Relay Protection and Substation Automation of Modern EHV Power Systems
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Adaptive 100% Stator Earth Fault Protection Based on Third Harmonic Voltage Measurement

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Introduction

Short circuit between the stator winding in the slots and stator core is the most common type of electrical fault in generators. According to a big US utility, 70 to 80 % of all electrical faults in their generators have been – or started as - earth-faults of the stator winding. The protection described in the paper is capable of detecting earth faults occurring at any point of the stator winding, and is sufficiently sensitive to indicate also the deterioration of insulation, leakages, in the winding sections situated close to the neutral point of the stator winding.
The 100 % stator earth-fault protection incorporates two separate protections which complement each other and together cover the whole stator winding. The sub-protections are:

1. The 3rd harmonic-voltage-based differential protection (ANSI designation 59 THD),

2. Fundamental frequency (zero-sequence) over-voltage protection (ANSI designation 59 N)

The paper describes in more detail only the 3rd harmonic-voltage-based differential protection..

Generator earth fault protection

The stator earth-fault protection of large generators connected to their step-up power transformers should preferably be able of detecting small earth current leakages occurring even in the vicinity of the generator neutral. A high resistance earth-fault close to the neutral is not deadly itself, but must anyway be detected in order to prevent a possibility for a double earth-fault when another earth-fault can for example occurs near the generator terminals.
A typical example is a water-cooled generator, where deteriorations of winding insulation near the neutral should also be detected, because any incipient leakage of cooling water in the vicinity of the neutral point would cause a gradual deterioration of insulation without giving rise to immediate breakdown (the voltage stress imposed on the insulation near the neutral being a few hundred volts only). If such deteriorations remain undetected, a sustained leakage of water may damage the insulation of another conductor in the same slot or, possibly, that of a conductor in an adjacent slot. If this conductor is situated close to the phase terminal, its normal service voltage with respect to the earthed stator frame lies in the order of magnitude of 10 kV. This voltage will of course sooner or later cause the breakdown of the deteriorated insulation, and the first earth-fault of the stator winding will

develop near the phase terminal. Under the effect of this first earth-fault, voltage of the generator neutral will rise to the level of up to 10 kV with respect to the earthed stator frame. This sudden voltage rise will cause most likely a flashover at the weakened spot near the neutral. Thus a most hazardous type of fault, a double earth-fault will result.
The 100 % stator winding protection described in this paper is capable of detecting not only any (low) resistance earth-faults anywhere along the stator winding of the protected generator, but is also sufficiently sensitive to indicate the deterioration of insulation in the winding sections situated close to the neutral point of the stator winding, which is not immediately critical, but must anyway be detected in order to prevent a double earth-faults.

The 100 % stator earth fault protection

The 3rd harmonic-voltage-based differential protection should detect earth-faults at the neutral point, and at least 10 to 15 % from the neutral point along the stator winding. The fundamental frequency over-voltage protection measures the fundamental frequency, (zero-sequence voltage), at generator neutral point. This protection should detect earth-faults at least in the range 15 to 100 % of the stator winding from the neutral point, as shown in Figure 1.

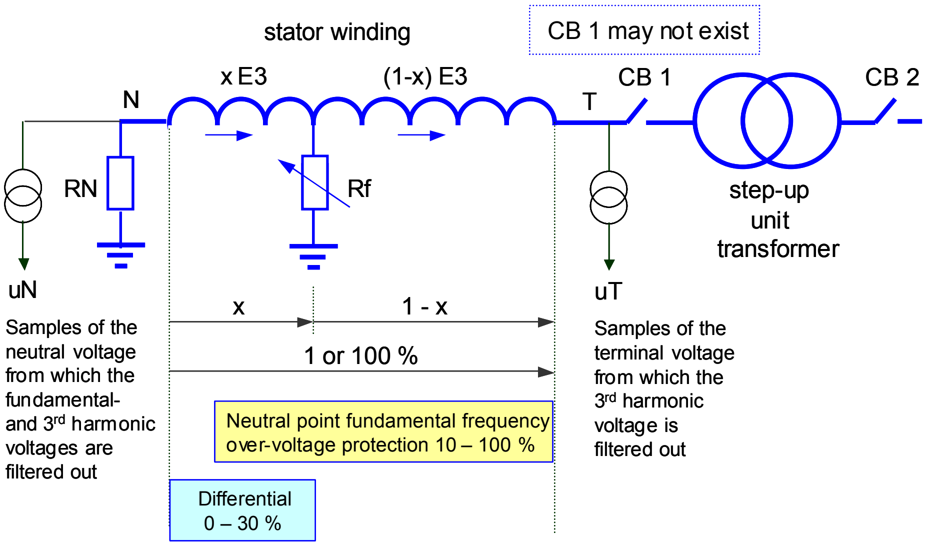

Figure 1: 100% Stator earthy fault protection principles

The fundamental frequency over-voltage protection measures the fundamental frequency, voltage at neutral point of the stator winding. The over-voltage protection cannot protect the whole stator winding, but should protect up to 90 to 95 % of the stator winding measured from the generator terminals. The limitation imposed to this protection is usually the (zero-sequence) voltage transferred via the capacitance between the high voltage- and the low voltage windings of the step-up power transformer. This voltage is usually kept on the level 1 to 3 % of rated generator phase voltage by the neutral resistor and the capacitance to earth of the stator winding. A selective protection for about 90 and up to 95 % of the stator winding can therefore be arranged by measuring the normal, no-fault fundamental frequency voltage between neutral and earth. Even if there were no “parasitic”, no-fault, fundamental frequency voltage at the neutral, it is obvious that an earth-fault at the neutral could not be detected as there would be no change at all in the neutral point fundamental frequency voltage for an earth-fault at the neutral point.

The two complementary protection principles may have separate, independently settable time delays.

The 3rd Harmonic Voltages

The simplest, linear model, which is usually applied for educational purposes, assumes a linear distribution of the 3rd harmonic voltage induced along the stator winding, and - regardless of the earth-fault position and resistance Rf - a constant angle of 180° between the 3rd harmonic phasors N3 and T3 measured on the opposite sides (N-neutral and T-terminal) of the stator winding. If the fault occurs closer to the neutral point, then the 3rd harmonic voltage at neutral, UN3, decreases, while the one at terminals of the winding, UT3, increases just as much.

The issue of the 3rd harmonic voltage induced in stator windings is in fact a complex one and out of scope of this paper. The subject is discussed in more detail in [1] and [2]. Nevertheless, it is indispensable to shed some more light on how an earth-fault affects the 3rd harmonic voltages at both ends of the stator winding. It will be shown by way of an example (Figure 2) how the voltages UN3 and UT3 change as functions of a resistance between the neutral point and the earth. It will be shown that also the angle between the phasors N3 and T3 changes as a function of the resistance. The stator winding will be represented by the customary simple Π model. Figure 2 shows how a resistance Rtot between the neutral point and the earth affects the angle, and the magnitudes of the 3rd harmonic voltage phasors at both sides of the stator winding.

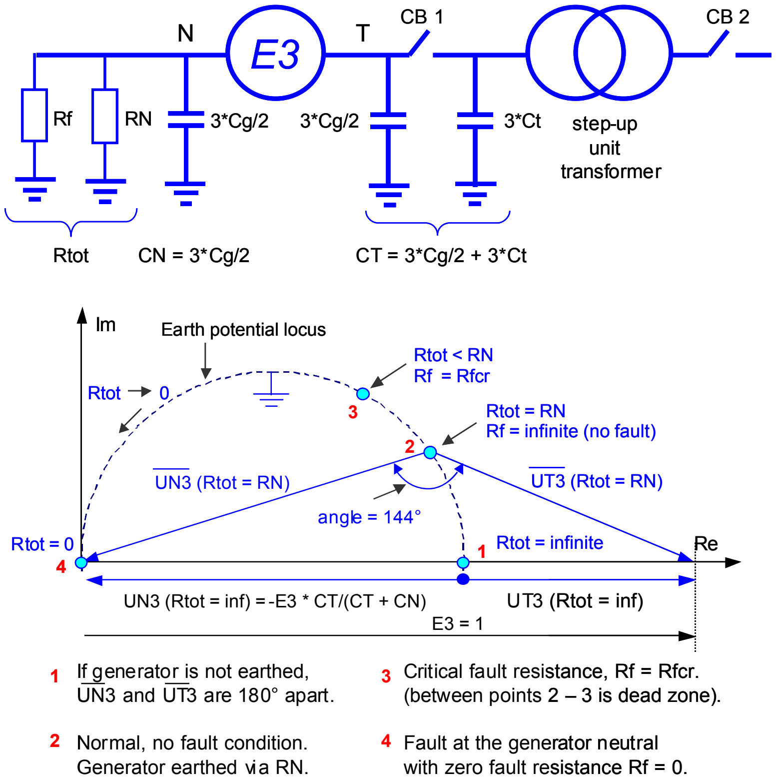

Figure 2: Magnitudes of phasors U_{N3} and U_{T3} and the angle between them as a functions of the total resistance Rtot from the neutral point of the winding and the earth

3rd Harmonic Voltage Protection

Operating equation of the protection

The 3rd harmonic voltage-based differential protection compares geometrically the 3rd harmonic voltages measured at both neutral (N) and terminal (T) side of the generator. The algorithm of the 3rd harmonic voltage differential protection is in short as follows. The operating equation of the protection is:

$$|\overset{\omega}{U}\text{N3} + \overset{\omega}{U}\text{T3}| - \text{Beta} * |\overset{\omega}{U}\text{N3}| = 0 \qquad (1)$$

The 3rd harmonic voltages U_{N3} and U_{T3} are phasors with their real and imaginary parts. U_{N3} is a phasor, normally with approximately opposite direction of that of the U_{T3}. The actual no-fault angle between these two phasors depends mainly on how the stator winding of the protected generator is earthed. For example, for generators earthed via a high resistance, the angle is typically about 140 to 150 electrical degrees. Equation (1) defines the “operate” and “block” regions of the protection. The 3rd harmonic differential protection operates, and disconnects (most often after a delay, specified by the user) the faulty generator, when the following condition is fulfilled:

$$|\overset{\omega}{U}\text{N3} + \overset{\omega}{U}\text{T3}| \geq \text{Beta} * |\overset{\omega}{U}\text{N3}| \qquad (2)$$

or

$$\text{DU3} \geq \text{BU3} \qquad (3)$$

The left-hand side of the expression (2) determines the operate quantity, DU3, while the right-hand side of this expression determines the bias (e.g. restraining) quantity, BU3. Beta is a proportionality factor used with the bias quantity in order to enhance the security of the protection, but which, indirectly, also determines the zone of protection.

The protection should detect earth-faults or leakages at the neutral point, and at least 10 to 15 % from the neutral point along the stator winding. How much of the winding can be protected is determined by factors over which one has no power, e.g. capacitances of the stator winding to earth, and other factors, such as the setting Beta, which indirectly affects what portion of the stator winding can be protected.

The above algorithm yields a protection, which is more sensitive closer to the neutral point, where the fundamental frequency zero-sequence over-voltage protection may fail. The two protection principles complement each other and together provide 100% stator earth fault protection..

Bias factor Beta – a security setting

Factor Beta guarantees a required degree of security against un-wanted disconnections of the protected generator under normal, no fault conditions, such as under different and changing load on the protected generator.

$$\frac{\text{Beta} * \text{UN3}}{|\overset{\omega}{U}\text{N3} + \overset{\omega}{U}\text{T3}|} = \frac{\text{BU3}}{\text{DU3}} = K \qquad (4)$$

K is the security factor. If for example, it is required that K = 2.0, then, factor Beta must be set so that, under normal, no fault conditions, even in the worst case, BU3 / DU3 ≥ 2.0. In other words, at any load on the healthy generator, the bias quantity BU3 must be at least two times the operate value DU3. Loading of the protected generator from zero- to full load is required in order to determine the value of factor Beta.

The protection operates when DU3 ≥ BU3 as shown in expressions (2) and (3). Whatever Beta, there is always a dead zone on the stator winding where an earth-fault, even a zero resistance fault, cannot be detected by the 3rd harmonic voltage differential protection. It is clear from Figure 3 that with Beta = 1, a zero resistance earth-fault, Rf = 0 kΩ, can be detected no farther than 33 % from the neutral point. The rest of 77 % are a blind zone for this protection. However, this blind zone is no problem, as the fundamental frequency neutral point over-voltage protection positively detects earth-faults occurring in the blind zone of the 3rd harmonic protection. The right-most column in Table 1 displays the protected zone if more exact calculations are done for Rf = 0 kΩ earth-fault moving along the winding. As the values obtained by the simple (e.g. linear) model are more conservative, they shall be used as guidance for function setting calculations.

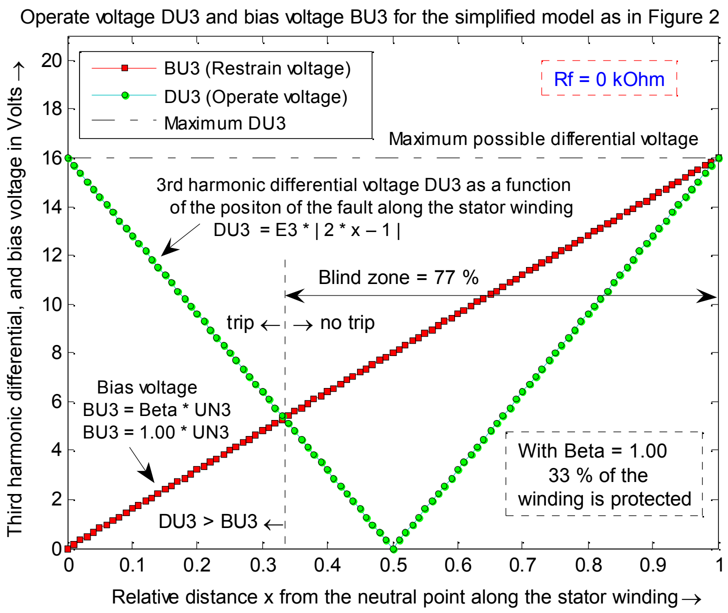

Figure 3. With Beta = 1, the protected zone is 33 % of stator winding from the neutral point. An earth-fault with zero resistance, Rf = 0 kΩ, can be detected as far as 33 % from the neutral.

Table 1: The protected zone from the neutral point of the stator winding as a function of factor Beta. Valid for zero resistance earth-faults, Rf = 0 kΩ.

Setting	Simple (linear) model	More advanced model
Beta	protected zone in %	protected zone in %
0.5	40.00	48.5
1.0	33.00	44.7
2.0	25.00	35.4
3.0	20.00	27.7
4.0	16.67	22.3
5.0	14.28	18.5
6.0	12.50	15.8

Sensitivity of the differential protection

The algorithm shown in equation (2) yields a protection, which is more sensitive closer to the neutral point of the winding. An important information is just how sensitive is the 3rd harmonic voltage differential protection for an earth-fault at neutral?

Sensitivity is a function not only of the stator and the unit power transformer windings parameters, such as their capacitances to earth, but as well a function of one setting of the protection, namely the security factor Beta.

Sensitivity can always be calculated. Observe from Figure 2 and Figure 3 that the 3rd harmonic voltages on the neutral side and the terminal side, UN3 and UT3, as well as the angle between them, can be calculated. It is possible to find even the magnitude of the differential voltage, DU3, and the bias voltage, BU3, as a function of the total resistance, Rtot, between the neutral point and the earth. With a known RN, it is then no problem to separate the unknown actual earth-fault resistance Rf from the total resistance Rtot.

An example is shown for a generator with earth-resistance R_N = 8.8 kΩ, Cg = 0.111 µF per phase, and with the circuit breaker CB 1 open as shown in Figure 1. Factor Beta was set to value 1.

Table 2 displays some values of the angle between UN3 and UT3, further, UN3, (which is equal to the bias voltage BU3 as Beta = 1), UT3, and the differential (operate) voltage DU3 for some values of total resistance, Rtot, near the value of the earth-resistance RN = 6.39 kΩ with which the neutral point is connected to earth.

Table 2. The angle, UN3 (= UB3 as Beta = 1), UT3, and DU3, as functions of the total resistance between the neutral point of the stator winding and the earth, Rtot, for some characteristic values.

Rtot [Ω]	Angle [°]	UN3 [relative]	UT3 [relative]	DU3 [relative]
1.0 kΩ	98.91	0.14970	0.96579	0.95412
6.3 kΩ	134.83	0.44536	0.63636	0.45167
8.8 kΩ	144.05	0.47005	0.58064	0.34086
99 kΩ	176.26	0.49973	0.50079	0.03266

Figure 4 has shown that magnitudes of phasors UN3 and UT3 can be determined as functions of the angle between the phasors. The angle is in its turn a function of the total resistance Rtot from the between the neutral point and the earth as shown in Figure 2. It is then just as easy to calculate the operate voltage, DU3, and the bias voltage, BU3, as functions of the angle between the 3rd harmonic voltage phasors. This is shown in Figure 4.

Figure 4 illustrates how the critical earth-fault resistance, Rfcr, is calculated for a generator earthed via R_N = 8.8 kΩ, and with winding per phase capacitance to earth Cg = 0.111 μFarad. The circuit breaker CB 1, as in Figure 1, was open. Setting Beta was assumed to be Beta = 1. Under normal, no-fault condition, with only by RN = 8.8 kΩ, one measures DU3 = 0.341, and BU3 = 0.470. As it holds here that BU3 > DU3, there will be no trip. If an earth fault happens in the neutral with Rf ≤ 22.2 kΩ, this fault will be detected. For critical resistance, Rfcr = 22.2 kΩ, it becomes DU3 ≥ BU3. (Rfcr can be separated from Rtot = 6.3 kΩ because of the known earth-resistance RN = 8.8 kΩ.)

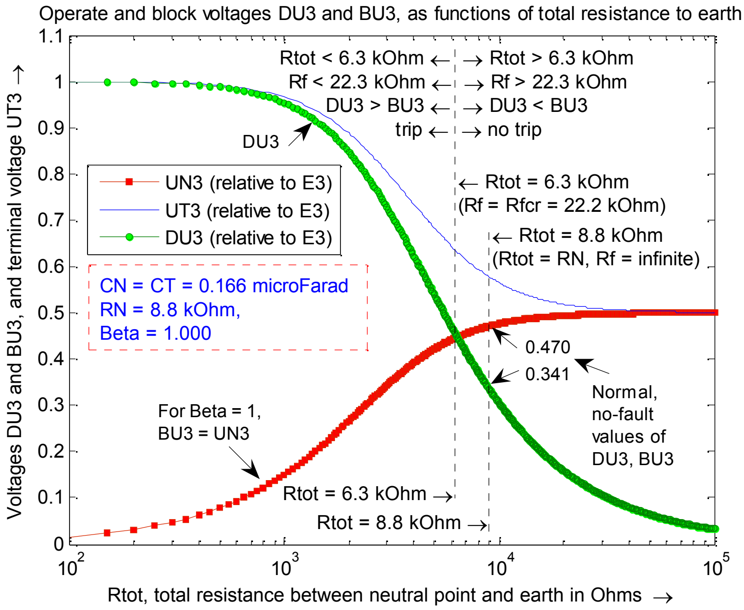

Figure 4. Critical fault resistance Rfcr = 22. 2 kΩ.

The presented 100% stator earth fault protection was as well successfully tested on the generator available in the ABB Corporate Research Laboratory.

Conclusion

The 3rd harmonic voltage-based differential protection has proved to be a good complement to the fundamental frequency over-voltage protection which cannot detect earth faults near or at the neutral point of the stator winding.

The algorithm of the 3rd harmonic differential protection yields a protection, which is more sensitive closer to the neutral point. Sensitivity is a function not only of the stator and the unit power transformer windings parameters, such as their capacitances to earth, but as well a function of one setting of the protection, namely security factor Beta.

The advantage of the 3rd harmonic voltage-based differential protection as described in the paper in comparison to other stator earth-fault protections, based on the measurement of the 3rd harmonic voltages, but not applying a differential principle is that this algorithm offers a protection which is independent of the changing load on the protected generator.

The laboratory measurements and tests based on these measurements have proved that the protection is efficient in detecting earth-faults/leakages close to the neutral point of the stator winding which cannot be positively be detected by any other means.

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