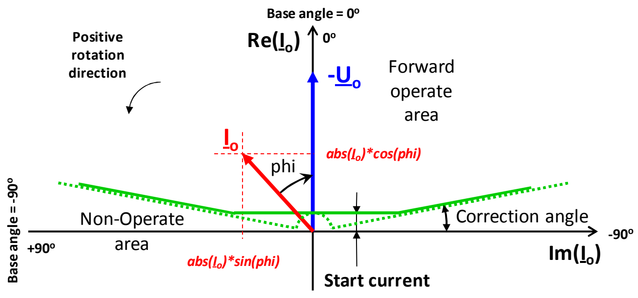

Fig. 1 *Operation characteristic of the Iocosphi and the phase angle principle.*

The disadvantage is that as the operate quantity is based on $\underline{I}_o$, the operation sensitivity decreases as the fault resistance increases. In addition, an adequate resistive current is always required for the operation, which must be ensured by the connection of a resistor in parallel with the compensation coil. If the coil is disconnected, the relay settings must be changed accordingly (e.g. from the *Iocosphi* to *the Iosinphi principle*), which in practice complicates the implementation and daily operation. Also problems in connection with intermittent earth-faults have been reported [2]. Furthermore, the introduction of distributed compensation coils challenges the traditional E/F protection functions, as they have not been originally designed for such network configurations.

In the *Y_o principle* the quotient between the fundamental (50 or 60 Hz) frequency phasors of $\underline{I}_o$ and -$\underline{U}_o$, i.e. the neutral admittance, is evaluated. The calculated admittance is compared to the boundary lines in the admittance plane in the same way as the calculated impedance is compared to the boundary lines in the impedance plane in distance protection. The operation in the *Y_o principle* is achieved, when the calculated admittance moves outside the boundary lines.

In reference [1] a novel neutral admittance characteristic was introduced. The idea is to set the "box"-shaped quadrilateral zone, representing the non-operation area, to cover the value of the total neutral admittance of the protected feeder with sufficient margin. This is analogous to distance protection, where zones are set according to the impedance of the protected line. An example of the novel Y_o protection characteristic and its analogy to distance protection is illustrated in *Fig. 2*.

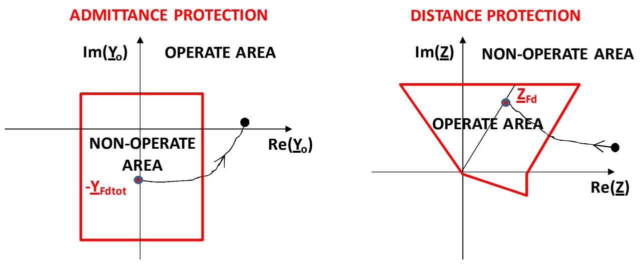

Fig. 2 *Novel Y_o characteristic and its analogy to distance protection.*

The novel Y_o characteristic enables universal protection: the same characteristic is valid also when the compensation coil is disconnected and no changes of settings defining the characteristic are needed. Furthermore, the characteristic optimizes the sensitivity enabling operation even without the parallel resistor (under certain conditions), which improves the operation speed and dependability.

The major advantage of the Y_o *principle* is that, unlike in traditional E/F protection functions, the operate quantity $\underline{Y}_o$ is practically not affected by the fault resistance. The result is single-valued and can be calculated from basic network parameters:

Inside fault: $\underline{Y}_o = \underline{Y}_{CC} + \underline{Y}_{Bgtot}$ *Eq. 1*

Outside fault: $\underline{Y}_o = -(\underline{Y}_{Fdtot} + \underline{Y}_{CCdistributed})$ *Eq. 2*

where $\underline{Y}_{CC}$ = admittance of the coil and the parallel resistor, $\underline{Y}_{Bgtot}$ = total neutral admittance of the background network, $\underline{Y}_{Fdtot}$ = total neutral admittance of the protected feeder, $\underline{Y}_{CCdistributed}$ = total admittance of the distributed compensation coils of the protected feeder.

Despite the undisputable advantages offered by the Y_o *principle*, up to the present time, extensive commissioning of such relays has been limited to just a small number of countries, first and foremost Poland [1].

In order to make the Y_o protection more attractive for the global relaying community, the authors suggest a novel method for converting the Y_o *principle* from the neutral admittance domain ($\underline{Y}_o$ *domain*) into the residual current domain ($\underline{I}_o$ *domain*). This allows more familiar setting principles and straight-forward application of the admittance based E/F protection. The conversion is based on the fact that when the $\underline{Y}_o$ calculation is done utilizing the changes in $\underline{I}_o$ and $\underline{U}_o$ due to a fault, as suggested in [1], the measured $\underline{Y}_o$ is not affected by the fault resistance and system unbalance. As in case of a solid fault ($R_F = 0\ \Omega$) the value of $\underline{U}_o$ equals the phase-to-earth voltage of the system U_{ph}, the measured $\underline{Y}_o$ can be converted into $\underline{I}_o$ *domain* using a fixed scalar conversion factor $q = U_{ph}$. Additionally, as the signs of reactances are reversed in the admittance domain, i.e. capacitive susceptance is positive and inductive susceptance is negative, the imaginary term of $\underline{Y}_o$ must be reversed, i.e. applying complex conjugate. Finally the conversion equation becomes:

$$\underline{I}_o^{*} = conj(\underline{Y}_o)\cdot q \qquad \textit{Eq. 3}$$

The notation $\underline{I}_o^{*}$ represents the equivalent residual current value, which is obtained through conversion from the calculated neutral admittance. It should be noticed that, as the measured $\underline{Y}_o$ is not affected by the fault resistance, the equivalent residual current value corresponds to the physically measurable $\underline{I}_o$ only when $R_F = 0\ \Omega$ and U_{ph} equals the actual system phase-to-earth voltage.

The conversion is illustrated in *Fig. 3*. The resulting E/F protection method is here called the *Iotanphi principle.*

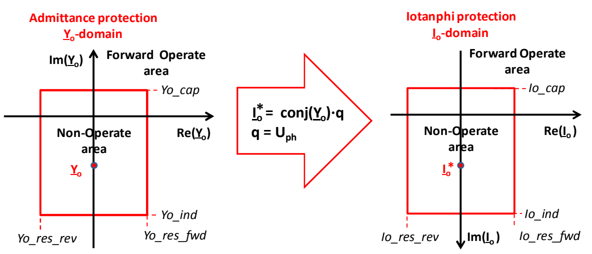

Fig. 3 *Conversion of Y_o protection into Iotanphi protection.*

The operation characteristic of the *Iotanphi principle* is preferably presented in the $\underline{I}_o$ *domain*, as illustrated in *Fig. 4*. The real axis is set to point upwards in the same direction as the reference phasor $-\underline{U}_o$ in traditional E/F protection. The conversion enables a comparison of performance between the *Iotanphi* and the traditional protection, as the characteristics and operate quantities $\underline{I}_o$ and $\underline{I}_o^{*}$ can be drawn in the same domain.

Thanks to the conversion procedure, the settings of the *Iotanphi principle* can be entered in current-related values, in which the effect of the fault resistance can be ignored. Due to this fact, the settings can be directly based on basic system data, such as the E/F current produced by each feeder and the current of the parallel resistor of the coil. In the simplest form, only one setting, *Io_res_fwd*, is required to define the characteristic. It is set based on the current value corresponding to the parallel resistor of the coil and the total resistive losses of the system, see *Fig. 4a*. Such a characteristic can be applied, when the E/F current produced by the protected feeder is unknown or it varies greatly during the daily operation. In order to improve sensitivity, the non-operate area may be limited with setting *Io_ind*. It is set based on the E/F current produced by the protected feeder, considering the maximum feeder length. The box-shaped characteristic is obtained by limiting the characteristic in reverse direction by setting *Io_res_rev* to the same value as *Io_ind,* see *Fig. 4b*. However, the best sensitivity is obtained by introducing a slope characteristic in forward direction with settings *Correction angle* and *Io_start*. The purpose of the *Correction angle* setting is the same as in traditional E/F protection and *Io_start* is set based on the minimum measurable current value taking into account the practical measurement inaccuracies, see *Fig. 4c*. In all cases it must be ensured that the characteristic is set to cover the value corresponding to the E/F current produced by the protected feeder, I_{Fdtot}, with sufficient margin.

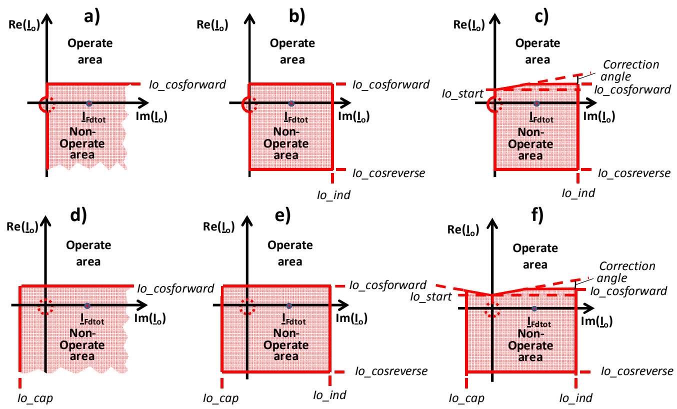

Fig. 4 *The operating characteristic and settings of the Iotanphi principle.*

The *Iotanphi principle* is also well applicable in distribution networks with distributed compensation. The characteristic can be set to take into account the situation, where the distributed coils located on the feeder would unwontedly overcompensate, i.e. the feeder would produce inductive E/F current in case of an outside fault. Such an overcompensation can be taken into account with the *Io_cap* setting. Valid characteristics for distribution networks with distributed compensation are shown in *Fig. 4d-f*.

In the same way as in traditional E/F protection functions, the *Iotanphi principle* uses the U_o> condition as a general start criterion defining the basic sensitivity of the protection. Due to this fact the selectivity between *Iotanphi* and a traditional E/F protection system can easily be ensured, when both principles are used in the distribution area of the substation.

EXAMPLE PROTECTION SCHEME

An example of a 20 kV feeder E/F protection scheme is presented in *Fig. 5*. The network data is presented in *Table 1*.

Table 1. *Network data of the example protection scheme.*

Network data/parameter	Value at 20 kV
E/F current produced by the protected feeder	3-6 A
E/F current produced by the background network	66 A
Rated current of the parallel resistor	4 A
Resistive losses of the system	1.3 A
Compensation degree, $K = I_C/I_L$ *I_C = total capacitive E/F current, I_L = coil current*	0.9, 1.0, 1.15
Maximum healthy state U_o	5% of U_n

The IED2 includes three protection stages implemented with the *phase angle* or the *Iotanphi principle*. IED1, a pole-mounted circuit recloser, is located downstream and it uses the *phase angle principle* and two protection stages. IED3 provides U_o based protection for the substation busbar and back-up protection for feeders. The notations and the general purpose of the protection stages are given in *Table 2*.

Table 2. *Protection stages of the example protection scheme.*

Prot. stage	Description
I_o>→(1) or Y_o>→(1)	Set to detect faults with as high a fault resistance value as possible, typically only alarming function.
I_o>→(2) or Y_o>→(2)	Set to detect faults with a moderate fault resistance in locations where typically no MV equipment earthing exists, tripping function.
I_o>→(3) or Y_o>→(3)	Set to detect solid or low resistance faults in locations where typically MV equipment earthing is used, such as MV/LV and disconnector substations, tripping function.
U_o>	Set to ensure coordinated operation with the feeder protection, tripping or alarming function.

When selecting settings for IEDs, the requirements for sensitivity, operating speed, selectivity and also the possibility for self-clearing of faults should be considered.

The resulting scheme is presented in *Fig. 5* with the help of a protection co-ordination diagram, which is an E/F current (I_{EF}) or U_o vs. time-characteristic showing the operate characteristics of all related protection stages. As seen in *Fig. 5*, the selectivity between the IEDs in terms of sensitivity and time is fulfilled.

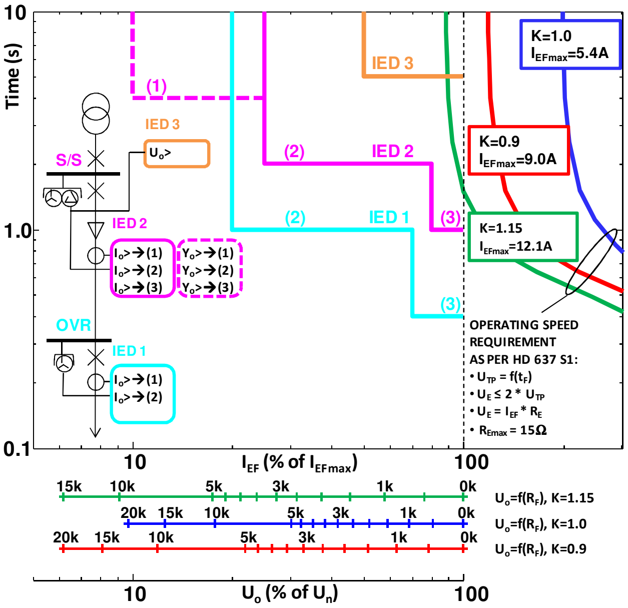

Fig. 5 Co-ordination diagram of a 20 kV feeder E/F protection.

The selected operate time and U_o start voltage settings for all protection stages can directly be read from *Fig. 5*, which apply to both protection principles. The setting of the "box"-characteristic of the *Iotanphi principle* for IED2 can be derived directly from the basic network data at primary voltage level without further calculations. The use of the *phase angle principle* for IED1 and IED2 requires additional network calculations for the I_o start current settings. These calculations are based on the resonance condition (K=1), where the measured $\underline{I}_o$ is the lowest and takes into account the variations in the E/F current supplied by the protected feeder. A summary of the settings is shown in *Table 3*.

Table 3. *Proposed settings for the example protection scheme at 20 kV level.*

Setting	Stage (1)	Stage (2)	Stage (3)
Uo_start	10% (IED2)	20% (IED1) 25% (IED2)	70% (IED1) 80% (IED2)
Correction angle	10°	10°	10°
Io_start (phase angle)	1 A	1 A	2.8 A
Io_start (Iotanphi)	0.5 A	0.5 A	0.5 A
Io_res_fwd	2.8 A	2.8 A	2.8 A
Io_res_rev	9 A	9 A	9 A
Io_cap	0 A	0 A	0 A
Io_ind	9 A	9 A	9 A

COMPUTER SIMULATIONS

In the following the sensitivity of the low-set stage (1) of IED2 using the *Iotanphi* or *phase angle principle* is compared with computer simulations. The parameters of the simulated network model can be found in *Table 1*. For the *phase angle principle* a I_o-start current value of 1 A is applied, which is assumed to be the minimum setting value. For the *Iotanphi principle* the "box"-characteristic is defined with the settings shown in *Table* 3. The results are presented in *Fig. 6* in the *$\underline{I}_o$ domain*. The result for the *phase angle principle* is marked with green dots representing different fault resistance values. For the *Iotanphi principle* the result is marked with red stars, which are valid for all fault resistance values.

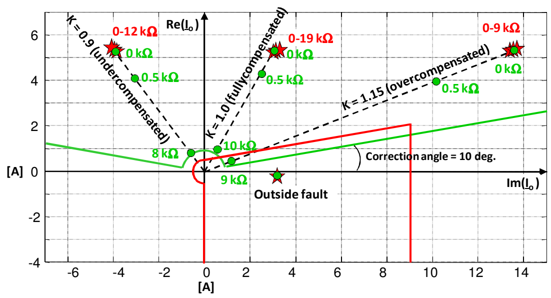

Fig. 6 Performance comparison based on computer simulations.

From *Fig. 6* it can be concluded:

Phase angle principle: The sensitivity is limited by the I_o start current and U_o start voltage settings, and affected by the fault resistance and the compensation degree. Theoretically the maximum detectable fault resistances are approximately 8 kΩ (K=0.9, U_o≈13%), 10 kΩ (K=1, U_o≈18%) and 9 kΩ (K=1.15, U_o≈10%).

Iotanphi principle: Due to the fact that the result is unaffected by fault resistance, the sensitivity is in theory only limited by the U_o start voltage setting and the minimum measurable current value, *Io_min*. Theoretically, with *Uo_start* = 10% and *Io_min* = 0.5%, the maximum detectable fault resistances are approximately 12 kΩ (K=0.9), 19 kΩ (K=1) and 9 kΩ

(K=1.15). Exceptional sensitivity is achieved in the under- and overcompensated cases, where the operation is possible even without the parallel resistor. Generally, this is valid when the E/F current produced by the protected feeder is less than the amount of system undercompensation in amperes, or when the amount of system overcompensation exceeds the *Io_ind* setting. Typically this is the case for short feeders.

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 E/F protection functions. Below, one field test series is studied. These tests were made in a 20 kV centrally compensated HV/MV-substation owned by *Fortum Oy*. The parameters of this network are presented in *Table 1*. Results are shown in *Fig. 7* with fault resistance values ranging from 0 to 10 kΩ. The result for the *phase angle principle* is marked with dots representing different fault resistance values. For the *Iotanphi principle*, the result is marked with stars, where slight variations in the results due to e.g. measurement inaccuracies can be observed. It can be seen that the results match the computer simulations quite closely and consequently the same conclusions apply.

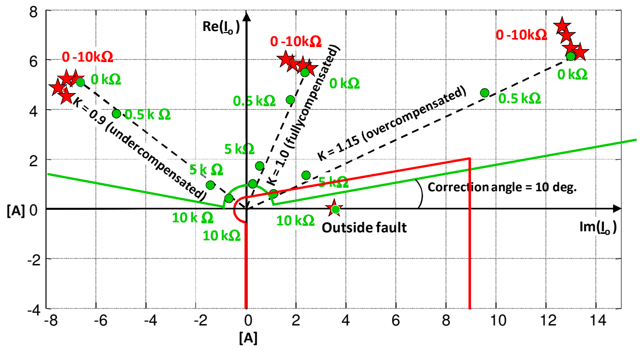

Fig. 7 *Performance comparison based on field test data.*

When evaluating E/F protection in general, attention should also be paid to *intermittent earth-faults, i.e.* a special fault type that is encountered especially in compensated cable networks. Such a fault is initiated as the phase-to-earth voltage exceeds the reduced insulation level of the fault point and extinguishes itself as soon as the fault current crosses zero for the first time. As a result a high amplitude transients of very short duration, i.e. "spikes", in I_o can be measured repeatedly. A similar irregular behavior can also be seen in U_o, see *Fig. 8*.

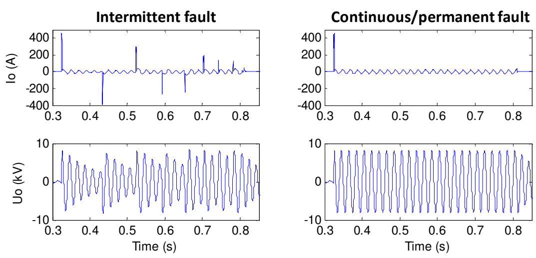

Fig. 8 *Typical U_o and I_o waveforms for an intermittent and a continuous earth-fault.*

As the waveforms of I_o and U_o are highly distorted, the operation of traditional fundamental frequency based E/F protection is endangered [2]. This is also demonstrated in *Fig. 9*, in which the operating point trajectory patterns are plotted in the *I_o domain* both for an outside and inside intermittent fault recorded in the field tests. *Fig. 9* shows that at an outside intermittent fault the operating quantity may temporarily enter the operate area of the traditional E/F protection, whereas the *Iotanphi principle* provides more security, as a larger margin against possible maloperation is provided by the novel characteristic. In order to ensure tripping of the faulted feeder, a dedicated protection function, such as *INTRPTEF* available in IEDs of the *ABB Relion®* product family, should be applied in parallel with both methods.

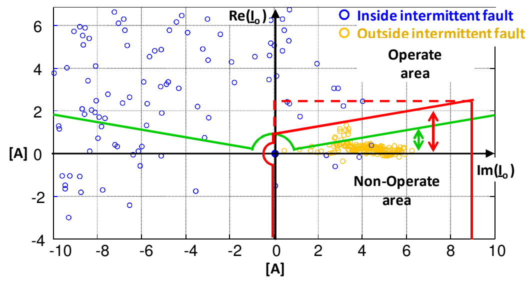

Fig. 9 *Typical operating point trajectory pattern for an intermittent earth-fault.*

CONCLUSIONS

In order to make the practical application of the neutral admittance based E/F protection as simple as possible a novel method has been suggested. Based on the performance evaluation of the method a number of attractive protection features can be pointed out, see *Table 4*. These include e.g. improved sensitivity and security both at continuous and intermittent earth-faults and a truly universal applicability including also networks with distributed compensation. In addition, the settings of the protection can be easily derived from the basic system data, which enables simple and practical optimization of the operation characteristic.

The authors expect the neutral admittance based E/F protection with the suggested method to gain a more widespread acceptance as protection principle in compensated MV-networks.

Table 4*. Comparison of E/F protection functions and their features.*

Feature	Traditional	Iotanphi
Measured signals	U_o and I_o	U_o and I_o
Measurement method	Fund. freq. comp.	Fund. freq. comp.
Directionality	Yes	Yes
Selectivity based on	U_o and/or I_o	U_o
Sensitivity	Up to some kΩ	Only limited by U_o-start voltage setting and minimum measureable I_o
Security	Good	Very good
Earthing method	Requires adaptation	Universal
Applicability in distributed compensation	Limited	Yes
Settings	Requires analysis	Directly from basic network parameters

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