COMPENSATED NETWORKS AND ADMITTANCE BASED EARTH-FAULT PROTECTION

Ari Wahlroos, Janne Altonen
ABB Oy Distribution Automation - Finland
ari.wahlroos@fi.abb.com, janne.altonen@fi.abb.com

ABSTRACT

This paper describes the fundamentals of admittance based earth-fault protection. As an introduction the concept of admittance is reviewed. The basics of compensated distribution networks are also briefly explained. The theory of earth-faults in compensated networks is described based on a network model utilizing admittances. Finally this model is applied to explain the theory and operation of admittance based earth-fault protection. It is shown that the admittance principle has many advantageous and attractive features by comparison with traditional earth-fault protection functions. As a novel idea an admittance protection principle utilizing harmonics is introduced. It can be anticipated that the application of admittance principle will become more popular in the future in distribution networks with centralized or distributed compensation.

INTRODUCTION

For AC-circuits in electrical engineering, the admittance $\underline{Y}$ is defined as being the inverse of the impedance $\underline{Z}$:

$$\underline{Y} = 1/\underline{Z}$$

or as the ratio between current and voltage or alternatively as the ratio between power and voltage squared:

$$\underline{Y} = \underline{I}/\underline{U} \qquad \text{or} \qquad \underline{Y} = \underline{S}/\underline{U}^2$$

The SI unit of admittance is siemens [S]. When applied in earth-fault protection of medium voltage distribution networks, where voltages are measured in kilovolts and currents in amperes, the appropriate unit for admittance is millisiemens [mS].

In Cartesian form, the admittance can be presented as:

$$\underline{Y} = G + j \cdot B$$

where

G is the real part of the admittance, denoted as the conductance and B is the imaginary part of the admittance, denoted as the susceptance.

In the admittance domain the signs of the imaginary terms are reversed as compared to impedance domain, i.e. the capacitive susceptance is positive and the inductive susceptance is negative. This means that, e.g. for conductors, due to their phase-to-earth capacitances, the admittance is of the form $\underline{Y} = G + j \cdot B$. On the other hand, the admittance of the compensation coil, due to the coil's inductance, is of the form $\underline{Y} = G - j \cdot B$, see *Fig. 1*.

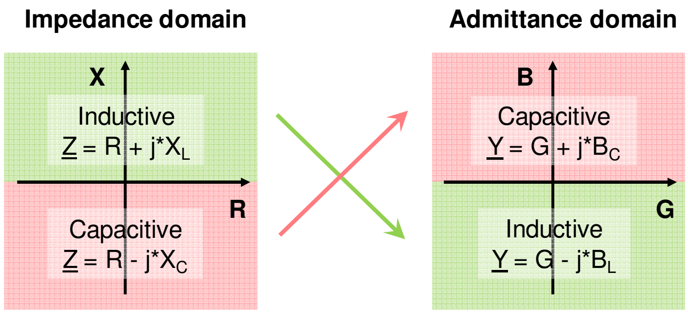

***Fig. 1** Inversion of* signs *of the imaginary terms in the admittance domain as compared to the impedance domain.*

In power system analysis, it is very convenient to replace the phase-to-earth capacitances of the lines and the neutral-to-earth connection impedances with the corresponding admittances. The "shunt" admittance for a single phase of a line is of the form:

$$\underline{Y}_o = G_o + j \cdot B_o = G_o + j \cdot (\omega \cdot C_o),$$

where the parameter C_o is the phase-to-earth capacitance per phase. The parameter G_o, shunt conductance, represents the (resistive) leakage current through a dielectric material, insulators and air. As such, it contributes to the resistive losses of the system. In practice, the shunt conductance of a line is usually very small, because insulators with good dielectric properties are used. A practical estimation for conductance can be obtained by assuming it to be 10…100 times smaller than the susceptance.

The "shunt" admittance for a neutral-to-earth connection impedance is of the form:

$$\underline{Y}_o = G_o - j \cdot B_o = \frac{1}{R_{PR}} - j \cdot \frac{1}{\omega \cdot L_{CC}}$$

where the parameter R_{PR} is the resistive part of the neutral-to-earth connection impedance (e.g. resistance of the earthing resistor or parallel resistor of the coil) and L_{CC} is the inductive part of the neutral-to-earth connection impedance (e.g. inductance of the compensation coil).

The total admittance of the admittances connected in parallel can be obtained simply by summing the individual admittances:

$$\underline{Y}_{tot} = \underline{Y}_a + \underline{Y}_b \ldots + \underline{Y}_n$$

For example, the total admittance of a three-phase line is the sum of three phase-to-earth admittances. In addition, the inductive and capacitive susceptance cancels each other.

COMPENSATED DISTRIBUTION NETWORKS

Waldemar Petersen invented that by introducing an inductance to the neutral point of the system, the capacitive earth-fault current of the network could be reduced close to zero and thus most arcing earth-faults would become self-extinguished. Such devices are today called Petersen coils, compensation coils or arc-suppression coils.

Networks utilizing compensation coils have become more popular during the last years in MV-distribution networks. The main reason is that the utilities focus increasingly on reliability and quality of the supply. Compensation significantly reduces the number of outages, as temporary faults represent the main share of the total number of faults. Compensation also enables the continuation of the network operation during a sustained earth-fault, if the conditions for hazard voltages set by legislation and regulations can be met.

In practice, the compensation may be implemented as centralized, distributed or a combination of them (here such a configuration is denoted as ”hybrid”). Traditionally networks have been centrally compensated, but in recent times also distributed and hybrid compensation have become more common.

CENTRAL COMPENSATION

In central compensation, the coil is located at the substation and it is typically equipped with automatic tuning and a parallel resistor. The admittance of the coil including the parallel resistor is given by:

$$\underline{Y}_{cCC} = G_{cCC} - j \cdot B_{cCC}$$

where G_{cCC} is the total conductance of the coil and the parallel resistor and B_{cCC} is the inductive susceptance of the coil.

The conductance G_{cCC} is the sum of the conductances representing the parallel resistor G_{cPR} and the resistive losses of the coil G_{cCR}:

$$G_{cCC} = G_{cPR} + G_{cCR}$$

The conductance of the parallel resistor (at primary voltage level) can be approximated from its rated power P_{PR}:

$$G_{cPR} = \frac{P_{PR}\,[W]}{U^2_{ph\_pri}\,[V]}$$

Alternatively, if the current of the parallel resistor I_{PR} at the primary voltage level is known, the corresponding conductance is:

$$G_{cPR} = \frac{I_{PR}\,[A]}{U_{ph\_pri}\,[V]}$$

An approximation for the conductance representing the resistive losses of the coil (at primary voltage level) can be calculated from equation:

$$G_{cCR} = R_{kCR} \cdot \frac{S_R\,[VA]}{U_{ph\_pri}^2\,[V]},$$

where R_{kCR} is typically in the order of a few per cent, U_{ph_pri} is the system phase-to-earth voltage, e.g. 11547 V in a 20 kV system and S_R is the rated power of the coil.

The parallel resistor of the coil is controlled according to the applied Active Current Forcing (ACF) scheme. Typical ACF schemes are:

- 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.
- The resistor is disconnected during the healthy state, and then connected during the fault until the protection operates.
- The resistor is permanently connected. The primary purpose is to limit the healthy state U_o. This may be advantageous in rural networks where, due to the non-transposed conductors, the healthy-state U_o would otherwise become unacceptably high. On the contrary, in pure cable networks, the healthy-state U_o may be so low that the introduction of a permanently connected resistor would practically eliminate the healthy-state U_o and thus disable the control of the coil.

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

The inductive susceptance of the coil, B_{cCC}, depends on the inductance of the coil and it is adjusted to compensate the capacitive susceptance of the network (at fundamental frequency) in order to reduce the fault current at fault location close to zero and alleviate the conditions for self-extinguishing of the fault arc. The term compensation degree, K , is used to indicate how large a portion of the total capacitive susceptance of the network $B_{Network}$ (i.e. capacitive earth-fault current) is cancelled by the inductive susceptance of the coil B_{cCC} (i.e. inductive current of the coil):

$$K = B_{cCC} / B_{Network} \Rightarrow B_{cCC} = K \cdot B_{Network}$$

When K equals 1, the inductive susceptance of the coil equals the capacitive susceptance of the network and the network is said to be fully compensated. It should be noticed that, in practice the compensation is newer perfect, i.e. the coil is able to compensate the fundamental frequency (50 or 60 Hz) capacitive component, but not the harmonics or the resistive component present in the earth-fault current. The magnitude of such component(s) may be significant in practice.

In case K < 1, the inductive susceptance of the coil (i.e. inductive current of the coil) is less than the capacitive susceptance of the network (i.e. capacitive earth-fault current) and the network is said to be undercompensated.

On the other hand, in case K > 1, the network is said to be overcompensated and the inductive susceptance of the coil (i.e. inductive current of the coil) is larger than the capacitive susceptance of the network (i.e. capacitive earth-fault current).

In practice, typically in most countries in Europe, the network is operated slightly overcompensated. This is based on the assumption that it is more likely for some parts of the network to become disconnected, which in the undercompensated case could lead to a resonant condition. This is generally not desired as resonance causes e.g. overvoltages, which can lead to insulation breakdown. Resonance also amplifies harmonics in the network, which can cause voltage distortion and thermal overloading of network equipment. However, despite all the before mentioned facts, the Finnish network is traditionally operated slightly undercompensated.

In recent studies, the application of central compensation in case of long rural cable feeders have been studied [1]. Based on these studies, the central compensation together with long cable feeders may produce dangerously high resistive earth-fault current, which can be reduced applying distributed compensation.

DISTRIBUTED COMPENSATION

In distributed compensation, one or more fixed (not adjustable) coils are placed at the feeders. The fundamental design principle is that the inductive susceptance of the distributed coil(s) partly compensates the capacitive susceptance of that particular feeder. When the feeder is disconnected, also the distributed coil(s) become(s) disconnected. Thus the compensation degree of the system is maintained. Also, as the compensation is done locally, the flow of earth current through the network impedances is limited. This is beneficial especially with long rural cable feeders, where otherwise a large resistive earth-fault current component would be introduced [1].

For the distributed coils located on the feeder, the total admittance is:

$$\begin{aligned}\underline{Y}_{cDST} &= \left(G_{cDST1} + G_{cDST2} + \ldots + G_{cDSTn}\right) - j \cdot \left(B_{cDST1} + B_{cDST2} + \ldots + B_{cDSTn}\right) \\ &= G_{cDST} - j \cdot B_{cDST}\end{aligned}$$

where G_{cDSTx} is the conductance of the distributed coil x, B_{cDSTx} is the inductive susceptance of the distributed coil x, G_{cDST} is the total conductance of the distributed coils located on the feeder and B_{cDST} is the total inductive susceptance of the distributed coils located on the feeder.

The conductance of a distributed coil (at primary voltage level) can be approximated from the equation:

$$G_{cDSTx} = R_{kDSTx} \cdot \frac{S_R\,[VA]}{U_{ph\_pri}^2\,[V]},$$

where R_{kDSTx} is typically in order of a few per cent , U_{ph_pri} is the system phase-to-earth voltage, e.g. 11547 V in a 20 kV system and S_R is the rated power of the coil.

In practice the conductance of a distributed coil is small and thus the admittance can be approximated by its susceptance:

$$\underline{Y}_{cDSTx} \approx -j \cdot B_{cDSTx}$$

The susceptance of a distributed coil (at primary voltage level) can be approximated from its rated power S_R:

$$B_{cDSTx} = \frac{S_R\,[VA]}{U_{ph\_pri}^2\,[V]}$$

Alternatively, if the rated current of the distributed coil I_{RDSTx} at the primary voltage level is known, then the corresponding susceptance is:

$$B_{cDSTx} = \frac{I_{RDSTx}\,[A]}{U_{ph\_pri}\,[V]}$$

The rated current of the distributed coil(s) and their location should be carefully selected in order to avoid the situation where, due to e.g. a feeder configuration change, the distributed coil(s) would overcompensate the feeder and therefore the earth-fault current produced by the feeder would become inductive. This is due to the fact that protection settings might not been adjusted to take such an operation condition into account.

In Finland distributed compensation has been used in a small scale since the 1980s. The application is typically long rural feeders, where the investment cost of distributed coils is less than in central compensation. In recent years there has been a lot of research concerning the application of distributed compensation in rural networks, which are being transformed from overhead lines into cable networks, see e.g. reference [1]. Based on these studies distributed compensation e.g. limits the resistive component of the earth-fault current in the network.

HYBRID COMPENSATION

In hybrid compensation, the “base” compensation is provided by a central coil located at the substation, but additionally one or more fixed (not adjustable) coil(s) is (are) placed on the feeders in carefully planned locations. Such a compensation arrangement may be used to provide optimal compensation for the network, as suggested in reference [1].

FUNDAMENTALS OF EARTH-FAULTS IN COMPENSATED NETWORKS

In order to explain the fundamental theory of earth-faults in compensated systems, the simplified equivalent circuit of a 3-phase distribution network illustrated in *Fig. 2* is used. The feeders are presented with their shunt admittances. The 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 earth-fault current. The compensation coils are presented with their specific admittances.

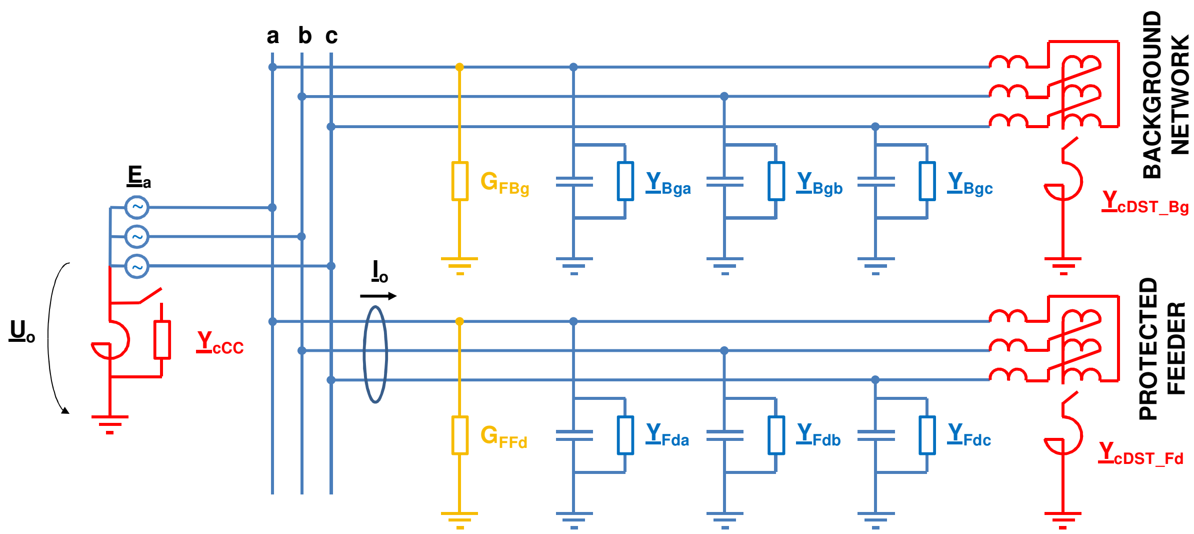

Fig. 2 *Simplified equivalent circuit for a compensated distribution network with a single-phase earth fault in phase L1 located either on the protected feeder or in the background network.*

The network consists of two feeders, one representing the protected feeder *(Fd)* and another representing the background network *(Bg)*. The background network represents the rest of the feeders in the substation. The total admittances of the distributed compensation coils located in the protected feeder and in the background network are noted as $\underline{Y}_{cDST\_Fd}$ and $\underline{Y}_{cDST\_Bg}$, while the admittance of the coil located at the substation is noted as $\underline{Y}_{cCC}$. The total network admittance $\underline{Y}_{Network}$, excluding the coils, consists of the total feeder and background network admittances:

$$\underline{Y}_{Network} = \underline{Y}_{Fdtot} + \underline{Y}_{Bgtot} = G_{Network} + j \cdot B_{Network}$$

where $\underline{Y}_{Fdtot} = \underline{Y}_{Fda} + \underline{Y}_{Fdb} + \underline{Y}_{Fdc} = G_{Fdtot} + j \cdot B_{Fdtot}$,

$$\underline{Y}_{Bgtot} = \underline{Y}_{Bga} + \underline{Y}_{Bgb} + \underline{Y}_{Bgc} = G_{Bgtot} + j \cdot B_{Bgtot}$$

and where

$\underline{Y}_{Fda}, \underline{Y}_{Fdb}, \underline{Y}_{Fdc}$ is the admittance of phase a, b or c of the protected feeder

$\underline{Y}_{Bga}, \underline{Y}_{Bgb}, \underline{Y}_{Bgc}$ is the admittance of phase a, b or c of the background network

From *Fig. 2*, the general equations required for earth-fault protection analysis, the zero-sequence voltage of the network $\underline{U}_o$ and the residual current measured at the beginning of the protected feeder $\underline{I}_o$, can be derived. The equations are valid for the phase a-to-earth fault, but similar equations can be derived for phase b-to-earth fault or phase c-to-earth fault.

$$\underline{U}_o = -\underline{E}_a \cdot \left(\frac{\underline{Y}_{uFd} + \underline{Y}_{uBg} + G_{FFd} + G_{FBg}}{\underline{Y}_{cCC} + \underline{Y}_{cDST\_Fd} + \underline{Y}_{cDST\_Bg} + \underline{Y}_{Fdtot} + \underline{Y}_{Bgtot} + G_{FFd} + G_{FBg}} \right) \qquad \textit{Eq. 1}$$

$$\underline{I}_o = \underline{U}_0 \cdot (\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd} + G_{FFd}) + \underline{E}_a \cdot (\underline{Y}_{uFd} + G_{FFd}) \qquad \textit{Eq. 2}$$

where

$$\underline{Y}_{uFd} = \underline{Y}_{Fda} + \underline{a}^2 \underline{Y}_{Fdb} + \underline{a}\underline{Y}_{Fdc}, \ \underline{Y}_{uBg} = \underline{Y}_{Bga} + \underline{a}^2 \underline{Y}_{Bgb} + \underline{a}\underline{Y}_{Bgc}, \ \underline{a} = \cos(120^o) + j \cdot \sin(120^o)$$

Admittances $\underline{Y}_{uFd}$ and $\underline{Y}_{uBg}$ represent the asymmetrical part of the corresponding total phase-to-earth admittances of the feeder and background network, $\underline{Y}_{Fdtot}$ and $\underline{Y}_{Bgtot}$.

Earth-faults are represented with their specific conductances, which are the inverses of the corresponding fault resistances $G_{FFd} = 1/R_{FFd}$ and $G_{FBg} = 1/R_{FBg}$. In case an earth fault is located inside the protected feeder, $G_{FFd} = 1/R_{FFd} > 0$ and $G_{FBg} = 1/R_{FBg} = 0$. Further, if an earth fault occurs outside the protected feeder, i.e. somewhere in the background network, $G_{FBg} = 1/R_{FBg} > 0$ and $G_{FFd} = 1/R_{FFd} = 0$.

Assuming a full symmetry of the phase-to-earth admittances of the network, the equations 1-2 can be simplified as $\underline{Y}_{uFd}$ and $\underline{Y}_{uBg}$ equal zero:

$$\underline{U}_o = -\underline{E}_a \cdot \left(\frac{G_{FFd} + G_{FBg}}{\underline{Y}_{cCC} + \underline{Y}_{cDST\_Fd} + \underline{Y}_{cDST\_Bg} + \underline{Y}_{Fdtot} + \underline{Y}_{Bgtot} + G_{FFd} + G_{FBg}} \right) \qquad \textit{Eq. 3}$$

$$\underline{I}_o = \underline{U}_0 \cdot (\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd} + G_{FFd}) + \underline{E}_a \cdot G_{FFd} \qquad \textit{Eq. 4}$$

Equations 1-4 can be used to analyze the behavior of $\underline{U}_o$ and $\underline{I}_o$ in relation to e.g. the fault location (inside/outside fault), the network and feeder size, the system compensation degree and configuration, and the fault resistance. Such an analysis provides the basis for the design, setting and implementation of earth-fault protection in a particular network.

ADMITTANCE BASED EARTH-FAULT PROTECTION

Admittance based earth-fault protection originates from the Poznan University of Technology in Poland, where a group of researchers lead by professor Józef Lorenc evaluated already in the beginning of 1980s the possibility of feeder earth-fault protection based on admittance measurement. Traditionally earth-fault protection was either based on the residual current (e.g. *Iocosphi* or *phase angle principle*) or the residual power (*Wattmetric principle*). The application of admittance based protection systems rapidly expanded in Poland after a few years of positive experience. Today this protection principle has become a standard earth-fault protection function and a requirement by the local utilities in Poland.

Originally, in order to perform the admittance based earth-fault protection, amplitude comparators $S_1, S_2, \ldots, S_5$ were used such as:

$$S_1 = k_r \cdot U_o \,,\; S_2 = k_i \cdot I_{oi} \,,\; S_3 = \left| k_u \cdot \underline{U}_o + k_i \cdot \underline{I}_{oi} \right| ,\; S_4 = \left| k_u \cdot \underline{U}_o - k_i \cdot \underline{I}_{oi} \right| ,\; S_5 = k_n \cdot U_o$$

The coefficients k_r, k_i, k_u and k_n describe the properties of the signal processing of the residual current $\underline{I}_o$ and the residual voltage $\underline{U}_o$ in the measuring circuits [2].

In the modern microprocessor based IEDs, admittance calculation can be conducted by simply dividing the fundamental frequency phasor of $\underline{I}_o$ with the phasor of $-\underline{U}_o$:

$$\underline{Y}_o = \underline{I}_o \big/ -\underline{U}_o \qquad \textit{Eq. 5a}$$

Alternatively the admittance calculation can be made utilizing the so called delta-quantities, i.e. utilizing the change in residual quantities due to the fault:

$$\underline{Y}_o = (\underline{I}_{o\_fault} - \underline{I}_{o\_prefault}) \big/ -(\underline{U}_{o\_fault} - \underline{U}_{o\_prefault}) \qquad \textit{Eq. 5b}$$

where “fault” denotes the time during the fault and “prefault” denotes the time before the fault. The advantage of the delta calculation is that theoretically, it totally eliminates the effects of network asymmetry and the fault resistance on the measured admittance (under certain conditions [3]).

Admittance protection, similarly as other earth-fault protection functions, uses U_o overvoltage condition as a common criterion for fault detection. The setting value for U_o start must be set above the maximum healthy-state U_o level of the network in order to avoid false starts.

The results of the admittance calculation during an outside or inside fault are presented in the following. The results are theoretically valid in symmetrical networks. If *Eq. 5b* is used, the results are also valid in unsymmetrical networks, provided that the conditions given in [3] are met. Cable networks are typically very symmetrical, but networks containing large portions of overhead lines may be heavily unsymmetrical. In such systems, the admittance should preferably be calculated using *Eq. 5b*.

Result of admittance calculation when the fault is located outside the protected feeder:

$$\underline{Y}_o = -(\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd}) \\ = -\left(\lfloor G_{Fdtot} + G_{cDST\_Fd} \rfloor + j \cdot \lfloor B_{Fdtot} - B_{cDST\_Fd} \rfloor\right) \qquad \textit{Eq. 6}$$

The result from *Eq. 6* states that in case of a fault outside the protected feeder, *the admittance principle* measures the total admittance of the protected feeder, including the admittances of the compensation coils located on the protected feeder (if applicable). The sign of this admittance is negative.

At central compensation the measured admittance simply equals the admittance of the protected feeder preceded by a minus sign. The conductance and the susceptance are therefore always negative. In practice, the conductance of the feeder may be too small to be measured accurately and due to inaccuracies in U_o and I_o measurement, even the sign of the conductance may be erroneously measured as positive.

When there are distributed coils on the protected feeder, the measured susceptance may even become positive due to overcompensation. Typically, such an operation condition is not desired, but must be taken into account when setting the feeder earth-fault protection. In the same way as at central compensation, the measured conductance is negative in theory, but in practice it may be too small to be measured accurately.

Result of admittance calculation when the fault is located inside the protected feeder:

$$\underline{Y}_o = \underline{Y}_{Bgtot} + \underline{Y}_{cCC} + \underline{Y}_{cDST\_Bg}$$

$$= \left(\lfloor G_{Bgtot} + G_{cCC} + G_{cDST\_Bg} \rfloor + j \cdot \lfloor (B_{Bgtot} - (B_{cCC} + B_{cDST\_Bg} \rfloor\right)$$

By inserting $B_{cCC} = K \cdot B_{Network}$ and $B_{Bgtot} = B_{Network} - B_{Fdtot}$ the following is obtained

$$\underline{Y}_o = \left(\lfloor G_{Bgtot} + G_{cCC} + G_{cDST\_Bg} \rfloor + j \cdot \lfloor (B_{Network} \cdot (1-K) - B_{Fdtot} - B_{cDST\_Bg} \rfloor\right) \qquad \textit{Eq. 7}$$

The result from *Eq. 7* states that when the fault is inside the protected feeder, the *admittance principle* measures the total admittance of the background network, including the admittances of the compensation coils located outside the protected feeder (in the substation or in the neighboring feeders). The sign of the conductance is always positive and in practice measurable, as there are always some losses in practical networks. The sign of the susceptance depends on the compensation degree of the system (*K*) and when distributed coils are used, also on their susceptances.

The most important point to notice from the results of the admittance calculation, *Eq. 6* and *Eq. 7*, is that the fault conductances $G_{FFd} = 1/R_{FFd}$ and $G_{FBg} = 1/R_{FBg}$ are not present in the results, i.e. the *admittance principle* is theoretically unaffected by fault resistance! This enables exceptionally easy setting principles to be used, as complex network calculations required by traditional residual current or power based earth-fault protection functions, are not necessary.

The summary of the admittance calculation results, *Eq. 6* and *Eq. 7*, are illustrated in the admittance domain in *Fig. 3*.

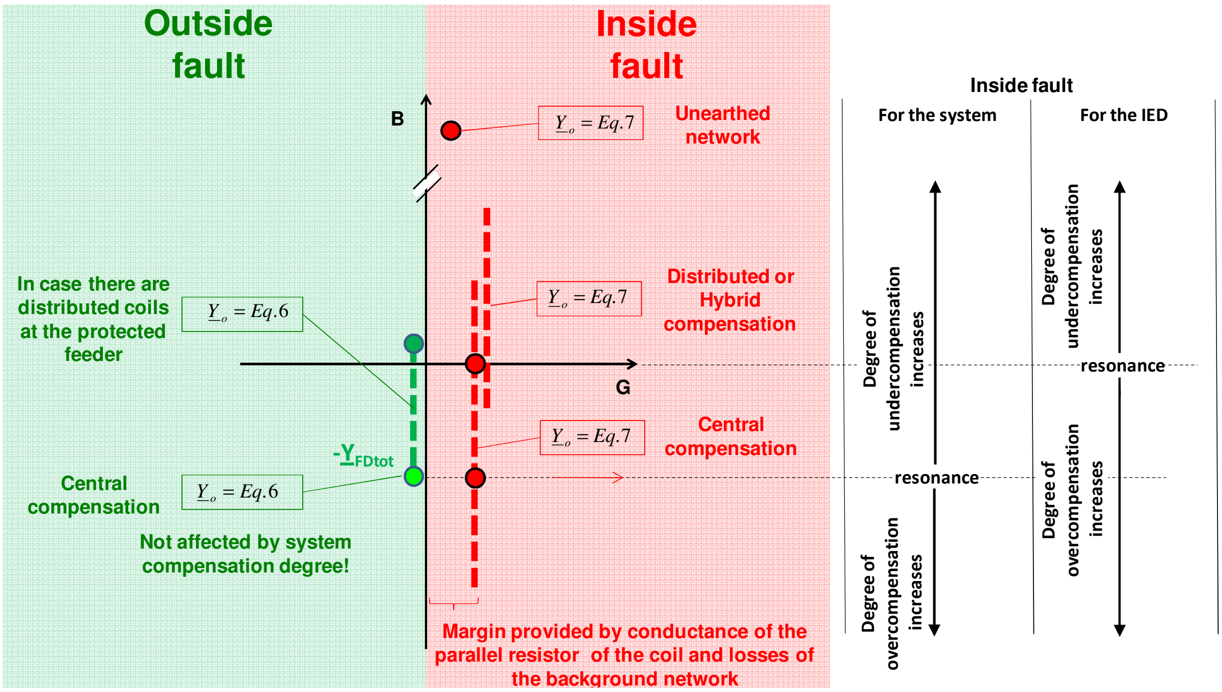

Fig. 3 *Illustration of the measured admittances of the admittance protection principle in inside and outside faults.*

The fundamental operation principle of the admittance based earth-fault protection is to discriminate between the admittances resulting from *Eq. 6* and *Eq. 7.* It operates when the admittance of *Eq. 7* is measured and blocks, when the admittance of *Eq. 6* is measured. Such an operation condition is achieved with the admittance characteristic, which may be circular or composed of single or multiple boundary lines. Also combinations of different criteria are possible. The protection operates, when the calculated admittance moves outside the boundary line(s) represented by the characteristics. In all cases, it must be ensured that the characteristic is set to cover the value corresponding to the admittance given in *Eq. 6* with sufficient margin. Examples of traditional operation characteristics for the *admittance principle* are presented in *Fig. 4*.

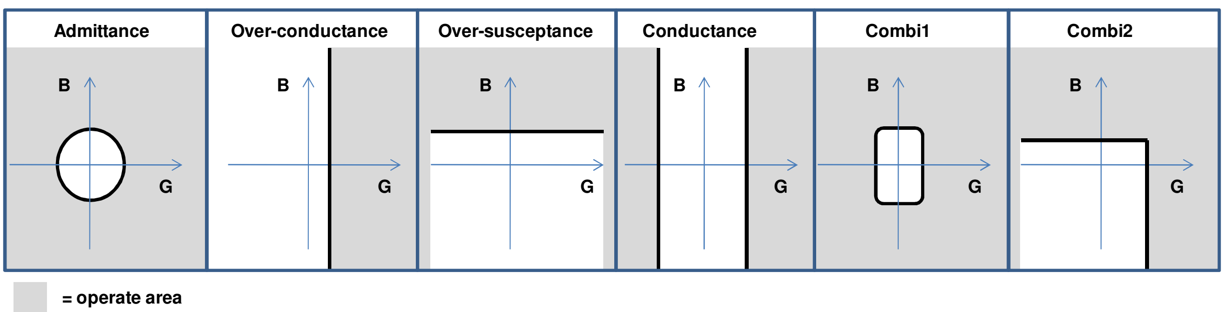

Fig. 4 *Examples of traditional operation characteristics for the admittance principle.*

The drawback of the traditional admittance characteristics is that they do not provide the optimal sensitivity and/or universal applicability. In order to enhance the performance of the admittance principle the novel neutral admittance characteristic was introduced in reference [3]. The novel admittance characteristic is presented in *Fig. 5*. It is based directly on the results from *Eq. 6-7*. The characteristic is box-shaped and offset from origin, to cover the measured admittance value in an outside fault: $\underline{Y}_o = -(\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd})$ with sufficient margin. The protection operates, when the calculated admittance moves outside the characteristics. The box-shaped admittance characteristic can be considered as a protection zone in the admittance plane similarly as the impedance characteristic of the distance protection in the impedance plane.

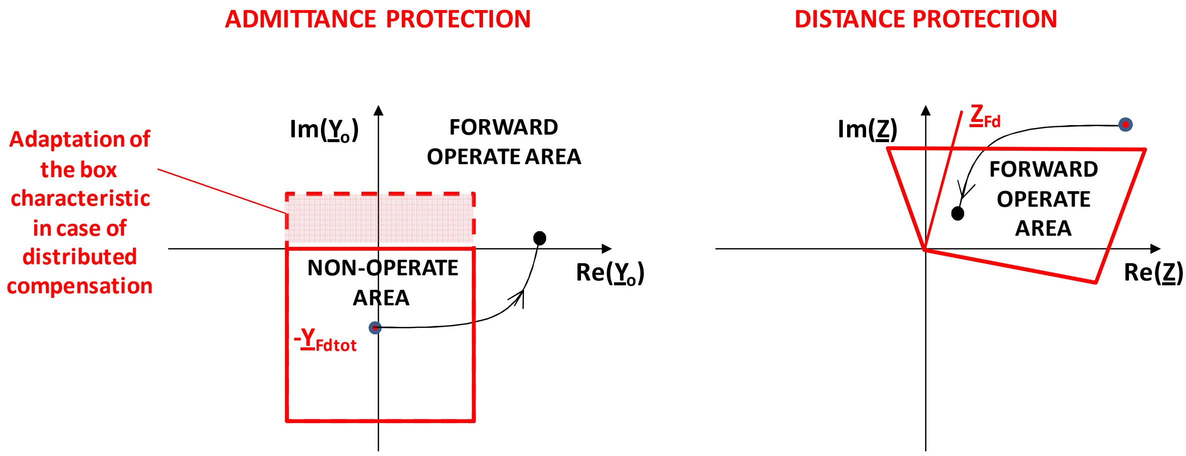

Fig. 5 *Novel admittance characteristic and analogy to distance protection.*

The box-shaped admittance characteristic (or admittance zone) provides operation also in case the compensation coil is disconnected and the network becomes unearthed. In this case the discrimination of faults inside / outside the protected feeder is easy, as the susceptances of the measured admittances have clearly different signs and amplitudes, refer to *Eq. 6-7* and *Fig. 3*.

Exceptional sensitivity can be achieved with the "Box"-characteristic in the undercompensated and overcompensated cases, where the operation is possible even without a parallel resistor. This is valid when the earth-fault current produced by the protected feeder is lower than the amount of system undercompensation in amperes, or when the amount of system overcompensation exceeds the boundary line limiting the non-operate area in the direction of the negative $\underline{\mathrm{Im}(Y_o)}$ -axis. Typically this is the case for short feeders.

In distributed compensation, the measured susceptance during an outside fault may become positive (i.e. the earth-fault current produced by the feeder is inductive), if the distributed coils would cause unwanted overcompensation of the feeder. Such a condition can easily be taken into account with the "Box" characteristic by setting the boundary line in the direction of the positive $\mathrm{Im}(\underline{Y}_o)$ -axis to a value exceeding the value obtained from *Eq. 6*.

ADMITTANCE BASED EARTH-FAULT PROTECTION UTILIZING HARMONICS

The compensation coil only compensates the fundamental frequency component of the capacitive fault current. However, the other frequency components present in the fault current are not compensated. As a novel idea, these harmonics could be used to improve the sensitivity of the admittance based earth-fault protection. This idea is based on the following facts:

For the harmonic component of the *n*-th order with frequency $f = n*f_n$, where f_n is the fundamental frequency, the admittance with capacitive susceptance (e.g. a feeder) is of the form (fundamental frequency of 50 Hz is assumed):

$$\underline{Y}_o^n = G_o + j \cdot B_{o\_50Hz} \cdot n,$$

On the other hand, for the harmonic component of the *n*-th order, the admittance with inductive susceptance (e.g. a coil) is of the form:

$$\underline{Y}_o^n = G_o - j \cdot \frac{B_{o\_50Hz}}{n}$$

It can be concluded that for the *n*-th harmonic, the inductive susceptance of the coil becomes *n* times smaller and the capacitive susceptance of the feeders, becomes *n* times larger compared with the fundamental frequency admittance.

In practical systems the most dominant harmonic present in the residual current and voltage during an earth fault is the 5^{th}, for which $n = 5$. An example of the waveforms of the residual current and voltage recorded during actual field tests is shown in *Fig. 6.*

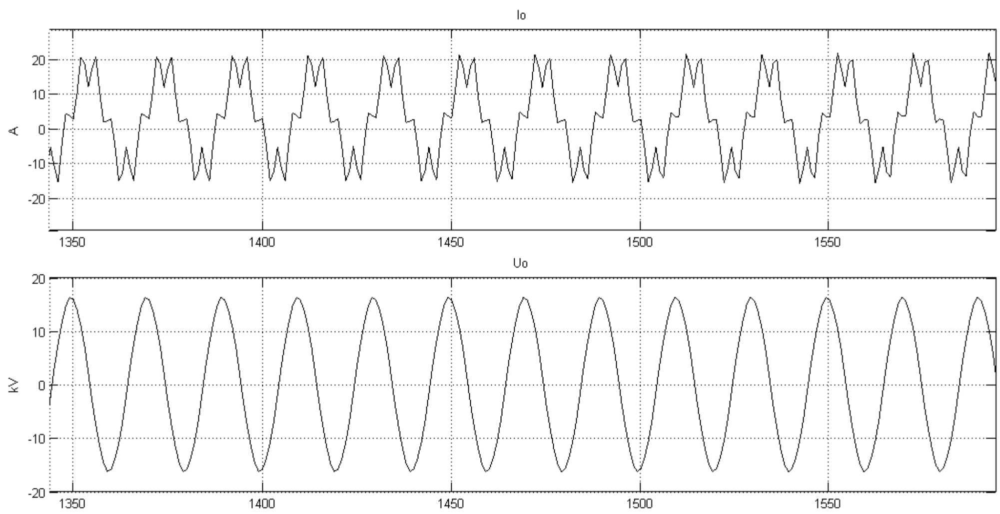

***Fig. 6** Example waveforms of residual current and residual voltage recorded during field tests.*

When the previously derived facts are applied in admittance based earth-fault protection, *Eq. 6* and *Eq. 7* can be re-written in the form:

Result of admittance calculation when the fault is located outside the protected feeder:

$$\underline{Y}_o^n = -\left(\left[G_{Fdtot} + G_{cDST\_Fd} \right] + j \cdot \left[B_{Fdtot\_50Hz} \cdot n - \frac{B_{cDST\_Fd\_50Hz}}{n} \right] \right) \qquad \textit{Eq. 6b}$$

Result of admittance calculation when the fault is located inside the protected feeder:

$$\underline{Y}_o^n = \left(\left[G_{Bgtot} + G_{cCC} + G_{cDST\_Bg} \right] + j \cdot \left[(B_{Bgtot\_50Hz} \cdot n - (\frac{B_{cCC\_50Hz} + B_{cDST\_Bg\_50Hz}}{n} \right] \right) \qquad \textit{Eq. 7b}$$

It can be concluded that the measured admittance for the 5th harmonic becomes always dominantly capacitive, despite of the system's actual compensation degree. This means that for the 5th harmonic the IED would see the network as being strongly undercompensated, even if the system's actual compensation degree would be overcompensated. This makes the discrimination between a fault and a non-fault condition exceptionally easy and even without the need of increasing the resistive current with a parallel resistor. The operation may be based on the sign of the measured susceptance (i.e. *over-susceptance principle*). Such characteristic is presented in *Fig. 7.*

Another advantageous feature of harmonics based admittance protection would be that the resulting admittances for harmonics of the *n*-th order can be calculated from the basic (fundamental frequency) network data with equations *Eq. 6b* and *Eq. 7b*. The knowledge of exact amplitudes of the harmonics present in the network is not required – it is only required that the *n*-th harmonic of I_o and U_o is measurable by the IED.

The suggested harmonic admittance principle could be used independently to complement the fundamental frequency based admittance principle. Another variation would be to add the harmonic admittance to the fundamental admittance in phasor format in order to provide a universally applicable admittance principle. The addition of harmonic admittance would be done only in case the harmonics in I_o and U_o are measureable by the IED. In this case, the operation criterion would be based on the following sum of admittances:

$$\underline{Y}_o = \underline{Y}_o^1 + \sum \underline{Y}_o^n$$

where

$\underline{Y}_o^1$ = fundamental frequency admittance,

$\sum \underline{Y}_o^n$ = sum of harmonic admittances from harmonics of *n*-th order, whose amplitude in I_o and U_o are measurable by the IED.

The addition of harmonic admittances to fundamental admittance would improve the sensitivity of protection in case sufficient levels of harmonics would be present in the measured residual quantities. On the other hand, the inclusion of fundamental frequency admittance would secure operation and sensitivity of the protection in case sufficient levels of harmonics would not be present in the network due to e.g. network loading condition or due to damping effect of fault resistance.

The addition of fundamental frequency admittance requires that the operation characteristic must include both over-susceptance and over-conductance criteria. The preferred operation characteristics of admittance protection utilizing harmonic admittances are presented in *Fig. 7*.

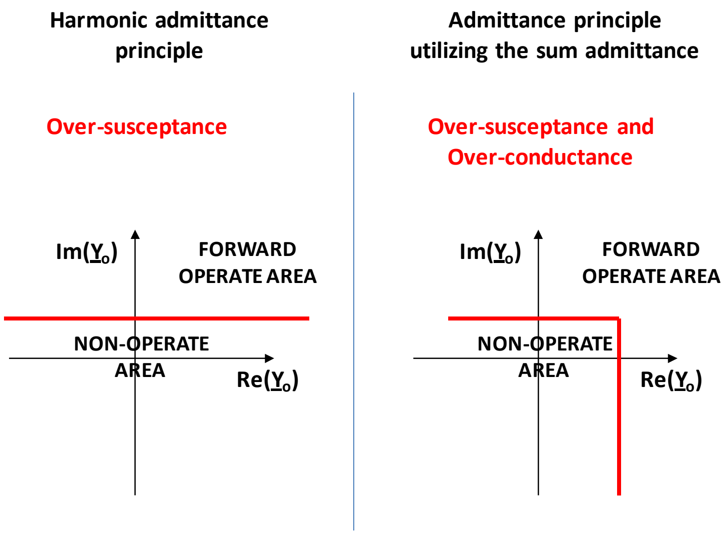

Fig. 7 *The preferred operation characteristics for harmonic admittance based earth-fault protection.*

NUMERICAL EXAMPLES

EXAMPLE #1

Consider a 20 kV distribution system with central compensation. The network data is presented in *Table 1*. The parallel resistor of the coil is disconnected during the healthy state, and connected during the fault until the protection operates.

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

Network data/parameter	**Value at 20 kV**
Maximum earth-fault current produced by the protected feeder	10 A
Earth-fault current produced by the background network	90 A
Rated current of the parallel resistor	5 A
Resistive losses of the system	2 %
Compensation degree, K	1.05 (overcompensated)
Maximum healthy state U_o	5% of U_n

Conversion of ampere values to admittances:

$$\underline{Y}_{Fdtot} = 2\% \cdot \frac{10A}{20/\sqrt{3}kV} + j \cdot \frac{10A}{20/\sqrt{3}kV} = 0.02 + j \cdot 0.87\, mS$$
$$\underline{Y}_{Bgtot} = 2\% \cdot \frac{90A}{20/\sqrt{3}kV} + j \cdot \frac{90A}{20/\sqrt{3}kV} = 0.16 + j \cdot 7.80\, mS$$

$\underline{Y}_{cCC} = \dfrac{5A}{20/\sqrt{3}kV} - j \cdot \dfrac{1.05 \cdot 100A}{20/\sqrt{3}kV} = 0.433 - j \cdot 9.09\, mS$ (prior to the connection of the parallel resistor, the conductance is assumed to be zero)

($\underline{Y}_{cDST\_Fd} = 0\, mS$, $\underline{Y}_{cDST\_Bg} = 0\, mS$ (central compensation))

Theoretical measured admittances in outside and inside fault:

Outside fault: $\underline{Y}_o = -(\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd}) = -0.02 - j \cdot 0.87\, mS$

Inside fault, prior to the connection of the parallel resistor:

$$\underline{Y}_o = \underline{Y}_{Bgtot} + \underline{Y}_{cCC} + \underline{Y}_{cDST\_Bg} = 0.16 - j \cdot 1.29\, mS$$

Inside fault, after connection of the parallel resistor:

$$\underline{Y}_o = \underline{Y}_{Bgtot} + \underline{Y}_{cCC} + \underline{Y}_{cDST\_Bg} = 0.59 - j \cdot 1.29\, mS$$

Admittance protection, similarly as other earth-fault protection functions, uses U_o overvoltage condition as a common criterion for fault detection. The setting value for U_o start must be set above the healthy-state the U_o level of the network in order to avoid false starts.

The "Box" characteristic is set to cover the value corresponding to the admittance given in *Eq. 6* with sufficient margin. An example is illustrated in *Fig. 8*.

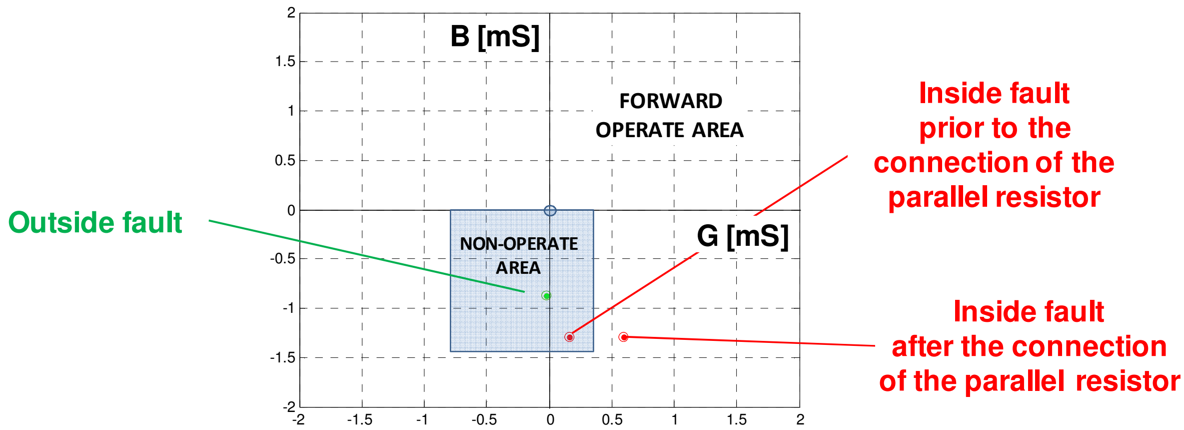

Fig. 8 *An example of a novel admittance characteristic applied in Example #1.*

EXAMPLE #2

Consider a 20 kV distribution system with distributed compensation. The network data is presented in *Table 2*.

Table 2. *Network data of the example #2 protection scheme.*

Network data/parameter	**Value at 20 kV**
Maximum earth-fault current produced by the protected feeder	10 A
Inductive current produced by the distributed coils located on the feeder	15 A
Inductive current produced by the distributed coils located outside the feeder	25 A
Earth-fault current produced by the background network	90 A
Resistive losses of the system	2%
Maximum healthy state U_o	5% of U_n

Conversion of ampere values to admittances:

$$\underline{Y}_{Fdtot} = 2\% \cdot \frac{10A}{20/\sqrt{3}kV} + j \cdot \frac{10A}{20/\sqrt{3}kV} = 0.02 + j \cdot 0.87\, mS$$

$$\underline{Y}_{Bgtot} = 2\% \cdot \frac{90A}{20/\sqrt{3}kV} + j \cdot \frac{90A}{20/\sqrt{3}kV} = 0.16 + j \cdot 7.80\, mS$$

$(\underline{Y}_{cCC} = 0\, mS$ (distributed compensation))

$$\underline{Y}_{cDST\_Fd} \approx -j \cdot \frac{15A}{20/\sqrt{3}kV} = -j \cdot 1.30\, mS$$

$$\underline{Y}_{cDST\_Bg} \approx -j \cdot \frac{25A}{20/\sqrt{3}kV} = -j \cdot 2.17\, mS$$

Theoretical measured admittances in outside and inside fault:

Outside fault: $\underline{Y}_o = -(\underline{Y}_{Fdtot} + \underline{Y}_{cDST\_Fd}) = -0.02 + j \cdot 0.43\, mS$

Inside fault: $\underline{Y}_o = \underline{Y}_{Bgtot} + \underline{Y}_{cCC} + \underline{Y}_{cDST\_Bg} = 0.16 + j \cdot 5.63\, mS$

The "Box" characteristic is set to cover the value corresponding to the admittance given in *Eq. 6* with sufficient margin. In case of distributed compensation this requires that the boundary line in the direction of the positive susceptance axis would have a value exceeding the value obtained from *Eq. 6*. Thus the box-characteristic is also well suited for networks with distributed compensation. An example is illustrated in *Fig. 9*.

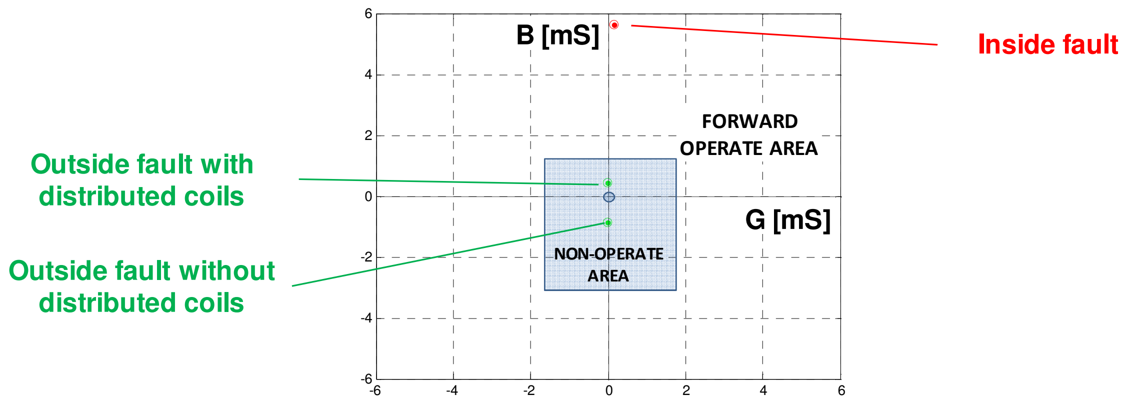

***Fig. 9** Novel admittance characteristic applied in Example #2.*

EXAMPLE #3

Consider a 20 kV distribution system with central compensation. A harmonics based admittance protection is applied and compared with a fundamental frequency based admittance protection. The network data is presented in *Table 3*. The parallel resistor of the coil is disconnected during the healthy state, and connected during the fault situation until the protection operates.

Table 3. *Network data of the example #3 protection scheme.*

Network data/parameter	**Value at 20 kV**
Maximum earth-fault current produced by the protected feeder	10 A
Earth-fault current produced by the background network	90 A
Rated current of the parallel resistor	5 A
Resistive losses of the system	2 %
Compensation degree, K	1.05 (overcompensated)
Maximum healthy state U_o	5% of U_n
Harmonic component present in I_o and U_o	5^{th} (250 Hz)

Conversion of ampere values to admittances:

$$\underline{Y}_{Fdtot\_50Hz} = 2\% \cdot \frac{10A}{20/\sqrt{3}kV} + j \cdot \frac{10A}{20/\sqrt{3}kV} = 0.02 + j \cdot 0.87\,mS$$

$$\underline{Y}_{Bgtot\_50Hz} = 2\% \cdot \frac{90A}{20/\sqrt{3}kV} + j \cdot \frac{90A}{20/\sqrt{3}kV} = 0.16 + j \cdot 7.80\,mS$$

$\underline{Y}_{cCC\_50Hz} = \frac{5A}{20/\sqrt{3}kV} - j \cdot \frac{1.05 \cdot 100A}{20/\sqrt{3}kV} = 0.433 - j \cdot 9.09\,mS$ (prior to the connection of the parallel resistor, the conductance is assumed to be zero)

($\underline{Y}_{cDST\_Fd\_50Hz} = 0\,mS$, $\underline{Y}_{cDST\_Bg\_50Hz} = 0\,mS$ (central compensation))

Theoretical measured admittances in case of outside and inside fault:

Outside fault: $\underline{Y}_o^1 = -(G_{Fdtot} + j \cdot B_{Fdtot\_50Hz}) = -0.02 - j \cdot 0.87\,mS$

$$\underline{Y}_o^{n=5} = -(G_{Fdtot} + j \cdot B_{Fdtot\_50Hz} \cdot 5) = -0.02 - j \cdot 4.35\,mS$$

Inside fault, prior connection of parallel resistor:

$$\underline{Y}_o^1 = (G_{Bgtot} + G_{cCC}) + j \cdot (B_{Bgtot\_50Hz} + B_{cCC\_50Hz}) = 0.16 - j \cdot 1.29\,mS$$

$$\underline{Y}_o^{n=5} = (G_{Bgtot} + G_{cCC}) + j \cdot (B_{Bgtot\_50Hz} \cdot 5 + \frac{B_{cCC\_50Hz}}{5}) = 0.16 + j \cdot 37.18\,mS$$

Inside fault, after connection of parallel resistor:

$$\underline{Y}_o^1 = (G_{Bgtot} + G_{cCC}) + j \cdot (B_{Bgtot\_50Hz} + B_{cCC\_50Hz}) = 0.59 - j \cdot 1.29\, mS$$

$$\underline{Y}_o^{n=5} = (G_{Bgtot} + G_{cCC}) + j \cdot (B_{Bgtot\_50Hz} \cdot 5 + \frac{B_{cCC\_50Hz}}{5}) = 0.59 + j \cdot 37.18\, mS$$

It can be seen that for the 5th harmonic the IED would see the network as being strongly undercompensated although the system is actually overcompensated, K = 1.05. This makes the discrimination between fault and non-fault condition exceptionally easy as the decision always could be based on the sign of the measured susceptance (*i.e. over-susceptance criterion*) without the need of increasing the resistive current with a parallel resistor. This is illustrated in *Fig. 10*.

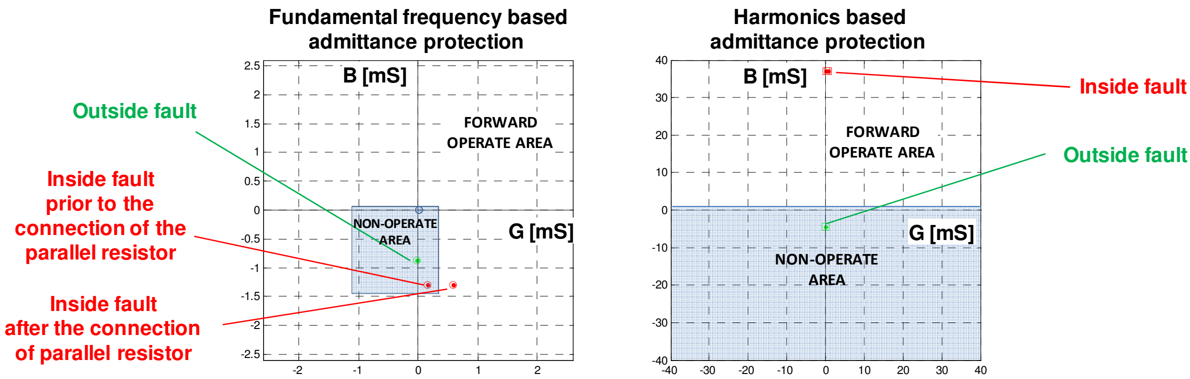

***Fig. 10** Comparison of fundamental frequency and harmonics based admittance criterion.*

CONCLUSIONS

The fundamental theory behind admittance based earth-fault protection has been presented. This theory shows that admittance protection has many attractive features, e.g. inherent immunity to fault resistance, universal applicability, good sensitivity and easy setting principles. Such a protection function is available in IEDs of the *ABB Relion*® product family. It can be anticipated that the application of admittance principle will become more popular in the future in distribution networks with centralized or distributed compensation.

REFERENCES

[1] H-M Pekkala, *Challenges in extensive cabling of the rural area networks and protection in mixed networks,* Master of Science Thesis, Tampere University of Technology, June 2010

[2] J. Lorenc et. al, *Admittance criteria for earth fault detection in substation automation systems in Polish distribution power networks*, CIRED 1997 Birmingham.

[3] A. Wahlroos, J. Altonen, *Performance of a novel neutral admittance criterion in MV feeder earth-fault protection*, CIRED 2009 Prague.