INRUSH CURRENTS AND THEIR EFFECT ON PROTECTIVE RELAYS

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ABSTRACT

This paper explains in detail the phenomena of inrush in single-phase transformers during three conditions: transformer energization, external fault clearing and sympathetic inrush. It then focuses on the inrush in three-phase transformers, explaining the influence of a delta winding and analyzing the types of transformer configurations that allows the flow of zero-sequence current.

The paper describes the influence of the inrush current on different types of protection functions as transformer differential, overcurrent, distance, busbar and line differential. It focuses mainly on the transformer differential describing the most common methods used for maintain the security during the inrush condition: harmonic restraint and harmonic blocking. Their differences are explained. It then explains the different crossed logics used and selects the most appropriate one. It finally describes a logic to inhibit the harmonic restraint / blocking based on an external fault detector. This logic reduces the tripping time of the differential unit mainly during internal faults with CT saturation.

Different cases are considered based on real events and RTDS simulations.

1 INTRODUCTION

Inrush currents are caused by DC saturation of the power transformer and can be several times the rated current of the transformer. They are not fault currents so they should not be tripped. Inrush currents specially influence the transformer differential protection but they can affect other protection functions such as overcurrent, distance, busbar differential and line differential. In all the cases they can produce a loss of security.

The inrush phenomena is a complex one. Its deep understanding will allow protection engineers to improve the balance between security and dependability in the protection schemes affected by it.

2 INRUSH CURRENTS

Inrush currents occur because the magnetic circuit of the power transformer saturates due to a DC offset in the flux. This DC offset is generated due to a change in the magnetizing voltage. The saturation of the power transformer core demands a high magnetizing current.

Inrush currents can occur during the following situations:

- Energization of the power transformer
- Voltage recovery after the clearing of an external fault
- Energization of a parallel power transformer (sympathetic inrush)

We will start by explaining the steady state magnetizing current and then we will focus on the transient magnetizing current (inrush current) for the mentioned three situations.

2.1 MAGNETIC FLUX

If we apply a voltage to the primary winding of a transformer and we neglect the leakage inductance and the winding resistance the following equation will be fulfilled:

$v = N1 \cdot \frac{d\phi}{dt}$, where:

v is the instantaneous value of the supply voltage connected to the primary winding
N1 is number of turns of the primary winding
Φ is the instantaneous value of the magnetic flux

If $v = Vm \cdot \sin(wt + \theta)$, the flux will be $\phi = \int_0^t v(t)dt = -\frac{Vm}{N1 \cdot w} \cdot \cos(wt + \theta) + k$ (1), where k is an integration constant.

The term $-\frac{Vm}{N1 \cdot w} \cdot \cos(wt + \theta)$ represents the steady state flux and the integration constant k represents a transient DC flux that is generated when there is a difference between the initial flux and the steady state flux.

As it can be seen in figure 1, the steady state flux will be lagging the voltage by 90º.

For t=0 $k = \phi_0 + \frac{Vm}{N1 \cdot w} \cdot \cos(\theta)$ (2), where

ϕ_0 is the initial total flux (flux at t=0)
θ is the angle of the voltage at t=0

k will be called ϕ_{DC}

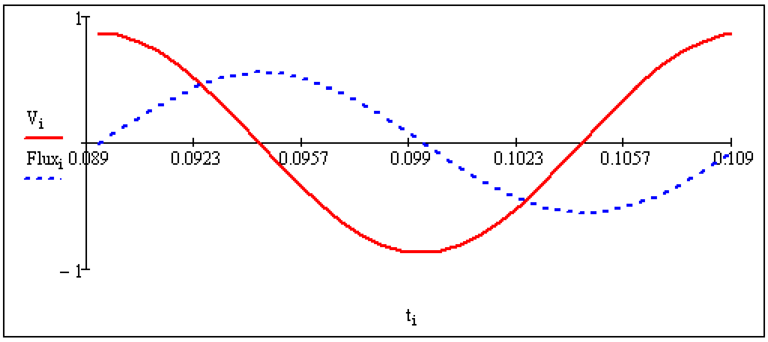

Figure 1. Steady state flux and supply voltage

2.2 STEADY STATE MAGNETIZING CURRENT

The steady state magnetizing current can be obtained from the steady state flux by using the magnetic curve (B-H or $\phi - i$ curve). Figure 2 shows the voltage, the flux and the magnetizing current. The latter one is obtained by applying different flux values to the $\phi - i$ curve. This process is shown in figure 3. It can be checked that the magnetizing current is not sinusoidal. The main harmonic is the third one.

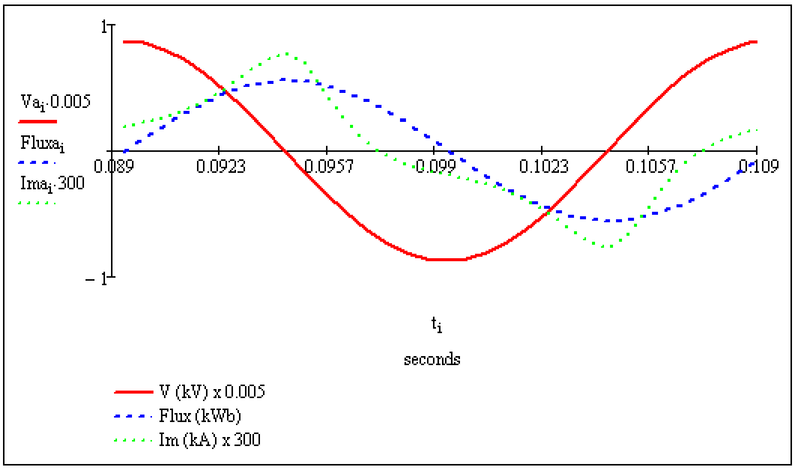

Figure 2. Steady state flux, supply voltage and steady state magnetizing current

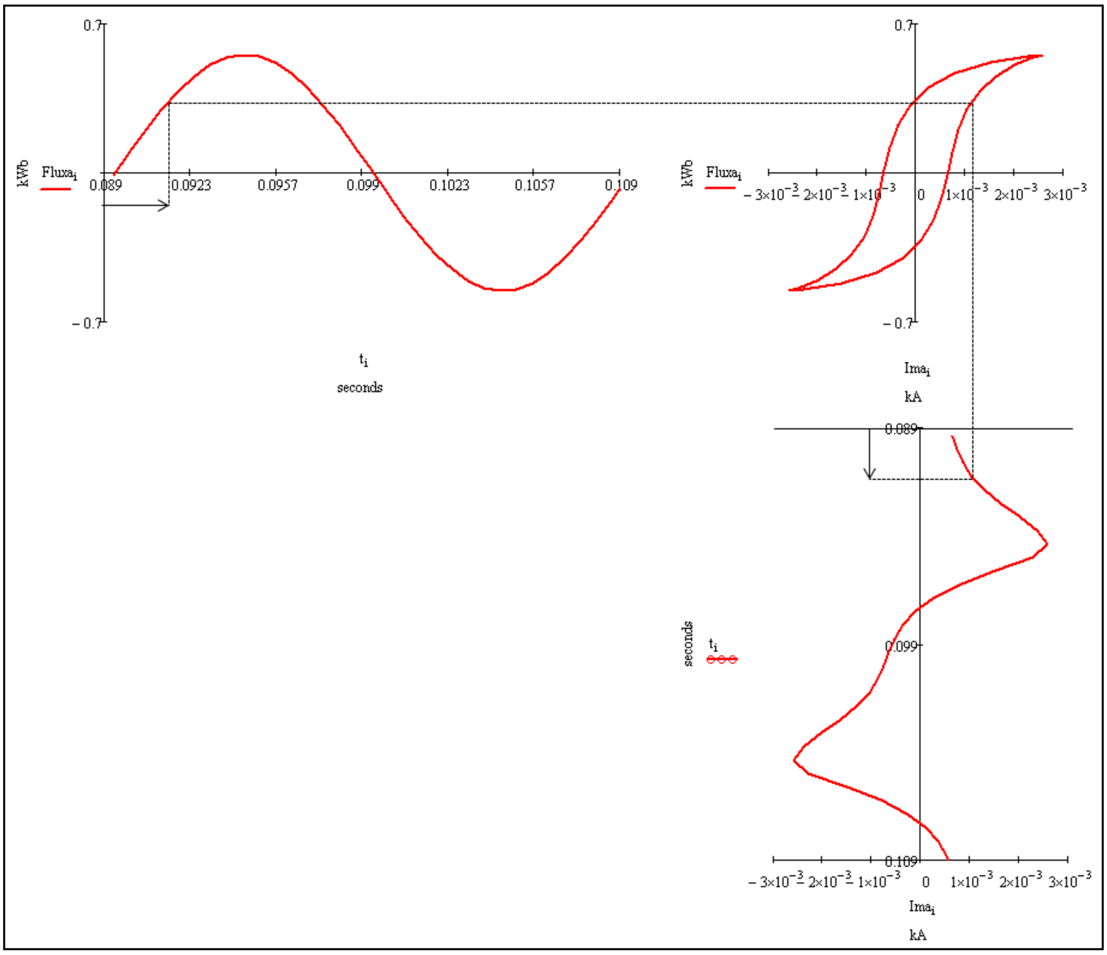

Figure 3. Calculation of the magnetizing current wave from the flux wave

2.3 TRANSIENT MAGNETIZING CURRENT

The transient magnetizing current will be studied for the following situations:

2.3.1 Power transformer energization

When the power transformer is energized the initial flux will be equal to the residual flux. The residual flux depends on the hysteresis of the B-H curve and on the point the magnetizing current is switched-off. The transient flux will be maximum for a maximum difference between the residual flux and the steady state flux. This will happen when both fluxes have opposite polarity and the steady state flux is maximum. This can be seen in figure 4. The source voltage is represented by Vs (red curve in dots) and the voltage applied to the transformer by V (straight blue curve). The breaker is closed at the zero-crossing of the source voltage (point A). At this point the steady state flux (pink dash-dot curve) will have a negative maximum. As the residual flux is positive (green dash curve), the transient flux will also be positive. The magnetizing current (light blue curve with crosses) starts increasing with a very high rate when the flux reaches the saturation density. The extraction of the magnetizing current from the total flux by means of the $\phi - i$ is shown in figure 5. The process is the same as the one shown in point 2.2.

If the breaker was closed at point B, when the steady-state flux is equal to the residual flux the transient flux would be null and the transformer would not be saturated.

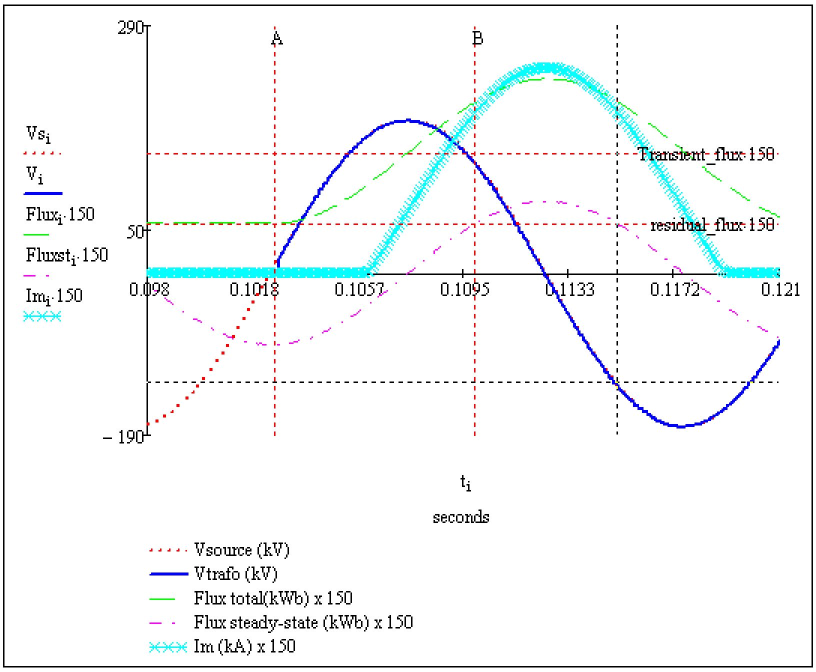

Figure 4. Source voltage, transformer voltage, total flux, steady state flux and magnetizing current for an energization at the zero-crossing of the voltage

When the flux is above the saturation density the relation between it and the magnetizing current will be linear so if the flux is sinusoidal the magnetizing current will also be sinusoidal. However, below the saturation density the relation between both quantities will not be lineal, especially in the bend of the magnetic curve. Figure 6 shows the curves of figure 4 during the first miliseconds of the energization. The magnetic curve for this period is shown at the right. The bend of the magnetic curve can be distinguished.

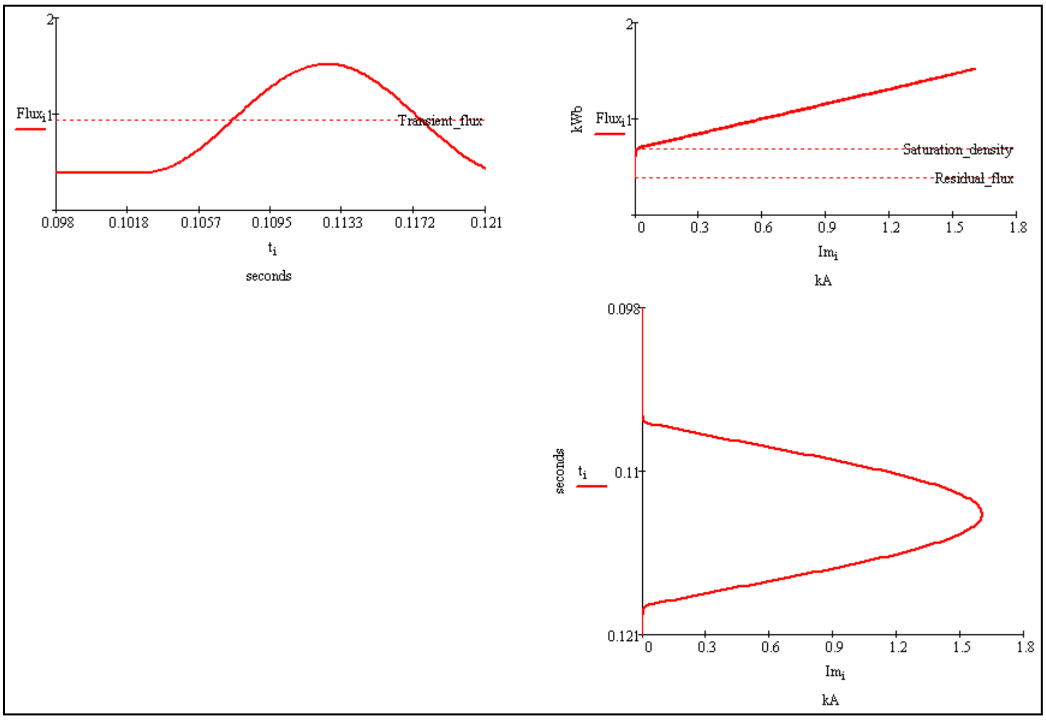

Figure 5. Calculation of the magnetizing current wave from the flux wave

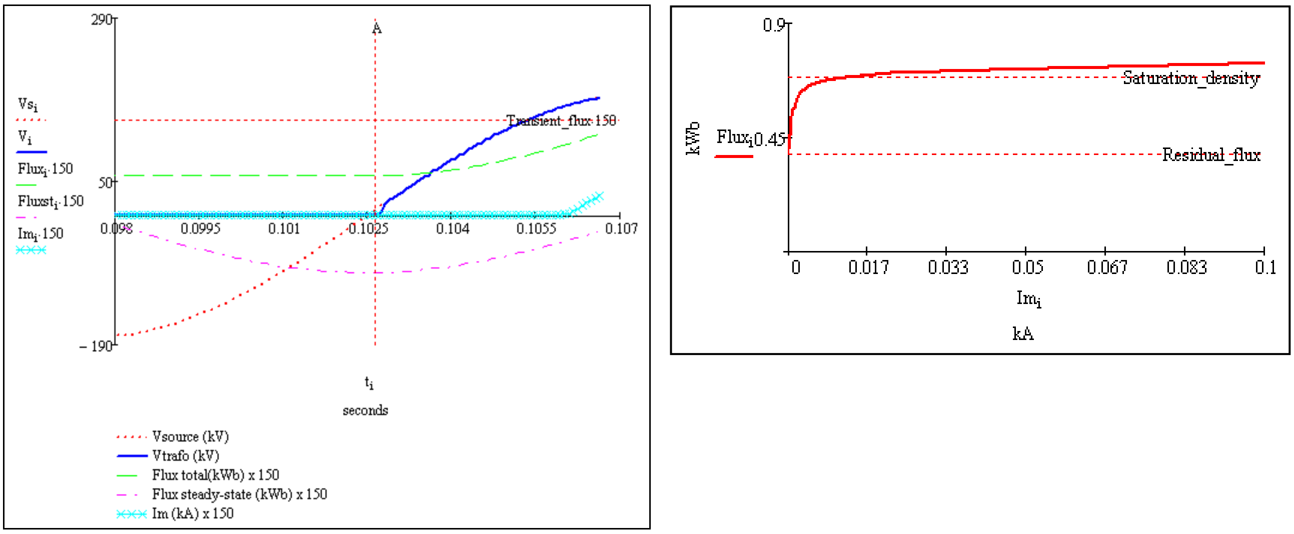

Figure 6. Quantities shown in figure 4 (left) and corresponding magnetic curve (right) during the first miliseconds of the energization

Figure 7 shows the voltage, the flux and the current during an inrush condition. As it can be seen there is a damping in both the current and the flux. The transient flux, which is a DC component, will be damped because of the voltage drop in the source resistance and in the winding resistance. The real formula for the flux will be:

$v' = N1 \cdot \frac{d\phi}{dt}$, where:

$$v' = v - R \cdot i - L \cdot \frac{di}{dt}$$

R is sum of the source resistance and the primary winding resistance
L is the sum of the source inductance and the primary winding leakage reactance

The flux will be calculated as: $\phi = \int_0^t v(t)\cdot dt - \int_0^t R\cdot i(t)\cdot dt - \int_0^t L\cdot\frac{di(t)}{dt}\cdot dt$

In order to see the damping of the flux we can see the differences in the total flux between values in instants with a difference of one period of time (T), as the waveforms are periodic [1].

$$\phi_t - \phi_{t-T} \simeq -\int_{t-T}^{t} R\cdot i(t)\cdot dt$$

As v(t), for time T, is a symmetrical waveform, $\int_{t-T}^{t} v(t)\cdot dt$, which represents the area under v(t) for one cycle, will be zero. The same happens with $L\cdot\frac{di(t)}{dt}$. Although i(t) is a totally asymmetrical waveform its derivative will be almost symmetrical. Figure 8 shows two cycles for the derivative of the magnetizing current. As it can be seen the waveform during each cycle is practically symmetrical.

$\int_{t-T}^{t} R\cdot i(t)\cdot dt$ is equal to the area under the current waveform during one cycle.

The voltage drop in the resistance R makes the voltage v' asymmetrical (as it can be seen in figure 9 the positive area is bigger than the negative one), so $\int_{t-T}^{t} v'(t)\cdot dt \neq 0$.

As the magnetizing current decreases the voltage drop in the source resistance also decreases. This makes the damping decrease.

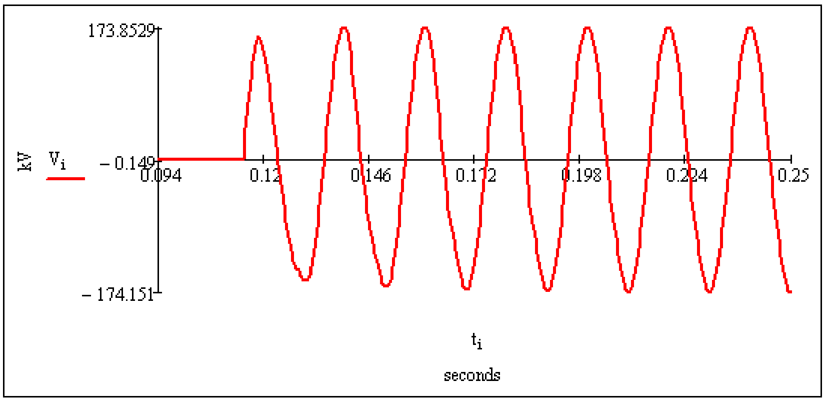

Figure 7.a. Voltage during an inrush condition

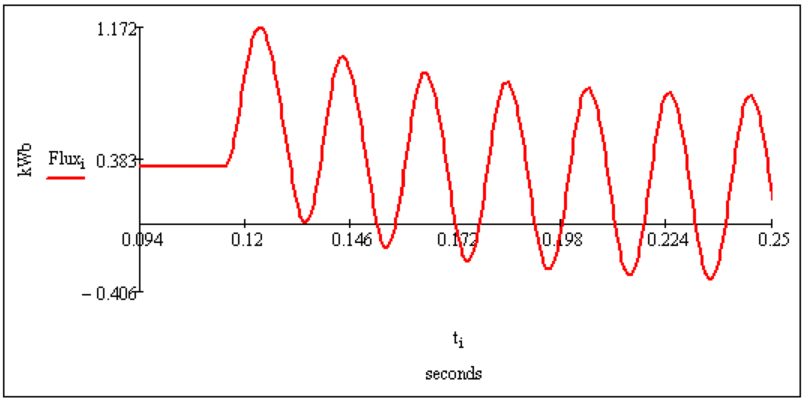

Figure 7.b. Flux during an inrush condition

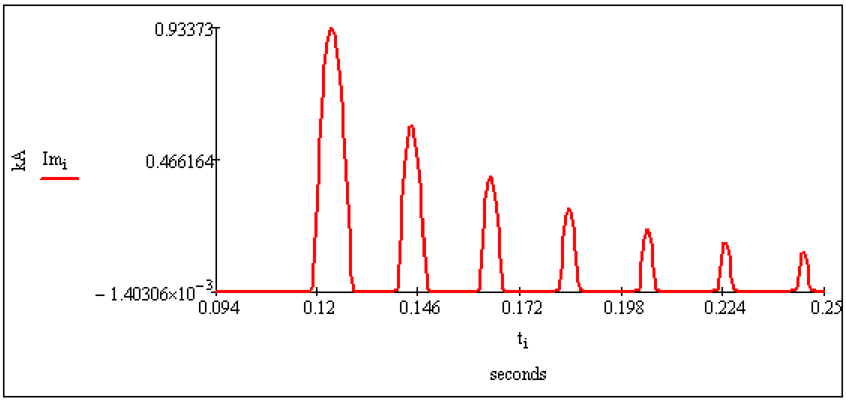

Figure 7.c. Current during an inrush condition

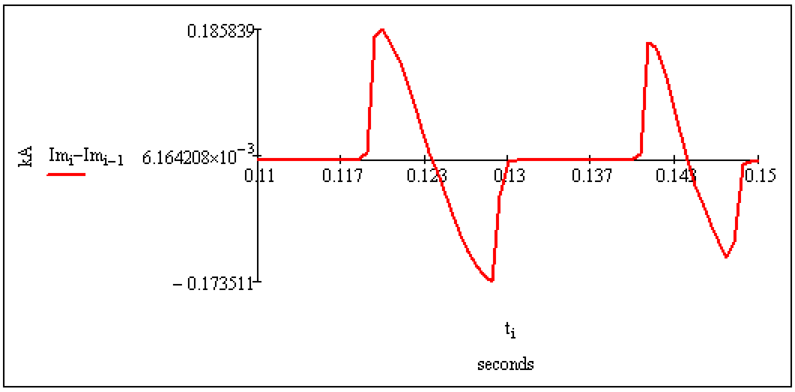

Figure 8. Derivative of the magnetizing current

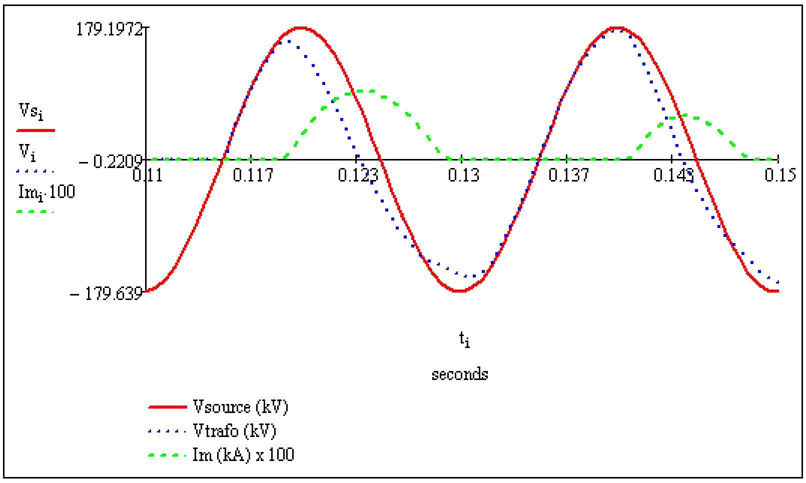

Figure 9. Deformation of the transformer voltage due to the voltage drop in the source resistance

Because of the large and slowly decaying DC component of the inrush currents CTs are very prone to saturate. The difference between primary and secondary currents is shown in figure 10. The CT tends to remove the DC component of the current. As it can be seen, in the last cycles the sum of the positive and negative areas, under the wave, during one-cycle, tends to be null.

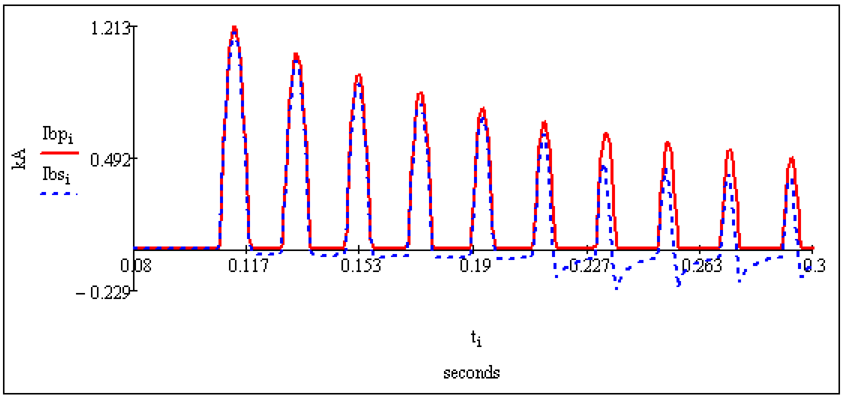

Figure 10. Primary and scaled secondary currents during an inrush

2.3.2 Voltage recovery after an external fault

When an external fault is cleared there will be a change in the voltage that can create a transient DC offset flux similar to the one in the energization of the transformer. Figure 11 shows the voltage, the flux and the magnetizing current of a transformer for an external fault. Due to the change in the voltage caused by the fault (point A) there is a DC offset in the flux. However the transformer does not saturate because the flux value is much lower than the rated one due to the low voltage. When the fault is cleared (point B) there is another change in the voltage that creates a new DC offset in the flux. As the flux magnitude turns into the rated value the transformer gets saturated.

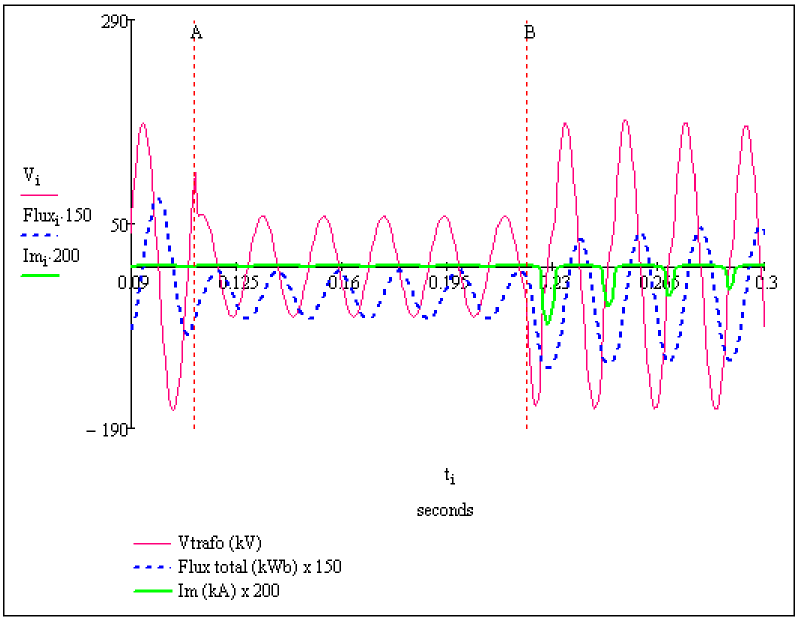

Figure 11. Voltage, flux and magnetizing current for an during an external fault and its clearing

2.3.3 Sympathetic inrush

Consider the two power transformers, T1 and T2, of figure 12. Both transformers are connected in parallel to the busbar B, which is fed by the voltage E. Rs represents the source resistance, Xs the source reactance, R1 the resistance of the primary winding for transformer T1 and R2 the resistance of the primary winding for transformer T2.

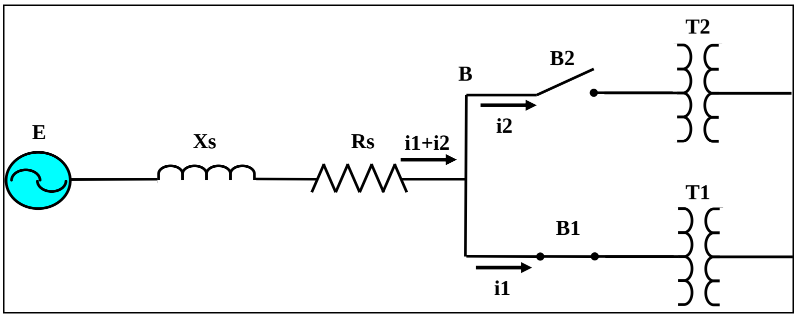

Figure 12. System considered for the sympathetic inrush phenomena

Transformer T1 is already energized and transformer T2 will be energized by closing the breaker B2. In order not to mix the inrush current with the load current we will neglect the load current in transformer T1, so current i1, just before T2 is energized, will be zero. When the breaker B2 is closed the transformer T2 will experience an inrush. We will assume a negative DC offset for the flux in transformer T2 (see figure 13). This DC offset will be damped because of the voltage drop caused by (i1+i2) in Rs and by i2 in R2. The following formula defines the flux change in one cycle:

$$\phi 2_t - \phi 2_{t-T} \simeq \int_{t-T}^{t} [Rs \cdot (i1 + i2) + R2 \cdot i2] \cdot dt$$

As it was explained before, the asymmetrical current i2 will make the voltage at the magnetizing branch of transformer T2 be also asymmetrical, due to the voltage drop in the source and winding resistances. This will make the integral of this voltage during one cycle be different from zero.

The asymmetry of the voltage at busbar B will affect transformer T1. As this transformer was already energized its flux did not have any DC offset. The voltage drop in the source resistance (there is no voltage drop in the winding resistance as i1 is considered zero at the beginning of this phenomena) starts creating a positive DC offset in the flux (see figure 13):

$$\phi 1_t - \phi 1_{t-T} \simeq \int_{t-T}^{t} [Rs \cdot (i1 + i2) + R1 \cdot i1] \cdot dt$$

This positive DC offset makes transformer T1 saturate.

The steady state component of both fluxes, Φ1 and Φ2, can be considered equal, as both transformers will be supplied from the same voltage. Flux Φ2 has a negative DC offset and flux Φ1 has a positive DC offset. This makes the saturation periods of T1 and T2 happen at opposite half-cycles. T2 is saturated during the negative half-cycles of the steady state flux and T1 is saturated during the positive half-cycles of the steady state flux. The currents i1 and i2 will therefore have opposite polarity and their peaks will occur at alternate half-cycles. The consequence is that the flux changes created by the voltage drop in the source resistance (caused by the sum current, i1+i2) changes its sign every half-cycle (until the instant that T1 saturates the flux change was always positive, for every half-cycle, as i1 was null): i1 tends to create a negative flux change (tending to get T1 out of saturation and, on the other hand, tending to maintain T2 saturated) while i2 tends to create a positive flux change (tending to get T2 out of saturation and, at the same time, tending to maintain T1 saturated). At the beginning of the sympathetic inrush, as i2 is higher (in absolute value) than i1 its effect is bigger, so, due to the positive flux change, it will make i2 decrease (in absolute value) and i1 increase, until its absolute value is equal. When both currents are equal the flux change for a cycle in both transformers due to the voltage drop in the source resistance will be zero (the flux change in every half-cycle will be equal and with opposite polarity). The only flux change is created by the voltage drop of each current in the winding resistance of the corresponding transformer. This generates a very slow damping making the inrush currents in both transformers be present for a long time.

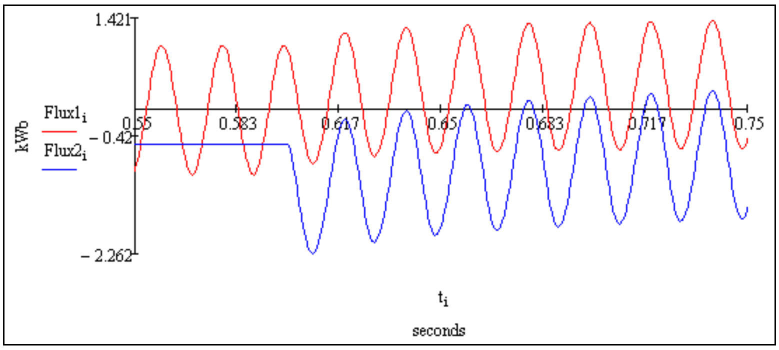

Figure 13. Fluxes in transformers T1 and T2 during the first cycles of a sympathetic inrush

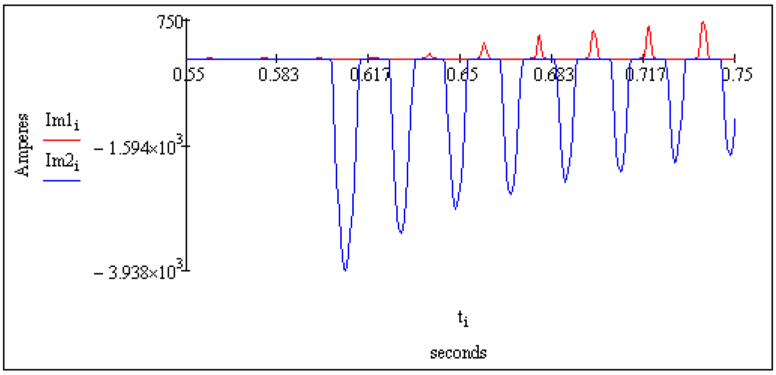

Figure 14. Currents in transformers T1 and T2 during the first cycles of a sympathetic inrush

Figures 15, 16 and 17 represent the currents i1, i2 and i1+i2 during 2 seconds of the phenomena. Note in figure 17 that when both currents get equal (in absolute value) the damping reduces very much.

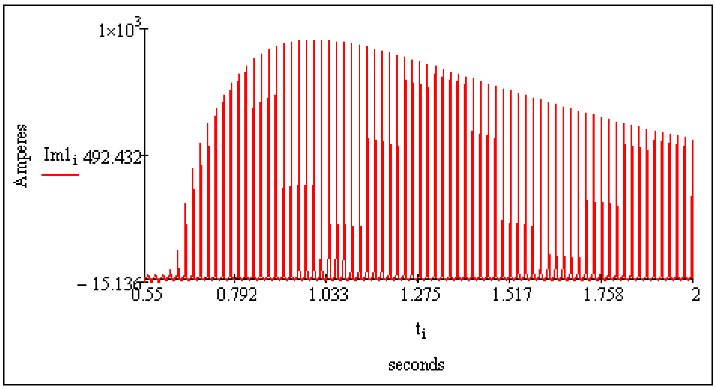

Figure 15. Current in transformer T1 during 2 seconds of the sympathetic inrush

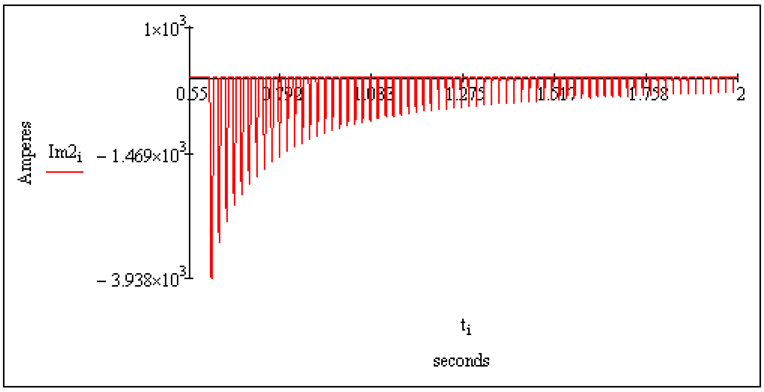

Figure 16. Current in transformer T2 during 2 seconds of the sympathetic inrush

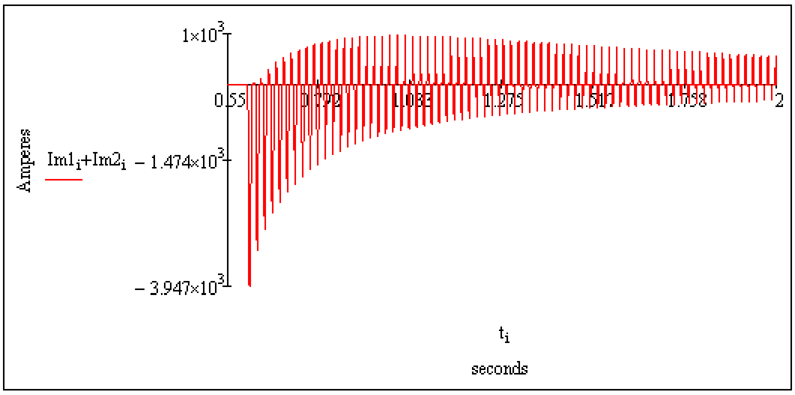

Figure 17. Sum of the currents in transformers T1 and T2 during 2 seconds of the sympathetic inrush

2.3.4 Inrush in three-phase transformers

When a three-phase transformer is energized there will be a different inrush current in each phase. The voltage switching point will vary from one phase to the other due to the phase-shift between the phases (theoretically 120º) and the breaker mechanism different times. On the other hand the residual flux in each phase may be different, depending on the point the magnetizing current was switched-off. When this point is to be calculated the presence of delta windings should be taken into account as they maintain the excitation in phases already de-energized from the wye side [3].

2.3.4.1 Helping effect

On wye-delta transformers, the delta winding provides magnetizing current through the non-saturated phase/s “helping” the wye winding [3].

Let´s consider the wye-delta power transformer represented in figure 18. Figures 19, 20 and 21 show the fluxes, the magnetizing currents and the primary currents in the three phases, respectively, when the transformer of figure 18 is energized from the wye side. Figure 22 shows the current in the delta winding. This current can only be zero-sequence, therefore the currents in the three phases will be equal. As it can be seen, the magnetizing current in phase B is zero, however there is a current in phase B flowing in the primary winding. This current is provided by the delta winding, energized by the primary source, to contribute to the magnetizing current in phases A and C from the secondary side. The phenomena can be explained as follows:

The first phase that saturates is A. Until the point D phase C is not saturated so both B and C phases contribute to the magnetizing current in phase A. It can be checked that the phase A primary current is lower than the phase A magnetizing current. The difference will be equal to the sum of the primary currents in phases B and C. Note that until point D the current in the delta winding is in phase with the phase A current in the wye winding (the CT polarity is considered), so this current is also “entering” the secondary winding. As the magnetizing currents in phases B and C are null, the current in the delta winding, already scaled with the transformer ratio, will be equal to currents B and C in the primary winding and with opposite polarity (also taking into account the CT polarity). So currents in phases B and C will “exit” the primary winding. When phase C saturates (point D), the phase C primary source has to provide the magnetizing current for phase C. At this moment it was also providing the magnetizing current for phase A. This magnetizing current provided to phase A will start decreasing. Phase B now has to supply magnetizing current for phases A and C at the same time. As the demands are opposite (magnetizing currents A and C have opposite sign), current in phase B starts decreasing. At the beginning, the magnetizing current in phase A will be higher than the magnetizing current in phase C so the primary current in phase B will remain positive. When the magnetizing current in phases A and C become equal, the current in phase B will be zero. From this point on the current in phase B starts increasing its magnitude, with a negative value. At point E the phase A exits the saturation period so starts helping phase C; this makes current in phase B start decreasing. When phase C exits saturation the three currents will be zero. This phenomena is repeated when phase A starts again the saturation period. It is worth noting that the phase B current in the wye winding and the current in the delta winding are bipolar waves instead of a unipolar ones.

Note that the “helping effect” will also happen in YY three-legged transformer, because of the phantom tertiary effect [4].

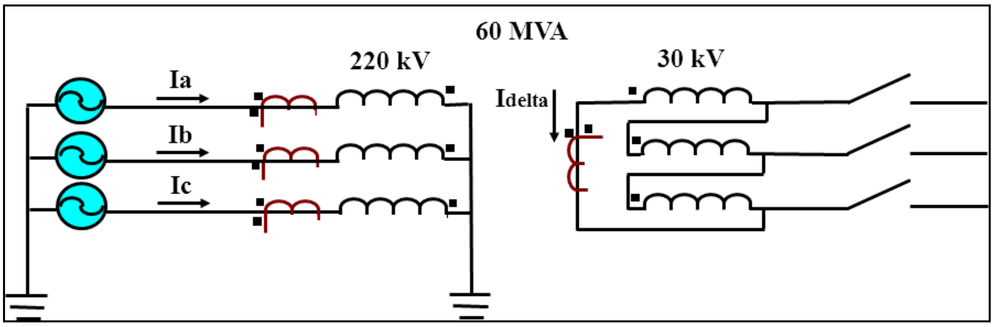

Figure 18. Phase fluxes during the energization from the wye side of a wye-delta transformer

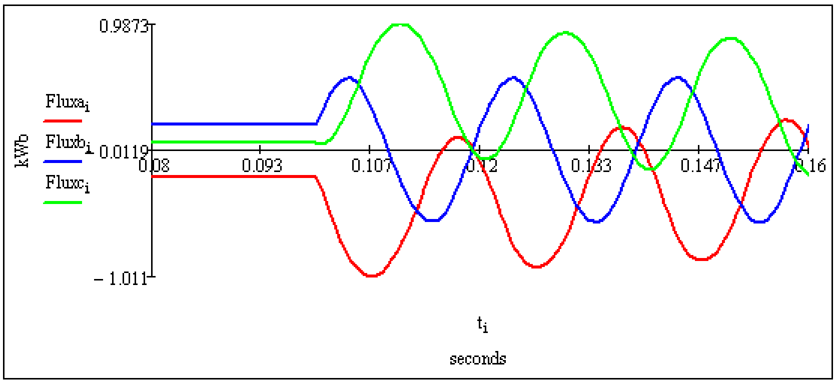

Figure 19. Phase fluxes during the energization from the wye side of a wye-delta transformer

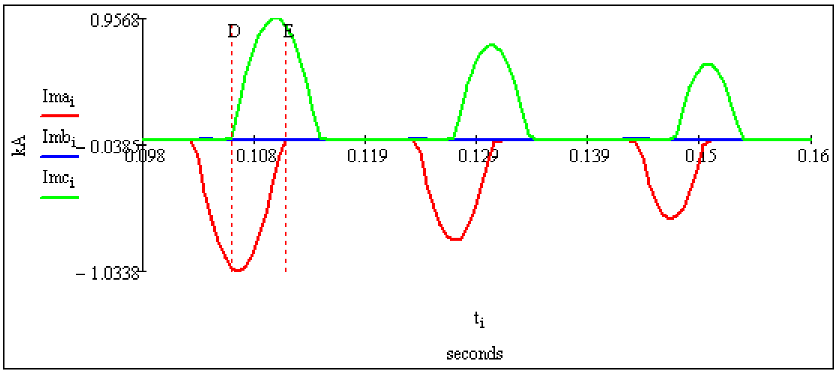

Figure 20. Phase magnetizing currents during the energization from the wye side of a wye-delta transformer

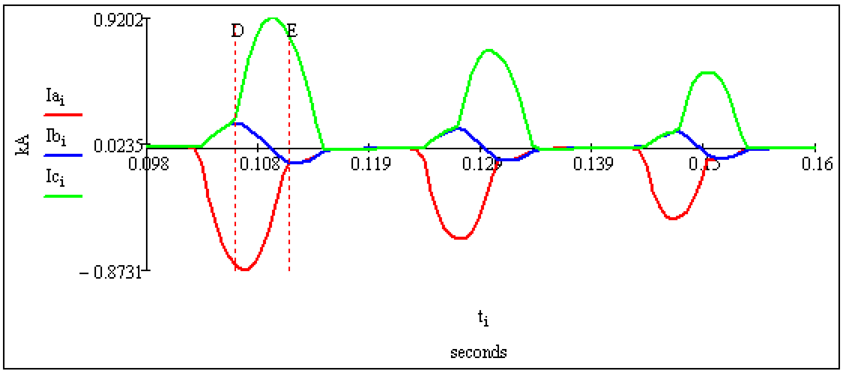

Figure 21. Phase currents in the wye winding during the energization from the wye side of a wye-delta transformer

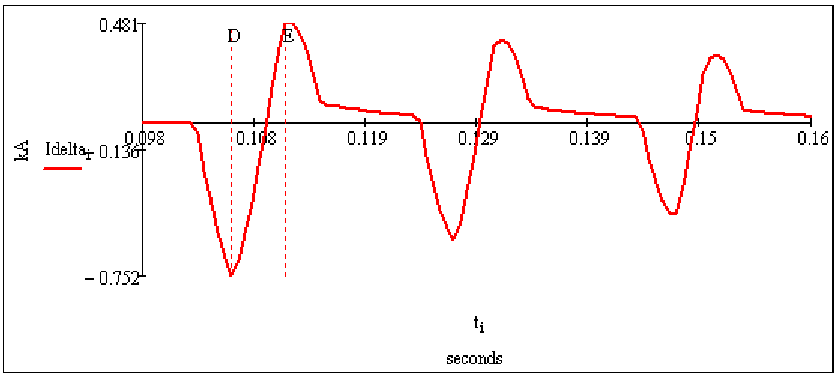

Figure 22. Current in the delta winding during the energization from the wye side of a wye-delta transformer

2.3.4.2 Zero-sequence filter influence

When the power transformer includes a delta winding a zero-sequence filter in the wye windings is used for the differential relays. In digital relays this filter is software implemented by any of the following ways [4]:

- Substracting the zero-sequence current calculated from the phase currents.
- Substracting the zero-sequence current measured in the ground connection.
- Applying a delta-wye transformation: converting the phase currents into phase-phase currents.

The first two methods give the same results during an inrush condition.The currents in figure 21 with the application of the first and third types of zero-sequence filters will be transformed into the currents shown in figures 23 and 24, respectively. As it can be observed the third type of zero-sequence has converted the bipolar wave into a unipolar one.

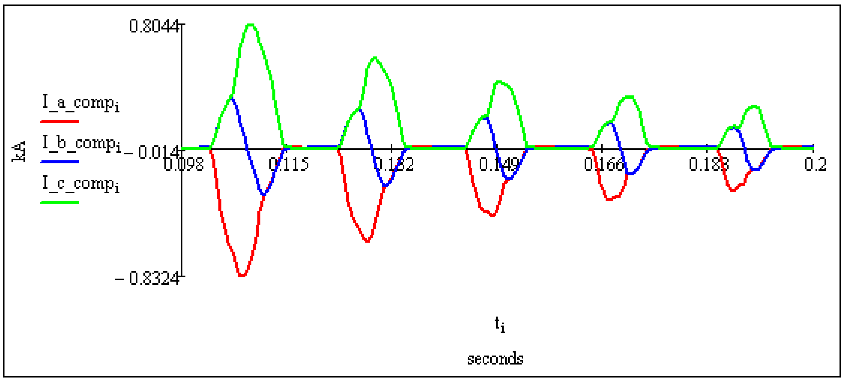

Figure 23. Currents in figure 21 with the first type of zero-sequence filter applied

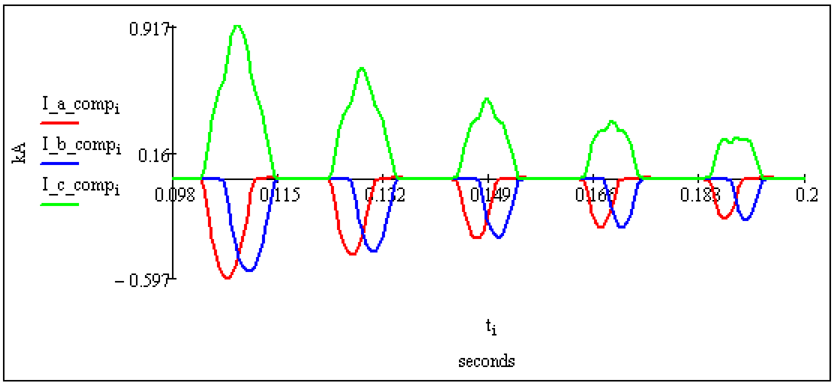

Figure 24. Currents in figure 21 with the third type of zero-sequence filter applied

2.3.4.3 Ground inrush current

The unbalance between the magnetizing phase currents will normally create a magnetizing zero-sequence current which will flow if it has the corresponding path. If this path is open the magnetizing currents will change their shape making the flux and, therefore, the voltage non-sinusoidal.

Below, the transformer connections that allow the flow of a zero sequence current during the inrush, are included. The energization is supposed to be done from the primary winding and the primary source is supposed to be grounded.

YNyn: the zero-sequence magnetizing current will flow in the primary winding
YNy: the zero-sequence magnetizing current will flow in the primary winding
YD: the zero-sequence magnetizing current will flow in the delta winding

The following transformer connections will not allow the flow of an inrush zero-sequence current during an energization produced from the primary: **Yyn**, **Yy**, **Dyn**, **Dy**.

Figures 25, 26 and 27 show the fluxes, the magnetizing currents, the currents in the primary wye winding and the currents in the tertiary winding (the latter ones only for the YD transformer) for an energization performed from the primary wye winding for different types of transformer connections: YD, YNy and Yy, respectively.

In the transformer YD (figure 25) the ground inrush current only circulates in the delta winding as it does not have a return path in the side of the wye winding. The fluxes are sinusoidal. In the transformer YNy (figure 26), the ground inrush current circulates in the primary wye winding. The fluxes are also sinusoidal. In the Yy transformer (figure 27) the ground inrush current is removed. This makes the fluxes be non-sinusoidal.

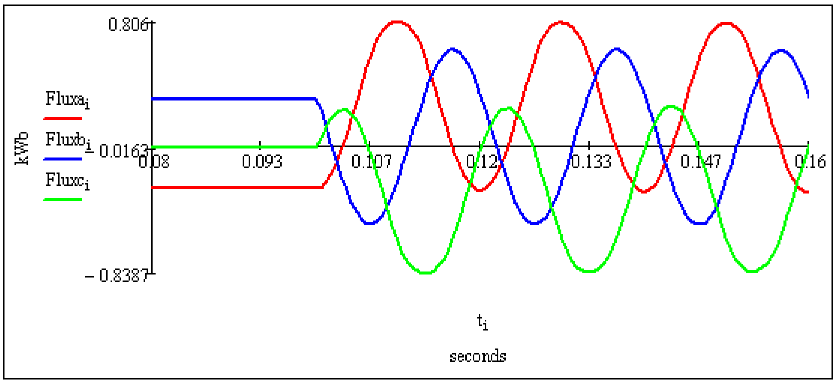

Figure 25.a. Phase fluxes during the energization from the wye side of a YD transformer

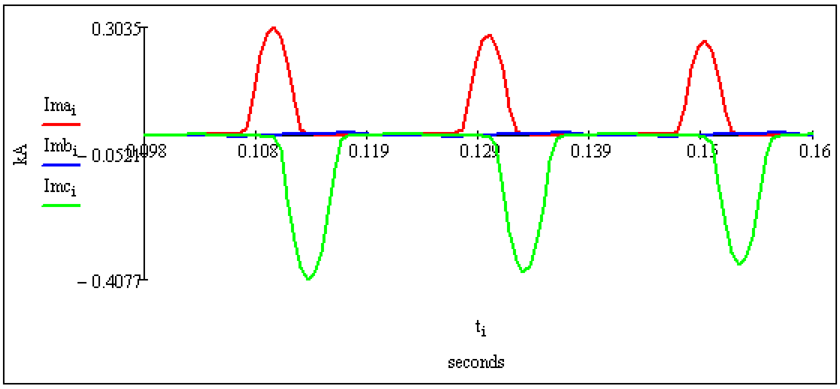

Figure 25.b. Magnetizing currents during the energization from the wye side of a YD transformer

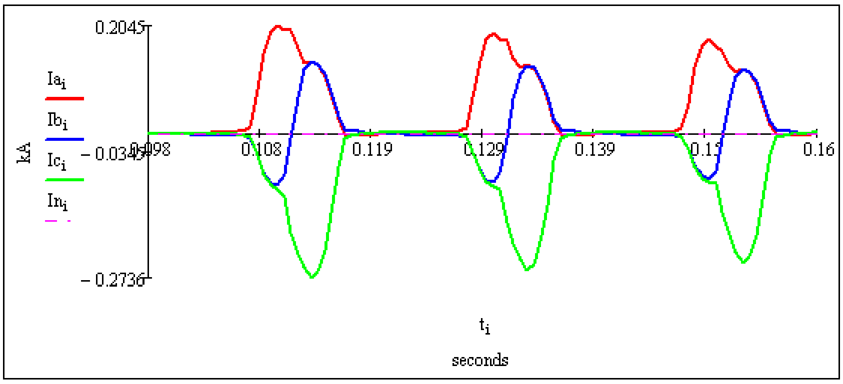

Figure 25.c. Phase and ground currents in the wye winding during the energization from the wye side of a YD transformer

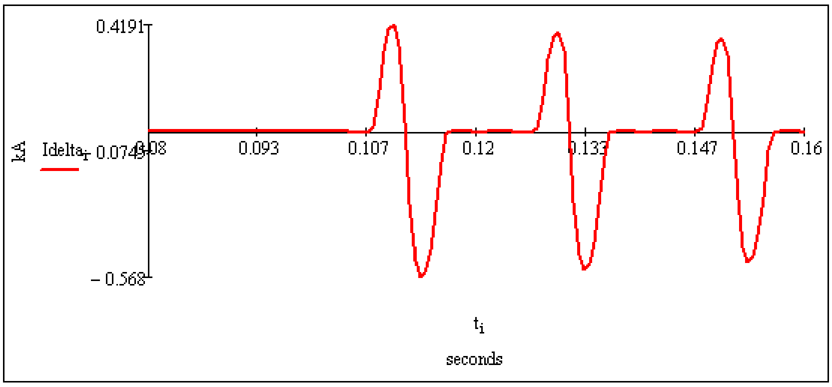

Figure 25.d. Currents in delta winding during the energization from the wye side of a YD transformer

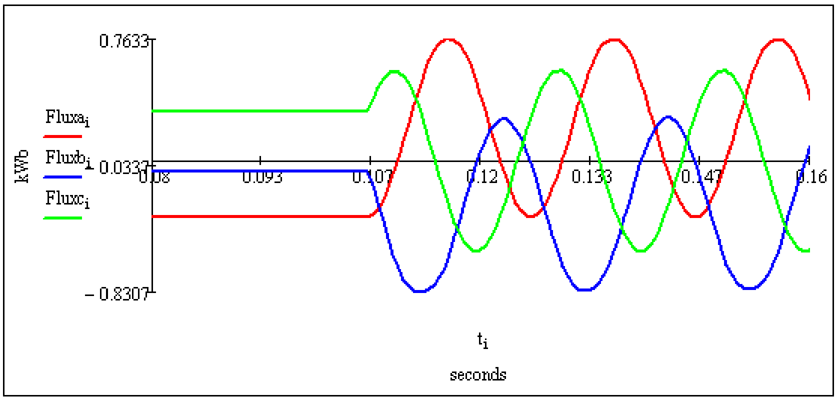

Figure 26.a. Phase fluxes during the energization from the wye side of a YNy transformer

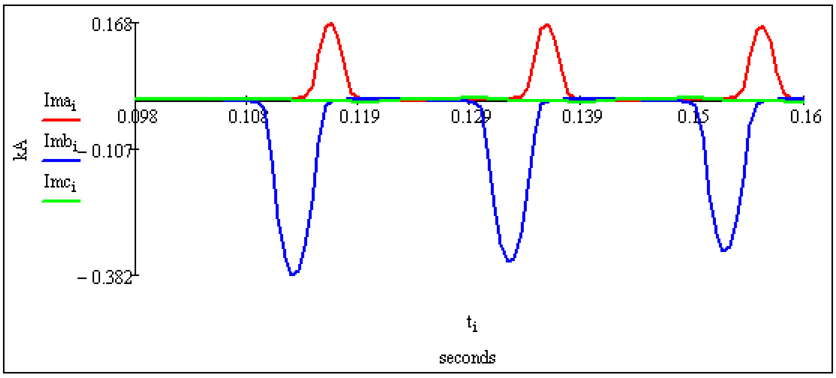

Figure 26.b. Magnetizing phase currents during the energization from the wye side of a YNy transformer

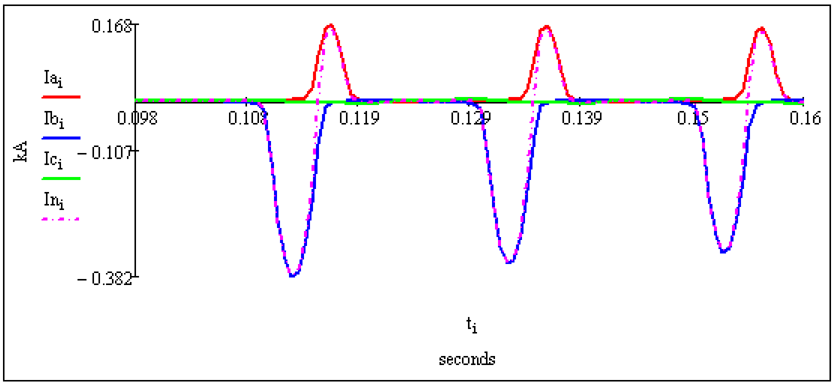

Figure 26.c. Phase and ground currents in the wye winding during the energization from the wye side of a YNy transformer

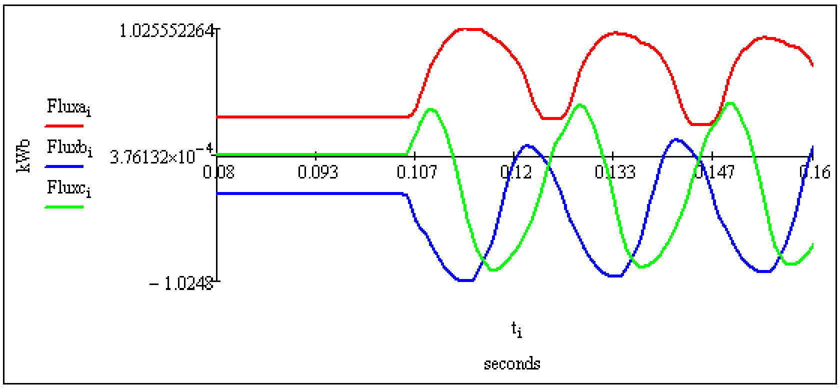

Figure 27.a. Phase fluxes during the energization from the wye side of a Yy transformer

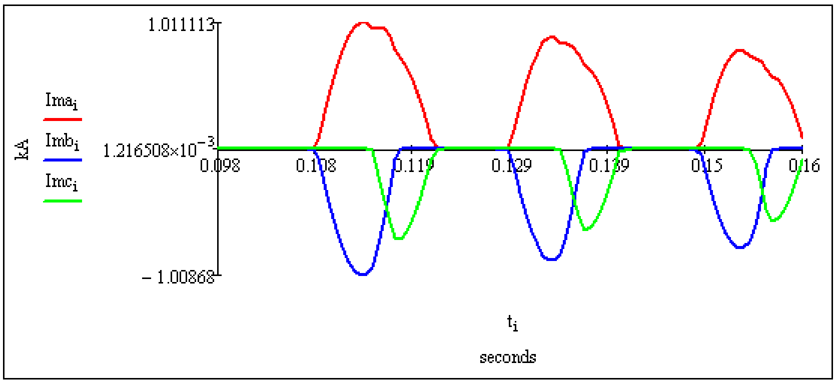

Figure 27.b. Magnetizing phase currents during the energization from the wye side of a Yy transformer

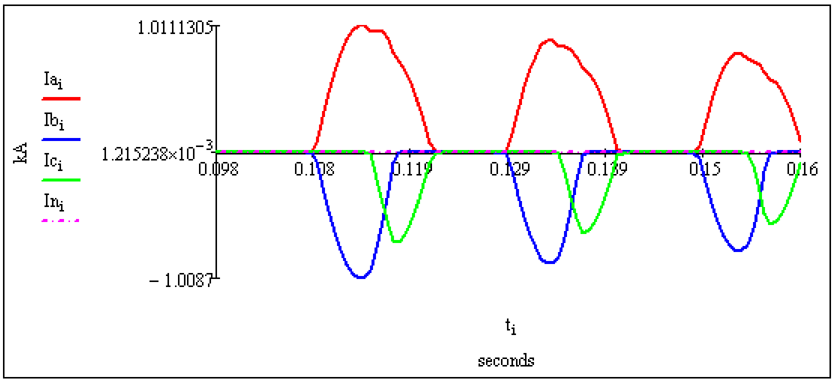

Figure 27.c. Phase and ground currents in the wye winding during the energization from the wye side of a Yy transformer

2.3.5 Harmonic content of the inrush current

In order to analyze the harmonic content of the inrush current the simplified waveform of figure 28 is considered. This waveform results from assuming a simplified B-H curve consisting of a vertical line in the non-saturated region and a straight line with a low slope in the saturated region. The transformer will be saturated during the angular span of 2α (which is normally called base angle); during this angle the magnetizing current will be an offset sine wave. The rest of the period the magnetizing current will be zero [5].

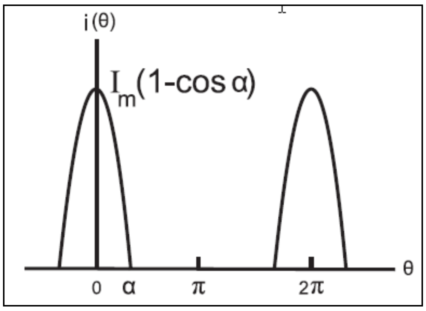

Figure 28. Simplified waveform for the inrush harmonic analysis

The equation for the simplified waveform will be:

$$i(\theta) = \mathrm{Im}\cdot(\cos\theta - \cos\alpha),\ 0 \le \theta \le \alpha,\ (2\pi\text{-}\alpha) \le \theta \le 2\pi$$
$$0,\ \alpha \le \theta \le (2\pi - \alpha)$$

In order to calculate the harmonics of this waveform a Fourier Series is considered. As the origin chosen gives a symmetric waveform about θ=0, a cosine Fourier series will be used. The nth harmonic will be given by the formula [5]:

$$a_n = \frac{\mathrm{Im}}{\pi}\cdot[\frac{1}{n+1}\cdot\sin((n+1)\cdot\alpha) + \frac{1}{n-1}\cdot\sin((n-1)\cdot\alpha) - \frac{2}{n}\cdot\sin(n\alpha)cos\alpha]$$

The harmonic content of this waveform for α values of 60º, 90º and 120º is given in the following table [5]:

Harmonic	an/a1		
	α=60º	α=90º	α=120º
2	0.705	0.424	0.171
3	0.352	0.000	0.086
4	0.070	0.085	0.017
5	0.070	0.000	0.017
6	0.080	0.036	0.019
7	0.025	0.000	0.006
8	0.025	0.029	0.006
9	0.035	0.000	0.008
10	0.013	0.013	0.003
11	0.013	0.000	0.003
12	0.020	0.009	0.005
13	0.008	0.000	0.002

Table 1. Harmonic content in the inrush current

It can be observed that the higher the α angle is the lower the second harmonic content is.

As explained in reference [3], the closer the residual flux is to the saturation density the larger the base angle 2α is. In this reference a 90% residual flux and a 140% saturation density was considered, resulting in a base angle (2α) of 240º. Modern transformers can operate closer to the knee point allowing higher residual fluxes, reducing the difference between the saturation density and the residual flux [6]. This results in lower second harmonic contents than the ones obtained in reference [3] which talked about a 17.1%. Modern transformers can have second harmonic contents as low as 7% [7]. The low second harmonic content will only be present in the first 4-5 cycles of the inrush [6]. This occurs because the damping reduces the DC offset of the flux so it reduces the time the flux is above the saturation density, decreasing the base angle of the magnetizing current.

The harmonic content of the bipolar waves, as the ones seen during the energization from the wye side of a wye-delta transformer, is normally quite high (see harmonic content of the representative inrush currents in reference [3]).

The application of the zero-sequence filter can reduce the harmonic content of the inrush current. Reference [6] states that the application of the delta-wye transformation matrix (method 3 described in 2.2.1.4.2) gives higher second harmonic content than the substraction of the zero-sequence current calculated from the phase currents (method 1 described in 2.2.1.4.2).

It is important to note that the harmonic content of the differential current (used by the transformer differential protection) is not the same as the harmonic content in the winding currents (used by any other type of protection as overcurrent or distance). The last currents will be mixed with the load current reducing the percentage of second harmonic. During a sympathetic inrush, the total current (sum of the currents in both parallel transformers) has a low second harmonic content [2]. Any protection unit based on this current would be very prone to trip.

3 INRUSH EFFECT ON DIFFERENT PROTECTION FUNCTIONS

3.1 TRANSFORMER DIFFERENTIAL

As the magnetizing reactance is a shunt branch in the equivalent circuit of the transformer, the inrush current flowing through it will be a differential current.

3.1.1 Review of the operation principle of a transformer differential relay

This section reviews the operation principles of a transformer differential unit with percentage restraint. To simplify the explanations, a two winding transformer is selected as represented in figure 29. The differential unit operates with the currents I-1 and I-2. Before calculating the differential current and the restraint currents, the discrepancies introduced by the different CT ratios, the power transformer ratio, the connection group and the zero sequence filters need to be compensated.

The differential unit operates based on two parameters:

- Differential current: $|I_{DIF}| = |I\text{-}1 + I\text{-}2|$
- Restraint Current: There are various restraint current formulas; some of them are:

[illegible]

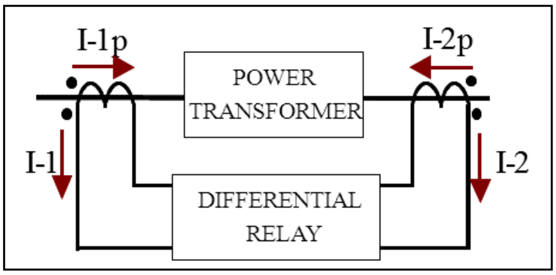

Figure 29. Circuit Diagram of the transformer protected by the differential unit

The differential unit will operate when the point ($|I_{DIF}|$, I_{RES}) is above the corresponding characteristic. In modern relays, such characteristic is similar to the one represented in figure 30, with either one or two restraint slopes.

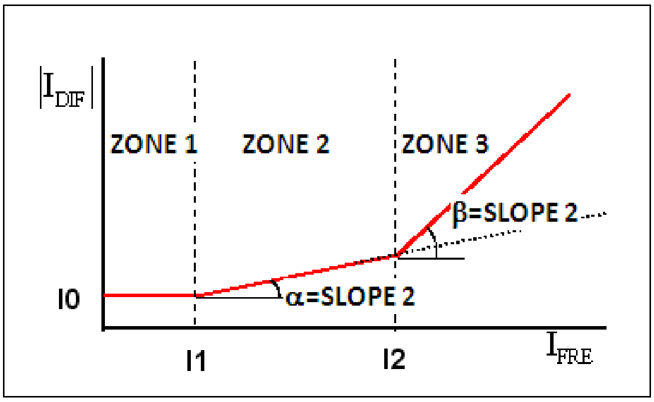

Figure 29. Differential Characteristic

3.1.2 Implemented solutions to avoid operation during inrush conditions

The most common methods included in modern relays are based either on the measurement of the harmonic content of the differential current or on a wave shape recognition of this current. This paper will focus on the first method and its implementation by means of the so-called harmonic restraint / blocking.

The methods based on the harmonic measurement of the waveform do not only use the second harmonic but also other harmonics. The fourth harmonic is also present in the inrush currents so it can also be used to restraint the operation. The third and fifth harmonics are normally used to detect an overexcitation condition of the power transformer. This situation occurs when the power transformer saturates with a symmetrical flux (the flux during an inrush condition was asymmetrical) because of an overvoltage or / and an underfrequency condition. The symmetrical flux originates a symmetrical magnetizing current (similar to the steady state magnetizing current represented in figure 2 but with a higher magnitude) that does not contain even harmonics but odd harmonics. The third harmonic is a good indicator for an overexcitation condition but, as it is a zero-sequence component (the three phase currents are equal), it is filtered by the delta windings or by the zero-sequence filters included in the differential relays so it will not be reliable in many transformer configurations. The fifth harmonic is normally used.

3.1.2.1 Harmonic restraint

Harmonic restraint was introduced in electromechanical relays [8]. The harmonic restraint method uses the harmonic content of the differential current to increase the theoretical fundamental differential current required to trip (obtained from the restrained differential characteristic). The effect is a rise in the differential characteristic.

Based on the nth (n=2, 3, 4, 5) harmonic restraint percentage set (kn) and on the harmonic content of the differential current (Idiff_harm_n, n=2,…,5) a fundamental differential current is obtained (Idiff_fund_n, n=2,…,5) (see figure 30). Note that the slope of the characteristic will be the inverse of the setting $\alpha n = \frac{1}{kn}$. This means that if a harmonic restraint percentage of 20% is selected, the slope of the characteristic will be 500%. The lower the harmonic restraint percentage is, the higher the slope is, therefore the higher the restraint is. This is done in order to relate the harmonic restraint percentage to the harmonic content of the differential waveform.

The four fundamental differential currents calculated (Idiff_harm_n, n=2,…,5) are sum to obtain a total fundamental differential current (Idiff_fund_total). The latter current will be added to the operating fundamental differential current calculated from the through current restrained differential characteristic (figure 31). Therefore, the total differential current required to operate will be a sum between the differential current calculated from the through current restrained characteristic and the differential current calculated from the harmonic restraint characteristic.

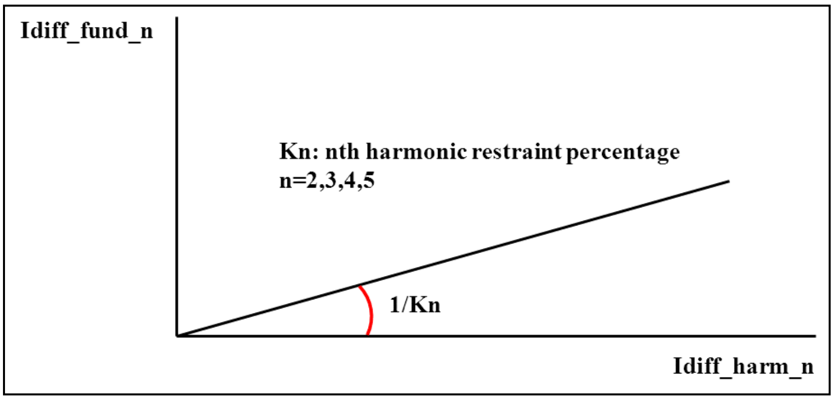

Figure 30. Characteristic for the extraction of the fundamental differential current based on the harmonic content

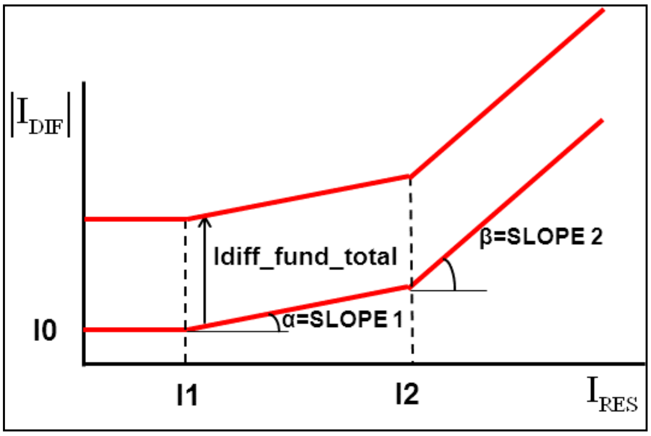

Figure 31. Rise in the through current restrained differential characteristic due to the harmonic restraint

The operating condition for the differential unit working with harmonic restraint will be:

$I_{diff\_fund} > I_{\substack{diff \\ through \\ current \\ restraint}} + I_{\substack{diff \\ harmonic \\ restraint}} = I_{rest} \cdot f(\alpha, \beta) + \sum_{n=2}^{5} \frac{I_{diff\_harm\_n}}{Kn}$ (1), with n having values for the harmonics selected to restrain; α and β are the first and the second slopes of the differential characteristic.

Reference [9] recommends the use of the fourth harmonic besides the second harmonic to increase the security during inrush conditions.

3.1.2.2 Harmonic blocking

Harmonic blocking calculates the ratio between the harmonic content and the fundamental content of the differential current. When this ratio is above the threshold set the harmonic blocking operates: $\frac{I_{diff\_harm\_n}}{I_{diff\_fund}} > Kn$ (n=2,…,5), with n having values for the harmonics selected to block.

The operating condition for the differential unit working with harmonic blocking will be:

$$\left(I_{diff\_fund} > \underset{\substack{through\\current\\restraint}}{I_{diff}} = I_{rest} \cdot f(\alpha,\beta) \right) \otimes \left(\frac{I_{diff\_harm\_n}}{I_{diff\_fund}} < Kn \right)$$

Reorganizing the terms:

$$\left(I_{diff\_fund} > I_{rest} \cdot f(\alpha,\beta) \right) \otimes \left(I_{diff\_fund} > \frac{I_{diff\_harm\_n}}{Kn} \right) (2)$$

From equations (1) and (2) we can see that harmonic restraint is more secure than harmonic blocking.

3.1.2.3 Crossed harmonic restraint / blocking

As it was mentioned in point 2.2.1.5 the inrush current can have low values of second harmonic, being as low as 7%. The settings normally used both for second harmonic restraint and blocking were around 20%. Changing to a 7% will increase the security very much but, on the other hand, it will decrease the dependability. A setting around 15%-20% is normally used for both harmonic restraint and blocking and crossed logics are enabled in order to increase the security. These logics take advantage of the fact that the low harmonic content will normally occur only in one of the phases. The harmonic content of the other phases will be used to increase the restraint.

3.1.2.3.1 Crossed logics for harmonic blocking

One out of three: if one phase has a high second harmonic content the blocking is activated in the other two phases, no matter their harmonic content. This logic is very secure but it can block the operation with internal faults occurring during the transformer energization as the healthy phases can have a high second harmonic percentage.

Two out of three: if two phases have a high second harmonic content the blocking is activated in the other phase, no matter its harmonic content. This logic provides a better balance between security and dependability than the “one out of three” logic as it will not operate for internal phase-phase faults that occur during the transformer energization. On the other hand, if the transformer is wye-delta and it is energized from the wye side, on a single-phase to ground fault happening during the transformer energization, fault current will flow in the healthy phases due to the coupling with the delta winding. The same will happen in a three-legged wye-wye transformer due to the phantom tertiary effect. If the zero-sequence filter is applied from the phase currents on the wye winding there will be an increase of the fundamental current in the healthy phases making the “two out of three” logic more dependable. However, if the zero-sequence filter is applied from the ground current, the currents in the healthy phases will be pure inrush currents making the “two out of three” logic block the trip [4].

Average: the second harmonic ratio used for blocking the three phases is the average of the second harmonic ratio for each phase:

$$average\_2nd\_harm\_ratio = \frac{1}{3} \cdot \left(\frac{I_{diff\_harm\_2nd\_A}}{I_{diff\_fund\_A}} + \frac{I_{diff\_harm\_2nd\_B}}{I_{diff\_fund\_B}} + \frac{I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_C}} \right)$$

This logic provides a good security due to the increase of the average ratio provided by the phases with a high second harmonic content. However it does not provide a good dependability as for an internal fault the average ratio can still be high due to the high ratio of the healthy phase/s.

Sharing: this logic calculates the 2^{nd} harmonic ratio of each phase with the following formula:

$$PhaseA\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_A}} \right)$$

$$PhaseB\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_B}} \right)$$

$$PhaseC\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_C}} \right)$$

This logic provides a good security during energization because the ratio for a phase with a low second harmonic content will be increased by the harmonic content of the other phases. On the other hand the logic will normally provide a good dependability as during internal faults the faulted phases will have a high fundamental current that will make the 2^{nd} harmonic ratio low. When using this option the harmonic blocking percentage set has to be increased with regard to normal values to take into account the extra harmonic content of the other phases. A value of 12% should be replaced by a value of 18% value [10].

Other variation for the sharing logic proposed in this paper that provides a higher dependability calculates a common ratio for the three-phases:

$$3phase\_2nd\_harm\_ratio = \left(\frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{I_{diff\_fund\_A} + I_{diff\_fund\_B} + I_{diff\_fund\_C}} \right)$$

This will make the healthy phases trip during a close onto an internal fault giving a wrong faulted phase indication. However this wrong indication also happens due to the application of the zero-sequence filter so an external phase selector should be used [4].

3.1.2.3.2 Crossed logics for harmonic restraint

An average of the second harmonic content of the three phases can be calculated:

$$I_{diff\_harm\_2nd\_average} = \frac{I_{diff\_harm\_2nd\_A} + I_{diff\_harm\_2nd\_B} + I_{diff\_harm\_2nd\_C}}{3}$$

This average value can be used to obtain the fundamental differential current to be added to the theoretical differential current obtained from the restrained differential characteristic.

3.1.2.3.3 Time for the application of the crossed logics

As the low content of the harmonic current only last for 4-5 cycles (see point 2.2.1.5) the cross-blocking will only be necessary during this time.

3.1.2.4 Dynamic harmonic blocking / restraint

Harmonic blocking / restraint tend to operate not only when the power transformer saturates (for an inrush or an overexcitation condition) but also for faults with CT saturation due to the harmonic content of the waveform during such conditions. When the fault with CT saturation is external the operation of the harmonic blocking / restraint units will increase the security. However, if the fault is internal the activation of these units will reduce the dependability.

DC CT saturation (with an asymmetrical current) is characterized by odd and even harmonics, while AC CT saturation (with a symmetrical current) is characterized by odd harmonics. Reference [9] recommends the use of second and fourth harmonic restraint and fifth harmonic blocking. The aim is not to add the odd harmonics restraint to increase the dependability during internal faults with CT saturation. A normal setting for the percentage of fifth harmonic blocking is 35% which is larger than the 15%-20% used for second harmonic blocking / restraint. This makes the fifth harmonic blocking less susceptible to operate during DC CT saturation than the second harmonic blocking / restraint.

Harmonic blocking / restraint also operates during any type of internal fault because of the discontinuities generated in the DFT for the transient state prefault-fault. Until the DFT window does not cover completely the fault current it does not measure the correct harmonics. This can delay the operation of the differential relay up to one cycle even if the CT has not saturated.

An unrestrained differential unit set above the maximum inrush current is normally used to increase the dependability. However, internal faults with CT saturation could happen for current values lower than the ones for the inrush currents.

An algorithm that inhibits the harmonic blocking / restraint is therefore necessary.

References [11], [12] and [13] describe an external fault detector based on three units that discriminate between external and internal faults. The blocking of the differential unit is performed based on a “two out of three” logic: if two of the three units indicate an external fault condition the blocking signal is activated.

3.1.2.4.1 Differential unit with instantaneous values

This unit is based on the ratio between the differential and restraint currents. It operates when this ratio is below a threshold. When the fault is external, during the time the CT is not saturated, the ratio will be very small. Figure 31 shows, for an external fault, and for the phase A, the currents for windings 1 and 2, the differential and restraint currents. This external fault makes CT in winding 1 saturate. As it can be observed, since the activation of a fault detector (signal FDET, based on a current change), there will be a consecutive number of samples for which the ratio idif/irest is very low. If this happens, the external fault condition will be activated.

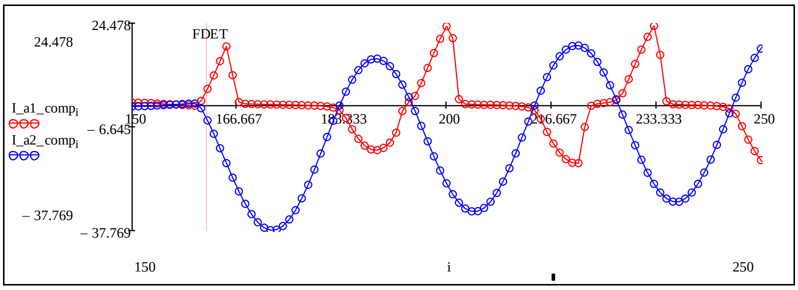

Figure 31.a. Winding currents for an external fault with CT-1 saturated

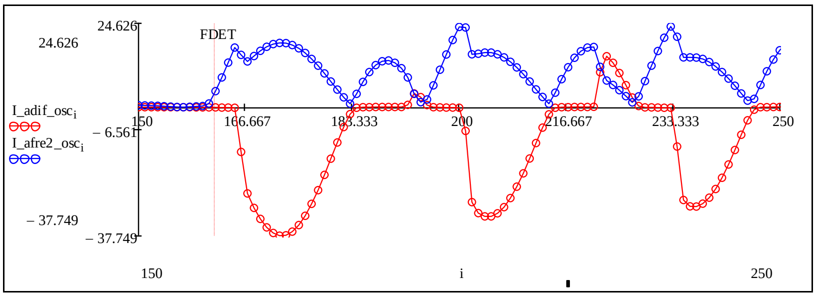

Figure 31.b. Differential and restrained currents for an external fault with CT-1 saturated

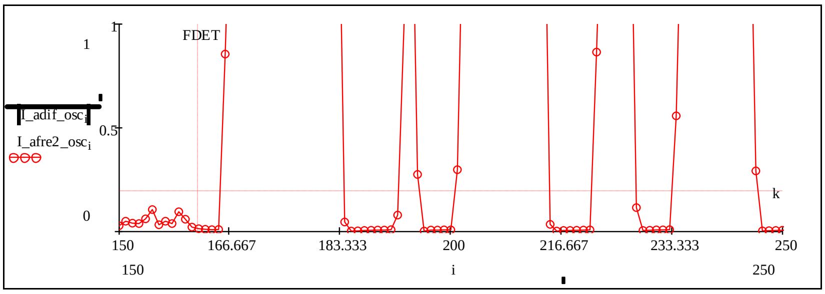

Figure 31.c. Ratio between differential and restrained currents for an external fault with CT-1 saturated

If the fault involves more than one phase and all the faulted phases saturate, a false zero-sequence current may be created continuously. This may happen as the non-saturation periods of the three phase CTs do not happen at the same time. If the zero-sequence filter is enabled, a false instantaneous differential current will be present even during the non-saturation periods which will make the ratio idif / ires increase, deactivating the external fault condition. Therefore once the external fault condition is activated it has to be latched until the external fault is cleared. A fault detector can be used for this purpose. More details can be found in [4] and [11].

3.1.2.4.2 Directional comparison units

Reference [12] describes a directional comparison unit that uses the angle between the currents measured at each end of the protected element (a transformer, in this case) in order to determine if the fault is internal or external. When this angle is lower than 90º the fault is considered internal; on the contrary, if the angle is higher than 90º the fault is considered external. The angular comparison requires that the currents are above a minimum threshold. Two directional comparison units are described, one that operates with phase currents and another one that operates with positive-sequence pure fault current. The removal of the prefault current allows this unit compensate the load flow effect. The prefault current is taken two cycles before the activation a fault detector, based on current changes. The fault detector supervises the operation of the two directional comparison units. More details can be found in [12].

3.1.2.4.3 Second and fourth harmonic restraint / blocking inhibit logic

Once the transformer has been energized a combination of the three mentioned units, differential unit with instantaneous values, phase directional comparison unit and positive-sequence directional comparison unit, will be used to inhibit the second and fourth harmonic restraint / blocking.

The inhibit logic for the second / fourth harmonic restraint / blocking will be enabled after a settable time since the detection of the energization of the transformer. When all the currents in the transformer are below a threshold and any of them changes above this threshold the energization is detected and a timer is started. Until this timer expires the second / fourth harmonic restraint / blocking is always enabled. When the timer expires the following logic will be applied:

If a fault detector activates (based on restraint current change, differential current change, sequence currents changes and sequence current levels), during a window time of three cycles the second / fourth harmonic restraint / blocking can have the chance of being disabled. This will only happen if the external fault detector, based on the three described units, indicates an internal fault condition. For this, a “two out of three” logic will also be applied: two of the units must indicate an internal fault condition without any of the units activating the external fault condition. After the three cycles, the application of the even harmonic restraint / blocking will be latched during a settable time, no matter if the fault detector activates again.

The three cycle window allows accelerating the trip during an internal fault. If the fault is external any of the units will activate the external fault condition. In this case the application of the second / fourth harmonic restraint / blocking is latched at this moment, without waiting for the three cycles. The units comprising the external fault detector operate very fast indicating the internal fault condition in less than a cycle.

It is worth noting that once the fault detector has activated, the harmonic restraint / blocking will not be inhibited again until a new fault detector activation occurs out of the latching period. The activation of an external fault condition during the latching period will extend this period.

When a transformer is already energized the only inrush condition can occur during an external fault clearing or during the energization of a parallel transformer (sympathetic inrush). Let´s see how the inhibit logic for the second / fourth harmonic restraint / blocking works in these situations.

External fault clearing

When there is an external fault, during the three cycle window, the internal fault conditions will not be fulfilled, so during this time the second and fourth harmonic restraint / blocking will be applied. On the other hand the application of the even harmonic restraint / blocking is latched during a settable time from the external fault detection. This latching assures that during the inrush condition generated by the clearing of the external fault the harmonic restraint / blocking will be enabled.

Sympathetic inrush

When a parallel transformer is energized there will be a change in the current in the already energized transformer that makes the fault detector activate. During these conditions and before the loaded transformer gets saturated any of the units comprising the external fault detector will activate the external fault condition. In this case the harmonic restraint / blocking will be latched during the settable time. This time does not need to be longer than the duration of the sympathetic inrush but it just need to assure that the harmonic restraint / blocking is latched until the start of the sympathetic inrush. The inrush of the loaded transformer will assure the activation of the fault detector. Only if the fault detector drops-out and activates again the harmonic restraint / blocking can be disabled. If the fault detector drops-out it means that the differential current will be very low. If an external fault occurs at this moment any of the units that form the external fault detector will activate, latching again the harmonic restraint / blocking.

If the current change due to the inrush of the parallel transformer is not enough to activate the fault detector, when the inrush in the loaded transformer starts, the current change in one of the windings (in the one not energizing the transformer) will also be very small. preventing the activation of the two directional comparison units: the phase one because it requires a current higher than the maximum transformer load; the positive sequence one because it uses pure fault current and if there is a small current change the minimum threshold will not be exceeded [12]. During this sympathetic inrush the two out of three logic for the internal fault condition will not be fulfilled.

The logic described to inhibit the even harmonic restraint / blocking will not operate during evolving external-internal faults as the harmonic restraint / blocking will be latched during the internal fault. It does not either operate during an internal close onto fault. In this two mentioned cases the measurement of the three phase voltages could be used to accelerate the tripping. During an inrush condition the voltage does not fall as much as during a fault. Voltage sags lower than 80% do not normally happen. An undervoltage unit working on a per-phase basis could be used. This unit will only operate when a voltage change is detected. If this voltage change is negative the undervoltage unit will not have any delay inhibiting the even harmonic restraint / blocking instantaneously. If the voltage change is positive, the undervoltage unit will have a time-delay of one cycle. This time delay will give the voltage enough time to go to its rated value when clearing an external fault.

3.1.2.4.4 Third and fifth harmonic restraint / blocking inhibit logic

The inhibit logic for odd harmonic restraint / blocking will be based on an “underexcitation” unit that measures the ratio V/f and compares it against a rated ratio Vrated/frated. When V/f<Vrated/frated the underexcitation unit operates. There will be three underexcitation units, one per phase. If any of them activates the odd harmonic restraint / blocking will be inhibited. The underexcitation units will change its status only when there is a voltage change. If the voltage change is negative they will not have any delay but if the voltage change is positive a one cycle delay will be applied.

3.1.3 Simulations and real cases experienced

3.1.3.1 Transformer energizations

Some cases are included to evaluate the operation of the differential protection during energizations both faulted or unfaulted. During this evaluation the inhibit logic for the harmonic restraint / blocking will not operate.

3.1.3.1.1 Energization with low second harmonic (real case)

A false trip of a transformer differential protection was caused by energization of a YND 115 kV / 30 kV transformer.

Figure 32.a shows the inrush secondary currents. Figure 32.b shows the second harmonic ratio per-phase. In this application harmonic blocking without crossed logics was used and a 20% harmonic ratio was set. As it can be seen, phase B ratio is below this value during two and a half cycles (energization time registered). This was enough for the phase B differential unit trip. In this case a cross-blocking based on a “two out of three” logic will correctly block phase B, as phases A and C have a high second harmonic content. Figure 32.c shows the sharing second harmonic ratio, on a per-phase basis and on a three-phase basis. As it can be seen the three ratios are far above the 20% required for blocking so the sharing logic will provide enough security.

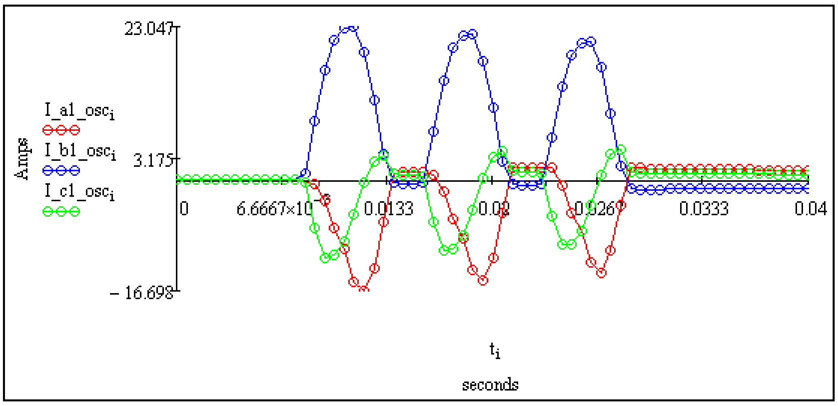

Figure 32.a. Inrush currents during the energization from the primary side of a YNynd transformer

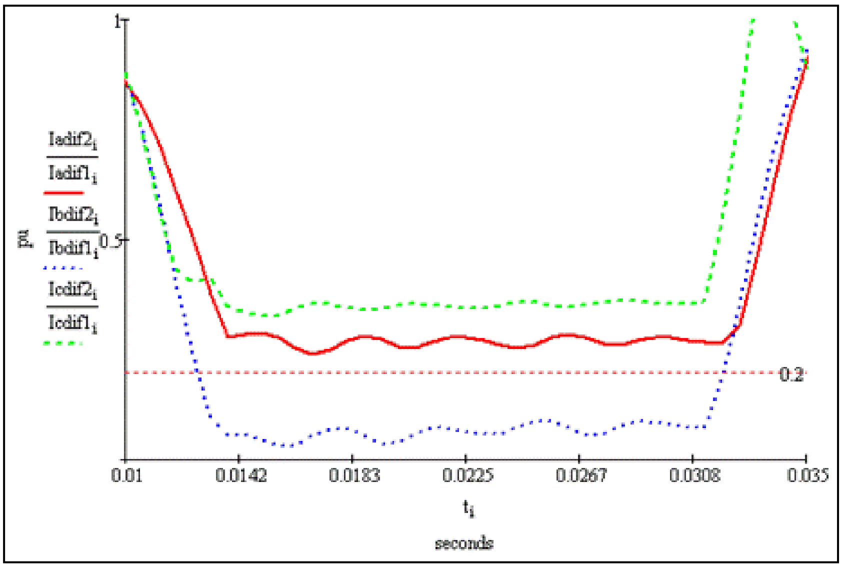

Figure 32.b. Per phase second harmonic ratios during the from the primary side of a YNynd transformer

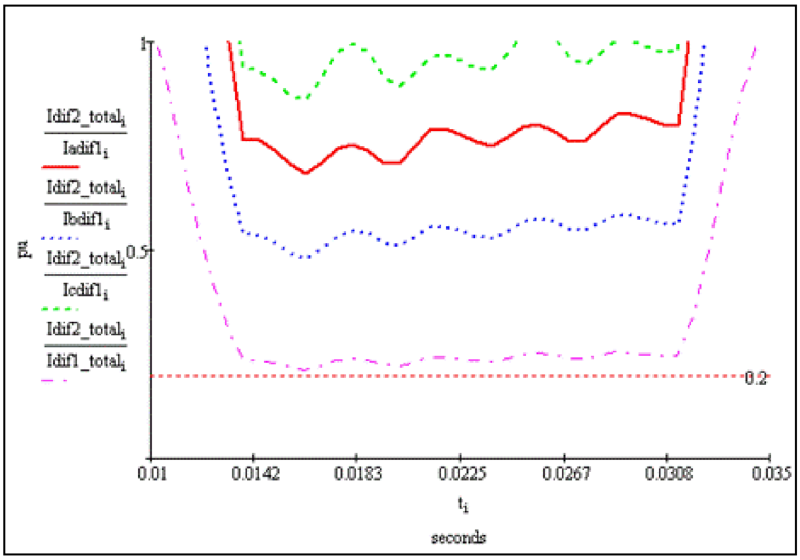

Figure 32.c. Per phase and three-phase sharing second harmonic ratios during the from the primary side of a YNynd transformer

3.1.3.1.2 A close onto a single-phase to ground fault (simulated case)

A YNynd 400 kV / 220 kV / 33 kV transformer was simulated with an RTDS. Figure 33.a shows the currents for a close onto an internal AG fault in the simulated transformer. As it can be seen, there is a fault current in the healthy phases, apart from the inrush current, due to the coupling with the delta winding. Figure 33.b shows the per-phase second harmonic ratios. As it can be observed the three of them are below the 20% threshold so the “two out of three” logic in the cross-blocking will not be fulfilled. Figure 33.c shows the per-phase and three-phase sharing second harmonic ratio. As it can be checked all the values are below the 20% threshold allowing the differential unit trip.

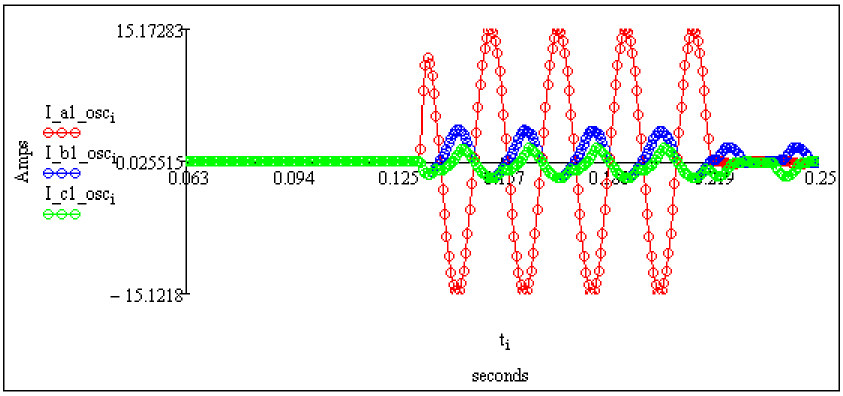

Figure 33.a. Currents in winding 1 for a close onto an AG fault in a YNynd transformer

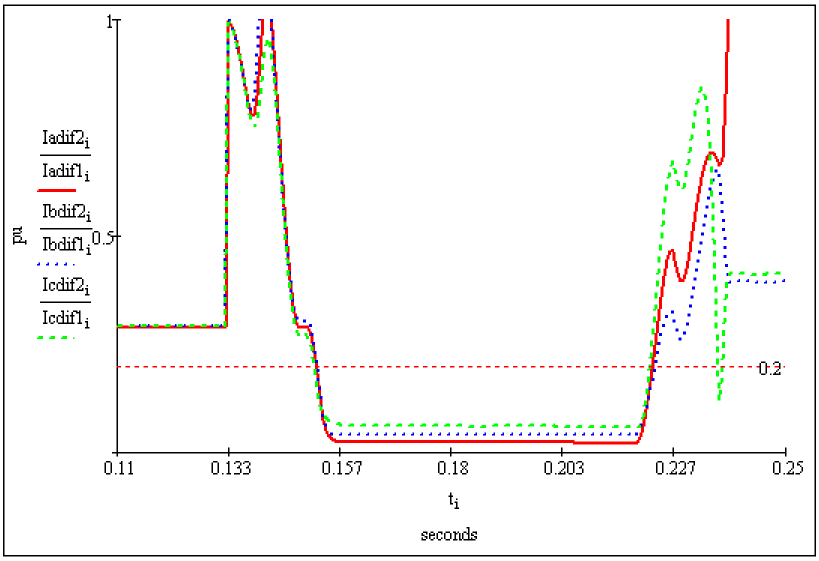

Figure 33.b. Per phase second harmonic ratio

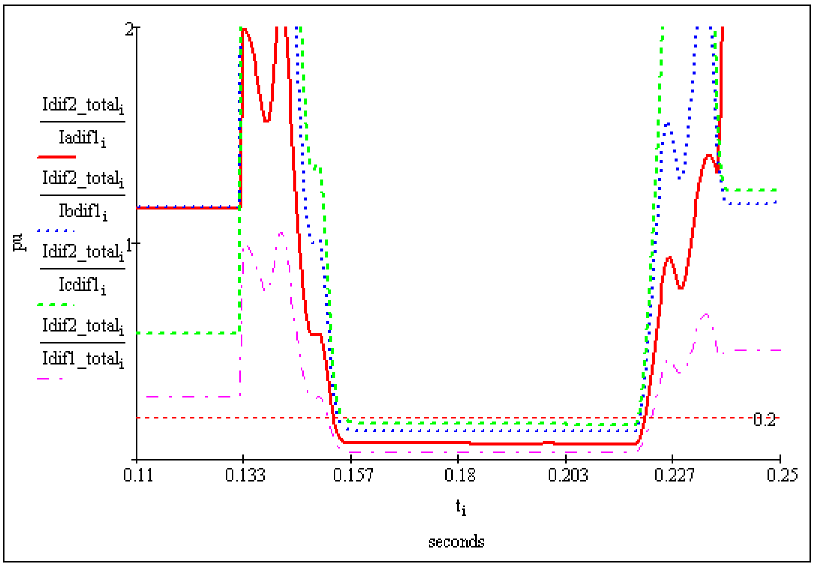

Figure 33.c. Per phase and three-phase sharing second harmonic ratio

3.1.3.1.3 A close onto a BC fault (real case)

A 220 kV / 132 kV autotransformer with a 30 kV tertiary is energized from the 220 kV side with a BC fault in the tertiary. The differential tripped in 1.5 seconds. Figure 34.a shows the recorded currents in the primary winding. Figure 34.b and 34.c show the harmonic ratios. In figure 35.b it can be seen that the ratio for phase A is above the 20%. In this case a “one out of three” cross-blocking logic was applied resulting in a loss of dependability. The differential unit tripped when the inrush currents where enough damped. The “two out of three” cross-blocking logic would have allowed the trip. Regarding the harmonic sharing, the three per-phase ratios are all far above the 20% resulting in all the phases being blocked. The three-phase ratio is in the limit of 20%. The last ratio is therefore more dependable. Anyway, an increase of the 20% setting should be done in order to maintain a good dependability. A 25%-30% ratio is recommended.

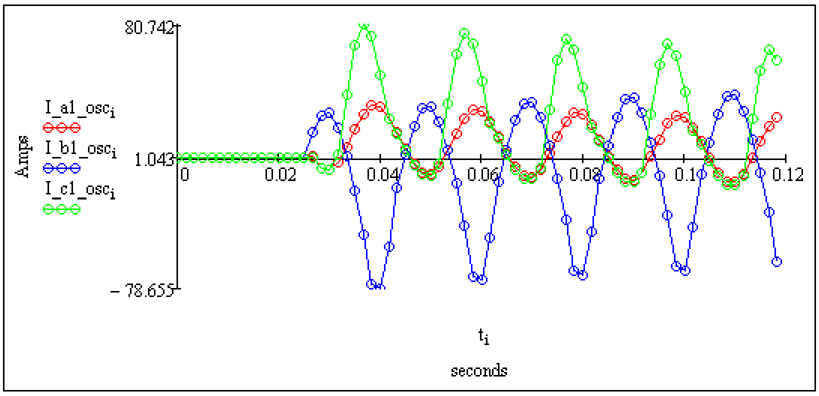

Figure 34.a. Currents in winding 1 for a close onto a BC fault in a YNynd transformer

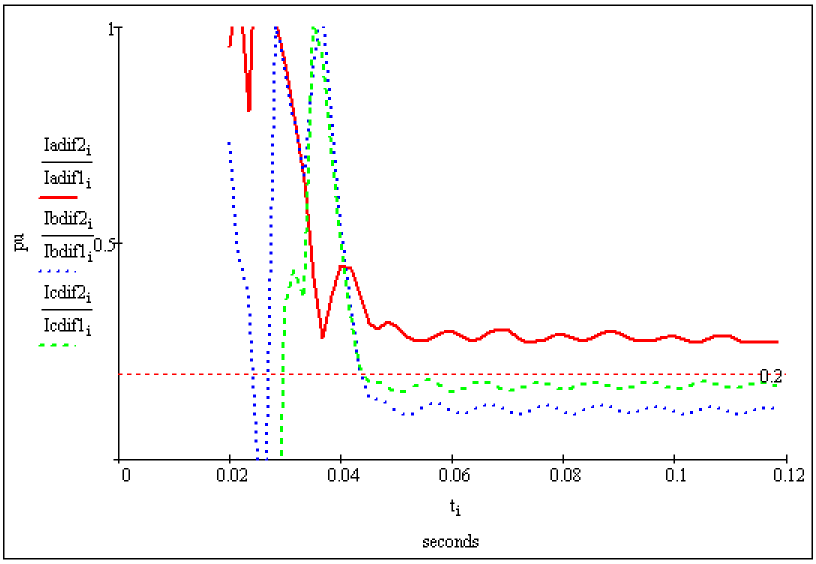

Figure 34.b. Per phase second harmonic ratio

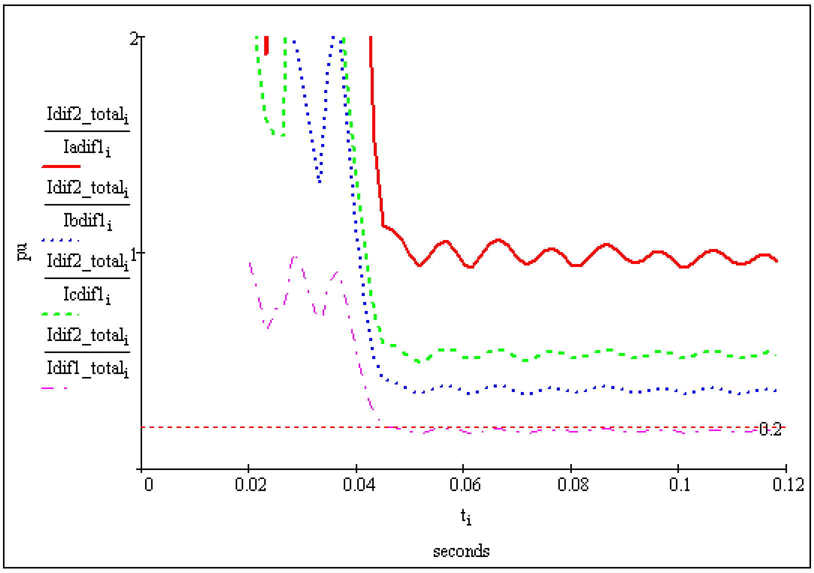

Figure 34.c. Per phase and three-phase sharing second harmonic ratio

3.1.3.2 Transformer disturbances once it has been energized

3.1.3.2.1 External and internal faults

The operation of the inhibit logic for harmonic restraint / blocking for internal and external faults totally depends on the behavior of the three units comprising the external fault detector: differential unit with instantaneous values, phase directional comparison unit and positive-sequence directional comparison unit. The combination of the three units provides a very good security and dependability for any type of fault: faults with CT saturation, outfeed faults, etc. The operation of these units for internal and external faults was already evaluated in references [11] and [12]. Figure 35.a and 35.b show two oscillos recorded during some testing of a transformer differential relay. The meaning of the digital signals is the following:

EXT_DIFI_A: External fault by phase A differential unit with instantaneous values
EXT_DIFI_B: External fault by phase B the differential unit with instantaneous values
EXT_DIFI_C: External fault by phase C the differential unit with instantaneous values
EXT_CDIR_A: External fault by phase A directional comparison unit
EXT_CDIR_B: External fault by phase B directional comparison unit
EXT_CDIR_C: External fault by phase C directional comparison unit
EXT_CDIR_PS: External fault by positive-sequence directional comparison unit
INT_CDIR_A: Internal fault by phase A directional comparison unit
INT_CDIR_B: Internal fault by phase B directional comparison unit
INT_CDIR_C: Internal fault by phase C directional comparison unit
INT_CDIR_PS: Internal fault by positive-sequence directional comparison unit

Figure 35.a shows an external AG fault. As it can be seen the external fault signals coming from the external fault detector activate very fast fulfilling the “two out of three” logic. The differential unit is therefore blocked.

Figure 35.b shows an internal fault BG with severe CT saturation in winding 2. The internal fault conditions activate in less than one cycle. This assures that the harmonic restraint / blocking will be inhibited. Note that due to the severe saturation the harmonic blocking will be activated for the whole duration of the fault so if the inhibit logic is not provided the differential unit would not trip.

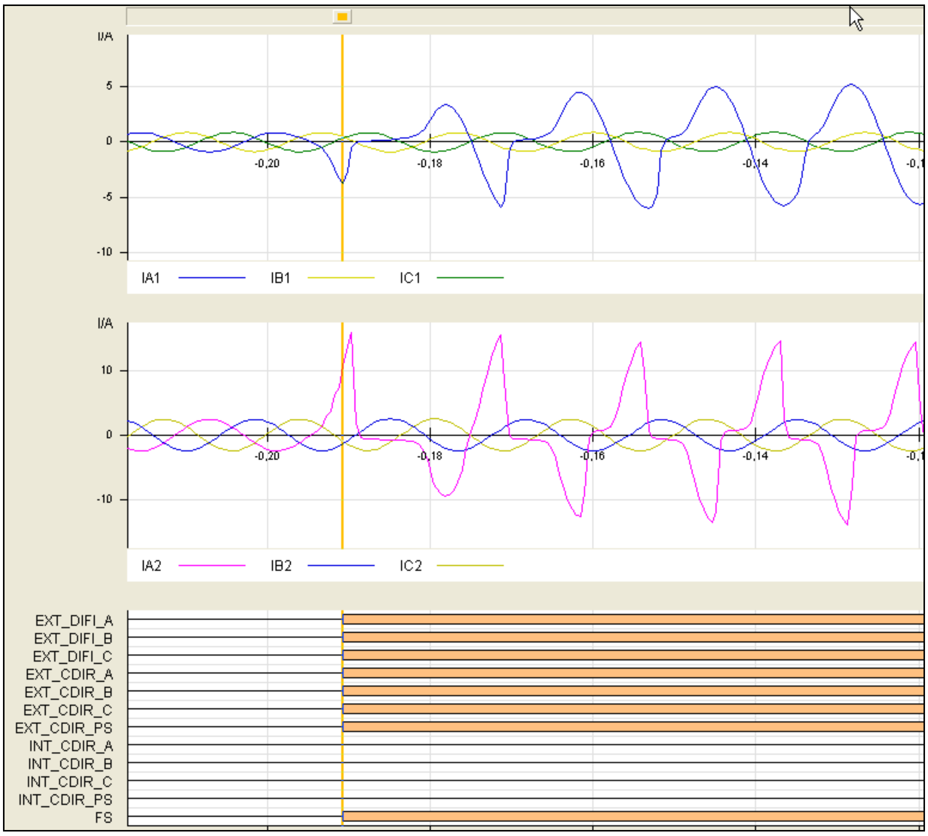

Figure 35.a. External AG fault with CT saturation

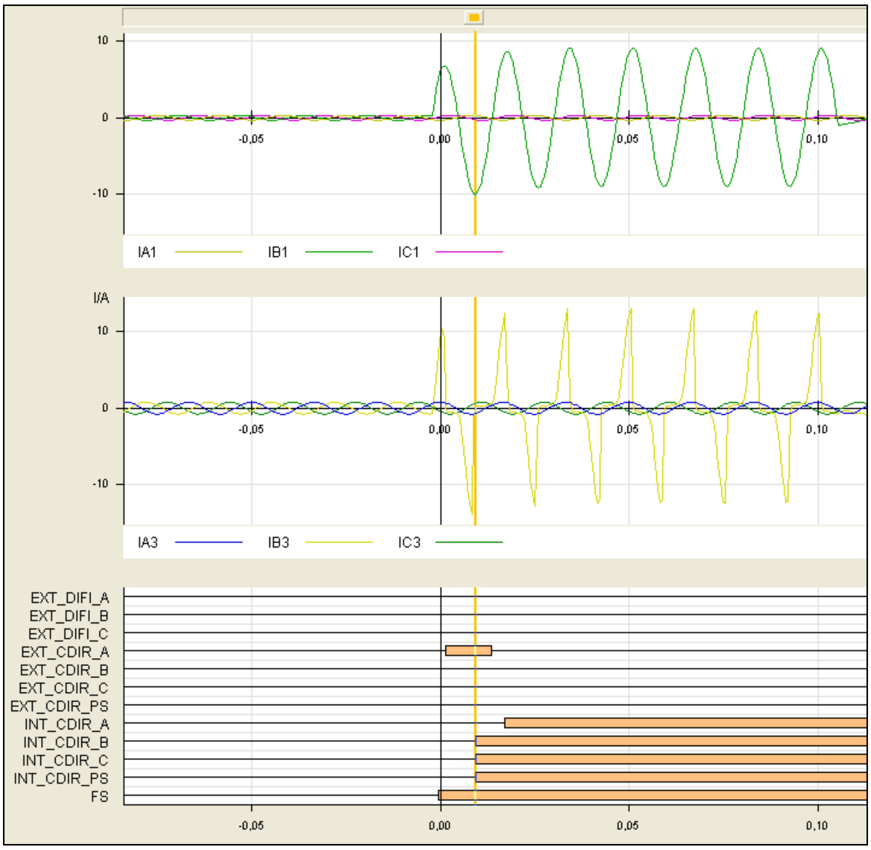

Figure 35.a. Internal BG fault with CT saturation

3.1.3.2.2 Sympathetic inrush

A model was created in the RTDS with two 400 kV – 220 kV - 33 kV YNynd transformers connected in parallel and a sympathetic inrush was generated. Figures 35.a and 35.b show the currents in the primary and secondary windings during the sympathetic inrush of the loaded transformer (the inrush currents are mixed with the load currents). The saturation of this transformer occurs at point A. As it can be seen there is a change in the winding currents and so in the restraint currents. This current change makes the fault detector activate. As the saturation of the transformer occurs six cycles after the saturation of the parallel transformer, the external fault detector has enough time to latch the application of the second / fourth harmonic blocking. It has to be noted that until the loaded transformer does not saturate, the conditions are completely for an external fault (differential current / restraint current ratio very low, angles for the phase currents and for the positive-sequence pure fault currents around 180º).

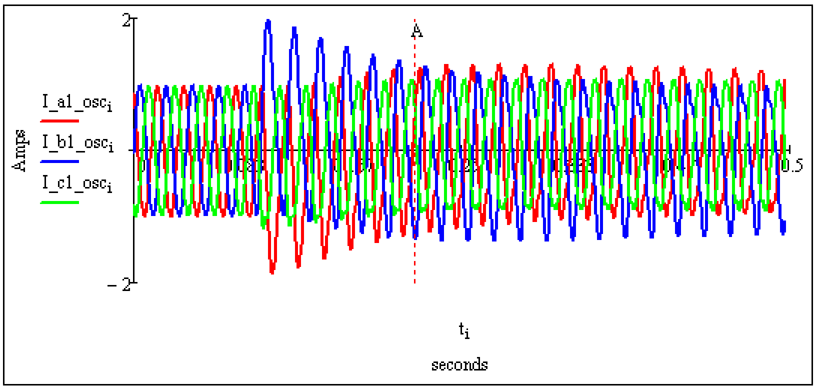

Figure 36.a. Currents in primary winding for a sympathetic inrush

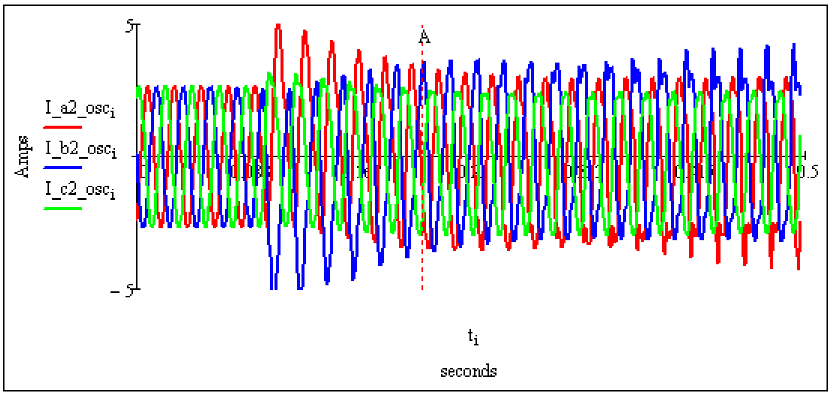

Figure 36.b. Currents in secondary winding for a sympathetic inrush

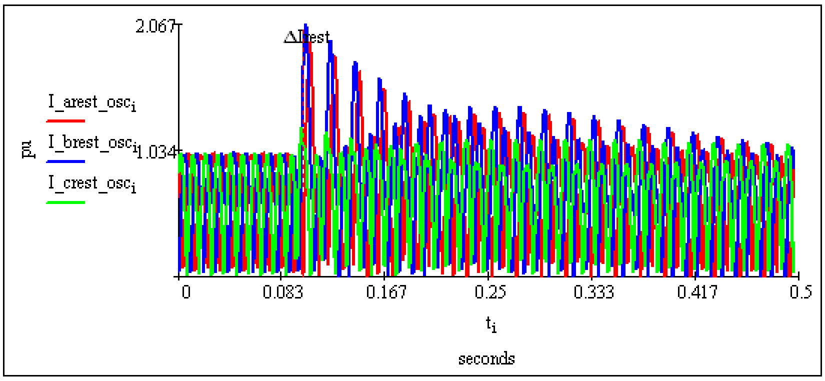

Figure 36.c. Restraint currents for a sympathetic inrush

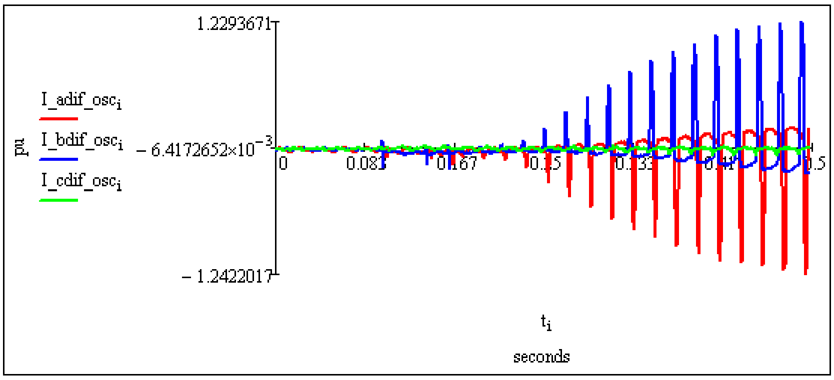

Figure 36.d. Differential currents for a sympathetic inrush

3.2 OVERCURRENT PROTECTION

Inrush currents can cause overcurrent units operate. The most affected overcurrent units are the ground ones because they are normally set more sensible. Point 2.2.1.4.3 has described the transformer configurations that allow the flowing of zero-sequence current.

Harmonic restraint / blocking will be implemented by measuring the harmonic content of the measured current. Inrush conditions occurring with load current will lead to lower second harmonic ratios. When using overcurrent units with harmonic restraint / blocking an unrestrained level should be used to increase the dependability. This unit has to be set above the maximum expected inrush current. Crossed-blocking logics are also convenient.

Point 2.2.1.5 has mentioned the low harmonic content of the sum current during a sympathetic inrush. If an overcurrent unit is going to operate with this current it will be very prone to trip. The third or fifth harmonic blocking could improve the security [2].

When overcurrent units are applied in a teleprotection scheme, for a through inrush current, the teleprotection scheme should not operate because both ends of the line would see the fault in opposite directions. In this case harmonic blocking would not be necessary. However care has to be taken with CT saturation if a DCB scheme or a POTT with weak infeed logic are used. Figures 36.a and 36.b show the currents measured at both ends of a line for the inrush of a downstream transformer (a real event). As it can be seen the second peak of the phase C in the end 2 is much lower than the one in the end 1 due to a CT saturation. This effect made the weak infeed logic in phase C trip, as in the end 2 the reverse unit did not pick-up. The solution given was based on the application of the second harmonic restraint only to the weak infeed logic with the aim of maintaining a good level of dependability.

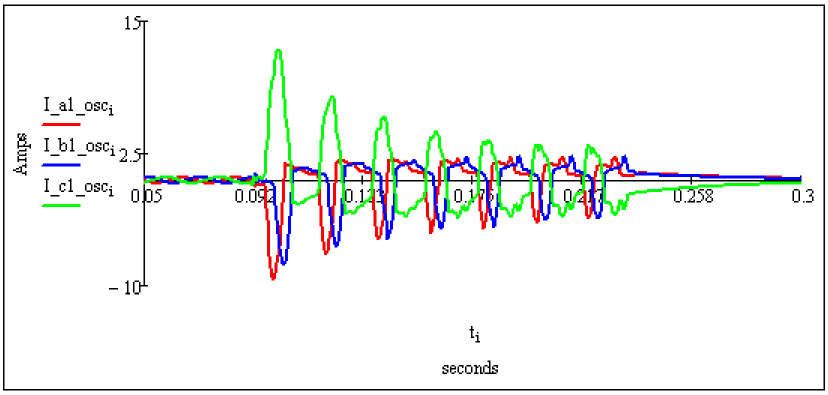

Figure 37.a. Currents measured in end 1 of the line during a downstream transformer inrush

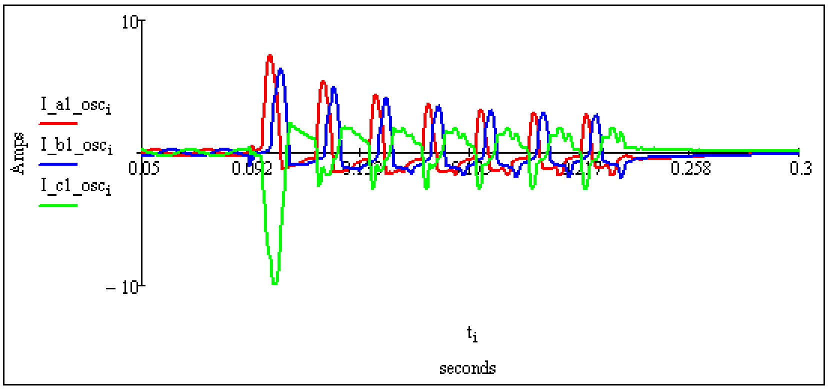

Figure 37.b. Currents measured in end 2 of the line during a downstream transformer inrush

3.3 DISTANCE PROTECTION

In normal distance protection applications there is a low probability that the distance function is affected by an inrush condition. However in some applications the distance protection is used as a transformer back-up protection, with one instantaneous zone (zone 1) looking towards the transformer [11]. In other applications the distance protection is used to protect the line plus the transformer, when there is no breaker in the primary side of the machine. Other applications include distance protection applied to lines with tapped transformers. In these cases there is a risk of false tripping during the inrush condition. The common solution is the use of second harmonic restraint / blocking, which can be inhibited if the voltage falls below a certain threshold (75%-80% can be used) or if the current is above a level (set above the maximum inrush current expected).

3.4 BUSBAR / LINE DIFFERENTIAL

CT saturation during the inrush of a downstream transformer can affect the security of any differential protection, including the busbar or the line ones. If the we sum the currents of figures 37.a and 37.b we will get a false differential current. The problem is that in this case the restrained differential characteristic will not restrain properly because of the low value of the restraint current. In this condition the use of an external fault detector as the one mentioned in point 3.1.2.4 will be very adequate to increase the security of the differential unit.

4 CONCLUSIONS

Inrush current phenomena has been explained in detail for three different conditions: energization, external fault recovery and sympathetic inrush. The influence of the connection group of the transformer has also been described.

The low second harmonic content of modern transformers requires the use of harmonic restraint / blocking crossed logics. The selection of this logic has to be analyzed in detail as it will compromise the security and dependability. For transformers with a delta winding (either real or phantom) energized from the wye winding/s the two out of three logic provides good balance between security and dependability. For other type of transformer connection group or in a wye-delta transformer if the energization is done from the delta side the harmonic sharing logic is considered the best one. In order to increase the dependability a three-phase sharing second harmonic ratio is recommended. It is important to increase a little bit the usual harmonic percentage set in order to maintain the dependability.Values of 25%-30% are recommended.

The logic that inhibits the harmonic restraint / blocking allows accelerating the trip for an internal fault that occurs once the transformer is energized. It is based on an external fault detector consisting of three units: differential unit with instantaneous values, based on the ratio between the differential and restraint instantaneous currents; the phase directional comparison unit, which compares the angles between the phase currents; and the positive-sequence directional unit which compares the angle between positive-sequence pure fault currents.

CT saturation during inrush can affect any type of differential relay and also overcurrent units working with a DCB or POTT with a weak infeed logic. The use of an external fault detector as the one described in this paper will increase the security of the differential units.

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6 BIOGRAPHY

Roberto Cimadevilla graduated in Electrical Engineering from the Superior Engineering College of Gijón, Spain in 2001. He later obtained a master´s degree in “Analysis, simulation and management of electrical power systems” from the University of País Vasco, Spain. He previously worked for Red Eléctrica de España (REE – Spanish TSO) as a Protection Relay Engineer. Roberto joined ZIV in 2003 as an Application Engineer, being responsible in this area for the development of a new distance relay, a new transformer differential relay, a phasor measurement unit and a line differential relay. Since 2011 Roberto is working as the Manager of the Application Engineering Department. He has written several technical papers, most of them presented at international conferences. Roberto has also participated in some CIGRE B5 working groups. He is currently a regular member of B5.48 working group.