Power Transformer Characteristics and Their Effect on Protective Relays

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Abstract

There are a variety of protective relays using different measuring techniques to provide reliable and secure transformer protection. This includes electro-mechanical, solid state and numerical relays. Within each group, various algorithms exist. Advancements made to transformer technology and design over the past 3 decades, have changed the characteristics of the transformer inrush current, and have often introduced incorrect operations in the existing harmonic restraint relays during energization. Topics to be presented include:

- Comparison between old and newly developed more accurate calculations of peak values, magnitude of the second harmonic, and other parameters of Inrush current
- Design and system parameters which influence the magnitude and wave-shape of inrush current, e.g. winding design and connections, core material, core joint geometry, short-circuit capacity of network, etc.
- Impact of transformer design & performance parameters and new developments in the Transformer technology on magnitudes and nature of inrush current
- Current transformer influence on the speed, selectivity, and dependability of transformer protection

This paper will address these topics as well as provide solutions for selecting and setting transformer protection. It is to be noted that the parts of the paper provided by the ABB Power Transformers (Dr. Girgis and Mr. teNyenhuis) are sections 1 - 3.

1. Introduction

Inrush Current is a form of over-current that occurs during energization of a transformer and is a large transient current which is caused by part cycle saturation of the magnetic core of the transformer. For power transformers, the magnitude of the inrush current is initially 2 to 5 times the rated load current but slowly decreases by the effect of oscillation damping due to winding and magnetizing resistances of the transformer as well as the impedance of the system it is connected to until it finally reaches the normal exciting current value. This process typically takes several minutes. As a result, inrush current could be mistaken for a short circuit current and the transformer is erroneously taken out of service by the over current or the differential relays. The transformer design and station installation parameters affect the magnitude of the inrush current significantly. Therefore, it is important to have an accurate calculated value of the magnitude and other parameters of inrush current in order for relaying to properly differentiate between inrush and short circuit incidents. Proper calculation of the minimum % of 2nd harmonic of inrush current is a very important parameter for this differentiation. Also, in recent years, there have been transformer design improvements that in fact have lead to a significant impact on magnitudes, wave shapes, and 2nd harmonic of inrush current.

2. Calculation of Inrush Current

The simplified equation often used to calculate the peak value of the first cycle of inrush current in Amps is as follows:

$$I_{pk} = \frac{\sqrt{2}U}{\sqrt{(\omega \cdot L)^2 + R^2}}\left(\frac{2 \cdot B_N + B_R - B_S}{B_N}\right) \qquad \text{[Amps]} \qquad \text{Equation [1]}$$

Where:

U = Applied voltage, Volts
L = Air core inductance of the transformer, Henry
R = Total DC resistance of the transformer windings, Ohms
B_R = Remnant flux density of the transformer core, Tesla
B_S = Saturation flux density of the core material, Tesla
B_N = Normal rated flux density of the transformer core, Tesla

In reality, the above equation does not give sufficient accuracy since a number of transformer and system parameters, which affect the magnitude of inrush current significantly, are not included in the calculation. As well, this equation does not provide information on the subsequent oscillations throughout the duration of the inrush current transient. An improved inrush calculation has been developed by ABB which provides the magnitude of inrush current versus time t; hence the entire wave-shape of the inrush current can be determined. The calculation also incorporates the following important transformer and system parameters which can have as much as 60% impact on the magnitudes of inrush current:

- The inductance of the air-core circuit adjusted for the transient nature of the inrush current phenomenon.
- Impedance and short circuit capacity of the system.
- Core geometry and winding configurations & connections, e.g., 1- vs. 3-phase, Y- vs. Delta windings connections, Grounded vs. non grounded Y connections, etc.

Below in Figure 1 is shown the first 5 cycles of the inrush current wave-shape for a large power transformer calculated using the ABB method of calculation.

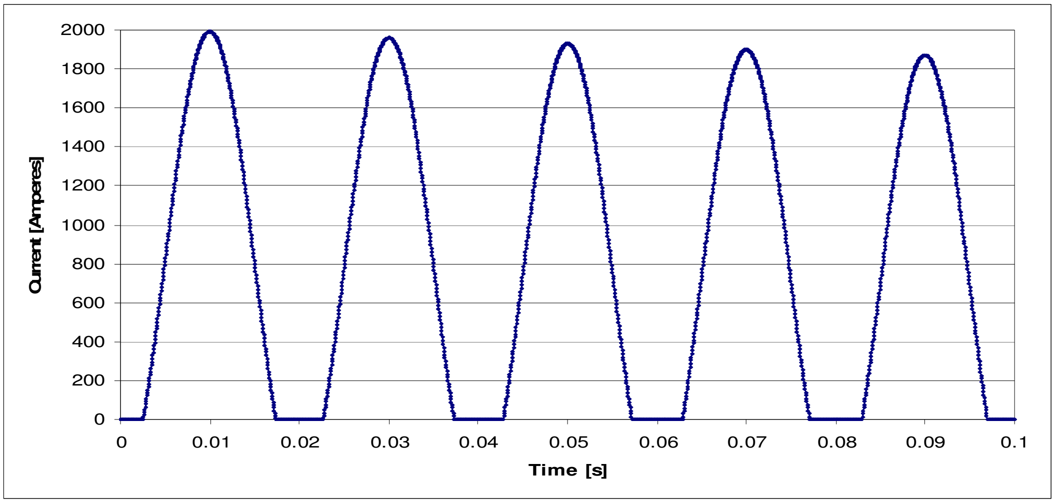

Figure 1 – Calculated Inrush Current Wave-shape for a 50 Hz Large Power transformer

A comparison between magnitude of the first cycle of inrush current as calculated by the old formula in equation [1] above versus that calculated using the rigorous ABB calculation, including the above mentioned parameters, provides much lower magnitudes of the first peak of inrush current compared to that calculated using the old formula commonly used by the industry.

3. Effect of Transformer Design Parameters on 2nd harmonic of Inrush Current

3.1 Effect of Design flux Density

The minimum % 2nd harmonic / peak inrush current ratio decreases with induction as shown in Figure 2 below. Modern transformers generally operate at higher flux density values since higher grain oriented steels are used more and more. It thus results that modern transformers will have lower minimum % 2nd harmonic / peak inrush current ratio.

3.2 Effect of Core material

Another new feature of modern transformers is the use of Hi-B electrical steel type materials which have higher saturation flux densities, a larger linear portion of the magnetization curve, and a lower remanence flux density values compared to Regular Grain Oriented (RGO) type materials. Thus, these higher grain orientation materials are associated with higher minimum % 2nd harmonic / peak inrush current ratios. For the same flux density, the Hi-B and Domain refined materials have an appreciably greater minimum % 2nd harmonic / peak inrush current ratio than RGO material.

3.3 Effect of Core Joint type

Until a decade or two ago, the non step-lap type joint was commonly used in transformer cores, however modern transformers use the step-lap type joint. Because of the high reluctance of the core joints, the remanence flux density levels of a transformer core is significantly lower than that of the core material itself. As the non-step lap joint has a greater reluctance than a step-lap joint, it follows that a core with the step-lap joint would have a much lower minimum % of 2nd harmonic / peak current ratio than those of a core with a non step-lap joint.

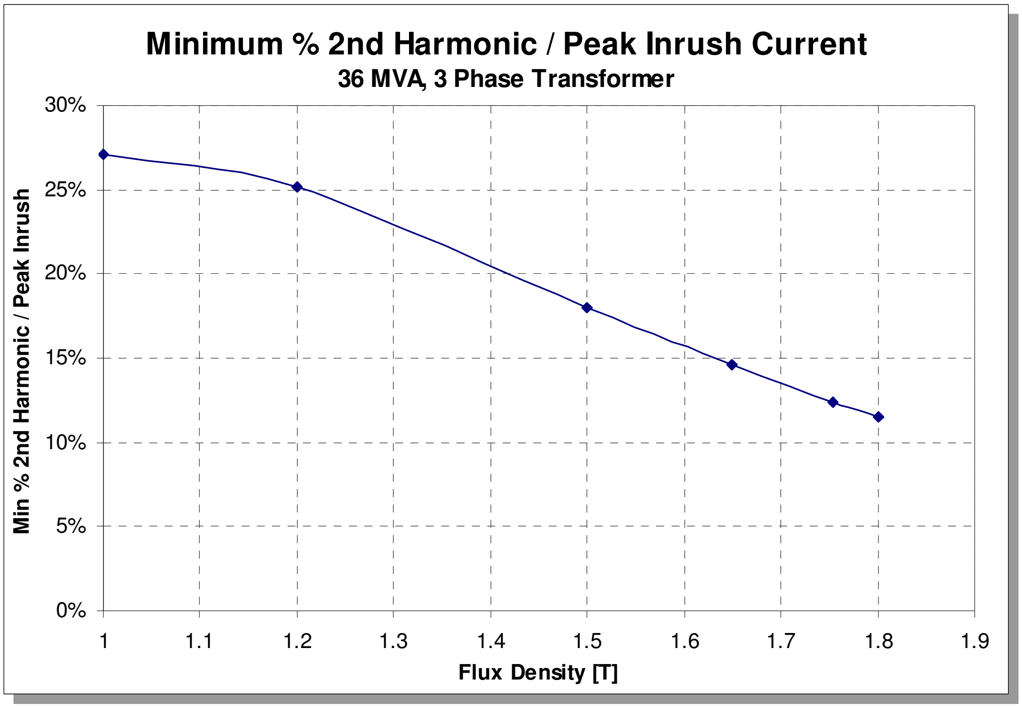

Figure 2 - % Minimum 2nd Harmonic / Peak Inrush Current Ratio versus Rated Flux Density

4. Effects on Relaying

4.1 Transformer differential protection

Any abrupt increase of the power transformer terminal voltage will result in a transient current that is greater than the rated current of the transformer. This transient current is generally termed inrush current and is typically caused by:

- Energization of the power transformer
- Voltage recovery after the clearing of a heavy short circuit in the power system (recovery inrush)
- Energization of another parallel connected power transformer (sympathetic inrush)
- Out-of–phase synchronization of a connected generator

4.1.1 Inrush detection by harmonic analysis of instantaneous differential current

Referring to Figure 2 above, it can be seen that the minimum 2nd harmonic content is in the range of 20 % - 25 % at low flux densities. Transformer protection relays that use the second harmonic as the restraint criteria have setting values for this 15 % - 20% range. This was correct for transformer designs operating at low flux densities. The second harmonic content for present day transformer designs are significantly lower, in the range of 5 - 10 %, as indicated in Figure 2 and Section 3 above. This will affect the performance of relays that use the second harmonic settings set to the range of 15-20%. Under a worst condition, the 15-20 % 2nd harmonic restraint relays may not restrain correctly during the energization of power transformer that have a higher rated flux density (1.5 - 1.75 T). For transformers which have the higher rated flux density, it is recommended that the lower (5-12%) 2nd harmonic restraint relay setting be used.

4.1.2 Inrush detection by waveform analysis of instantaneous differential current

It can be observed from Figure 1 of the inrush current waveform that there is a period of time in each power system cycle during which very low magnetizing currents flow. From this, an inrush condition can be identified where a low rate of change of the instantaneous differential current exists for at least a quarter of the fundamental power system cycle. This criterion can be mathematically expressed for Phase A as:

$$\left|\frac{\partial I_{diff\_a}}{\partial t}\right| \le C_1 \qquad \text{Equation [2]}$$

Where, I_{diff_a} is instantaneous differential current in Phase A, t is a time and C_1 is a constant fixed in the relay algorithm.

Practice has shown that although using the second harmonic restrain/blocking approach may prevent false tripping during inrush conditions, it may sometimes increase fault clearance time for heavy internal faults followed by CT saturation. On the positive side, the second harmonic restrain/blocking approach will increase the security of the differential relay for a heavy external fault with CT saturation.

4.1.3 Inrush detection by adaptive techniques

The combination of the 2nd harmonic / fundamental inrush current ratios (“I2/I1”) and waveform analysis methods, allows the relay designer to take advantage of both methods, while at the same time avoid their drawbacks. Two possible ways to combine these methods are:

Conditional (recommended) - In this mode of operation these two criteria are used as follows:

- Employ both the “I2/I1” and the waveform criteria to detect initial inrush condition
- Disable the “I2/I1” criterion one minute after power transformer energizing in order to avoid long clearance times for heavy internal faults and let the waveform criterion alone take care of the sympathetic and recovery inrush
- Temporarily enable “I2/I1” for 6 seconds when a heavy external fault has been detected to gain additional security for external faults

Always (traditional approach) - This option is similar to the usual “I2/I1” criterion. The “I2/I1” is active at all times, and in addition, the waveform criterion works in parallel. This has no benefits in terms of speed for heavy internal faults.

4.1.4 Internal faults followed by the CT saturation

For heavy internal transformer faults followed by CT saturation, the distorted CT secondary current may contain the high level of the second harmonic. As a consequence, delayed operation of the restrained differential protection will occur as indicated in Figure 3 below.

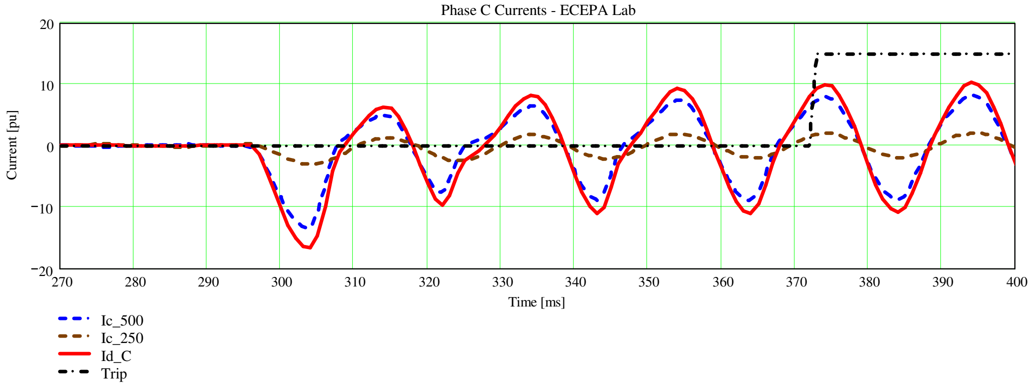

Figure 3 – Late 87T trip due to 2^{nd} harmonic blocking

For an external fault, the fictitious negative sequence source will be located outside the differential protection zone at the fault point. Thus, the negative sequence currents will enter the healthy power transformer on the fault side, and exit on the opposite side, properly transformed. The negative sequence currents on the respective power transformer sides will have opposite directions. In other words, the internal/external fault discriminator sees these currents as having a relative phase displacement of exactly 180 electrical degrees, as shown in Figure 4.

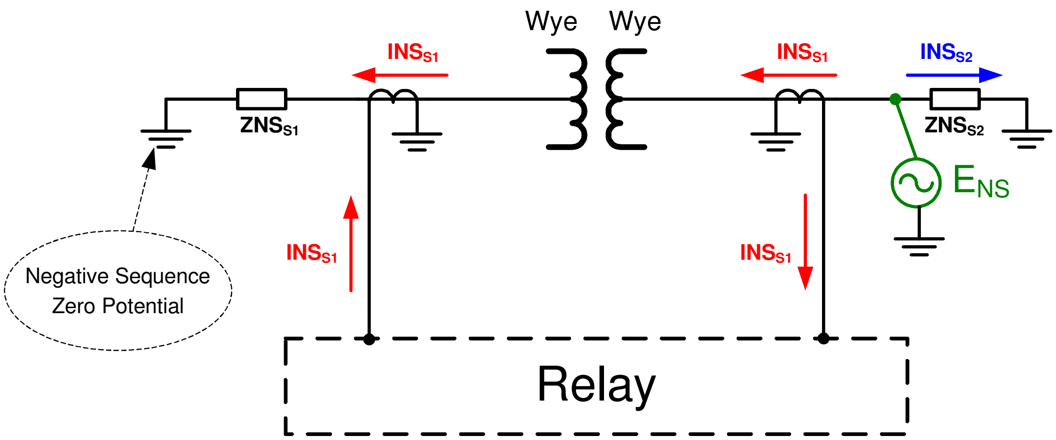

Figure 4 - Flow of Negative Sequence Currents for power transformer external fault

For an internal fault (with the fictitious negative sequence source within protected power transformer), the negative sequence currents will flow out of the faulty power transformer on both sides. The negative sequence currents on the respective power transformer sides will have the same direction. In other words, the internal/external fault discriminator sees these currents as having a relative phase displacement of zero electrical degrees, as shown in Figure 5. In reality, for an internal fault, there might be some small phase shift between these two currents due to possible different negative sequence impedance angles of the source equivalent circuits on the two power transformer sides.

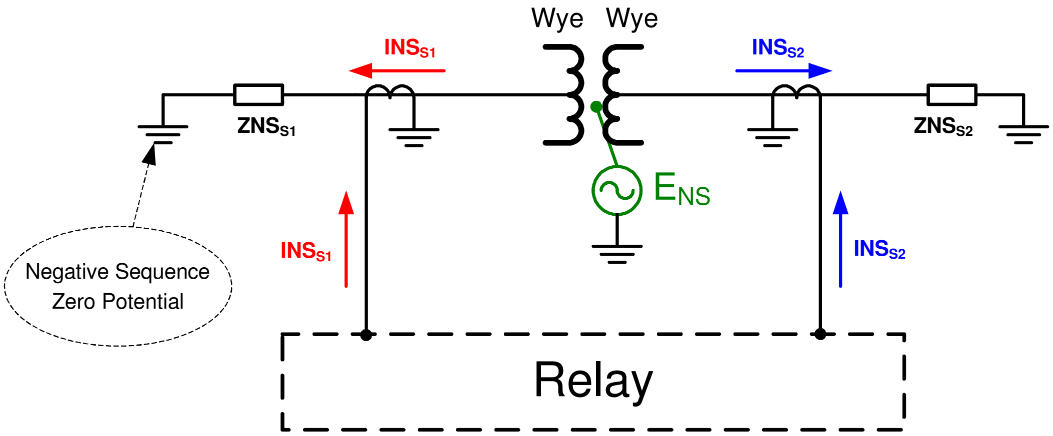

Figure 5 - Flow of Negative Sequence Currents for power transformer internal fault

Its operation is based on the relative position of the two phasors representing HV and LV negative-sequence current contributions. It practically performs directional comparison between these two phasors. First, the LV side phasor is positioned along the zero degree line. Next, the relevant position of the HV side phasor in the complex plain is determined. The overall directional characteristic of the internal/external fault discriminator is shown in Figure 6.

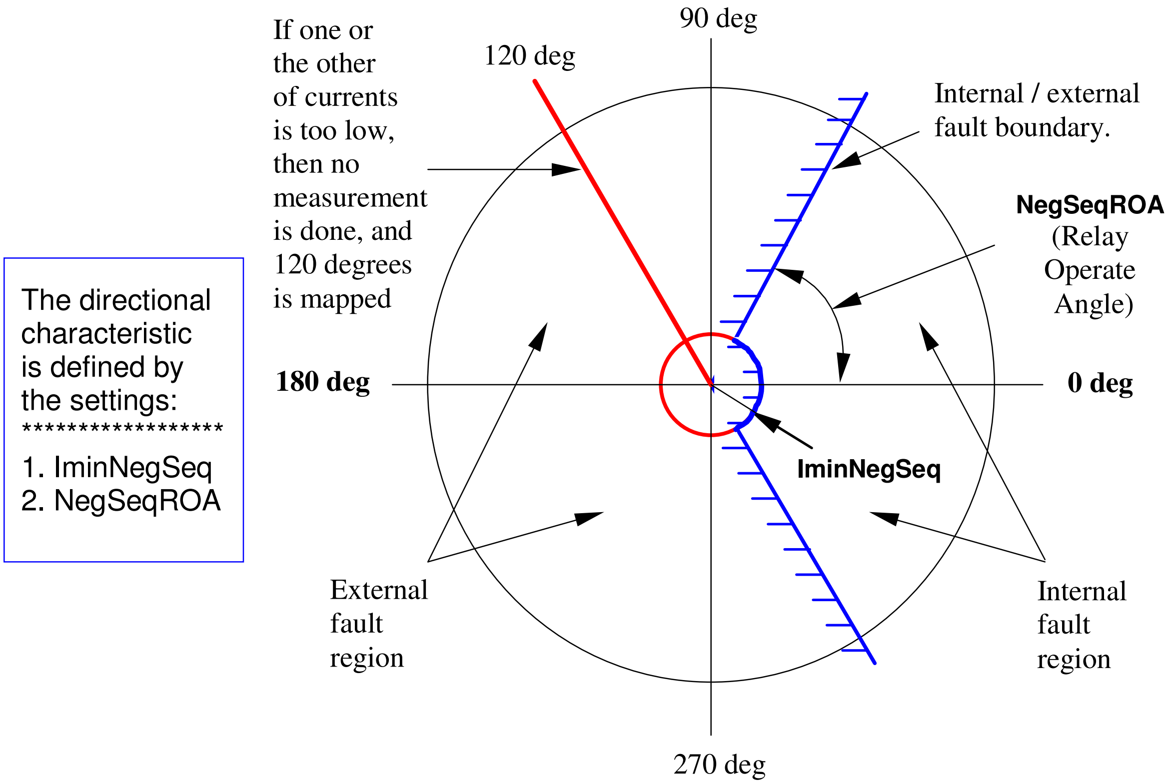

Figure 6 - Operating characteristic of the internal/external fault discriminator

Using the negative sequence internal/external fault discriminator, the second harmonic blocking feature can be bypassed and faster operation of transformer diff protection will be achieved as shown in the Figure 7.

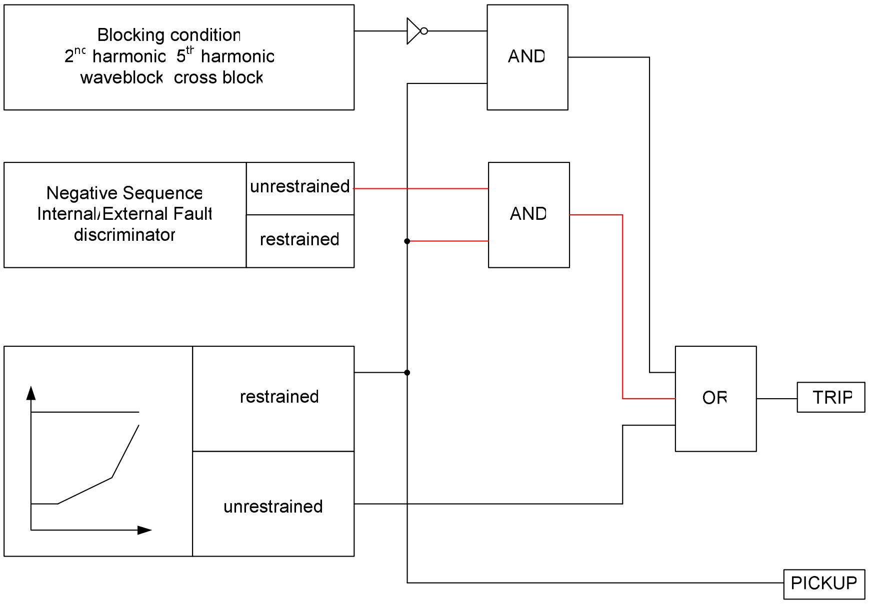

Figure 7 – Negative sequence fault discriminator

4.2 Restricted earth fault protection

Break-down of the insulation between a phase conductor and ground in an effectively grounded or low impedance grounded power system results in a large fault current. A breakdown of the insulation between a transformer winding and the core or the tank may result in a large fault current which in turn causes severe damage to the windings and the transformer core. A high gas pressure may develop, rupturing the transformer tank.

Fast and sensitive detection of ground faults in a power transformer winding can be obtained in solidly grounded or low impedance grounded networks by the restricted earth fault protection. The only requirement is that the power transformer winding is connected to ground in the neutral point (in case of Wye-connected windings) or via separate grounding transformer (in case of delta-connected windings).

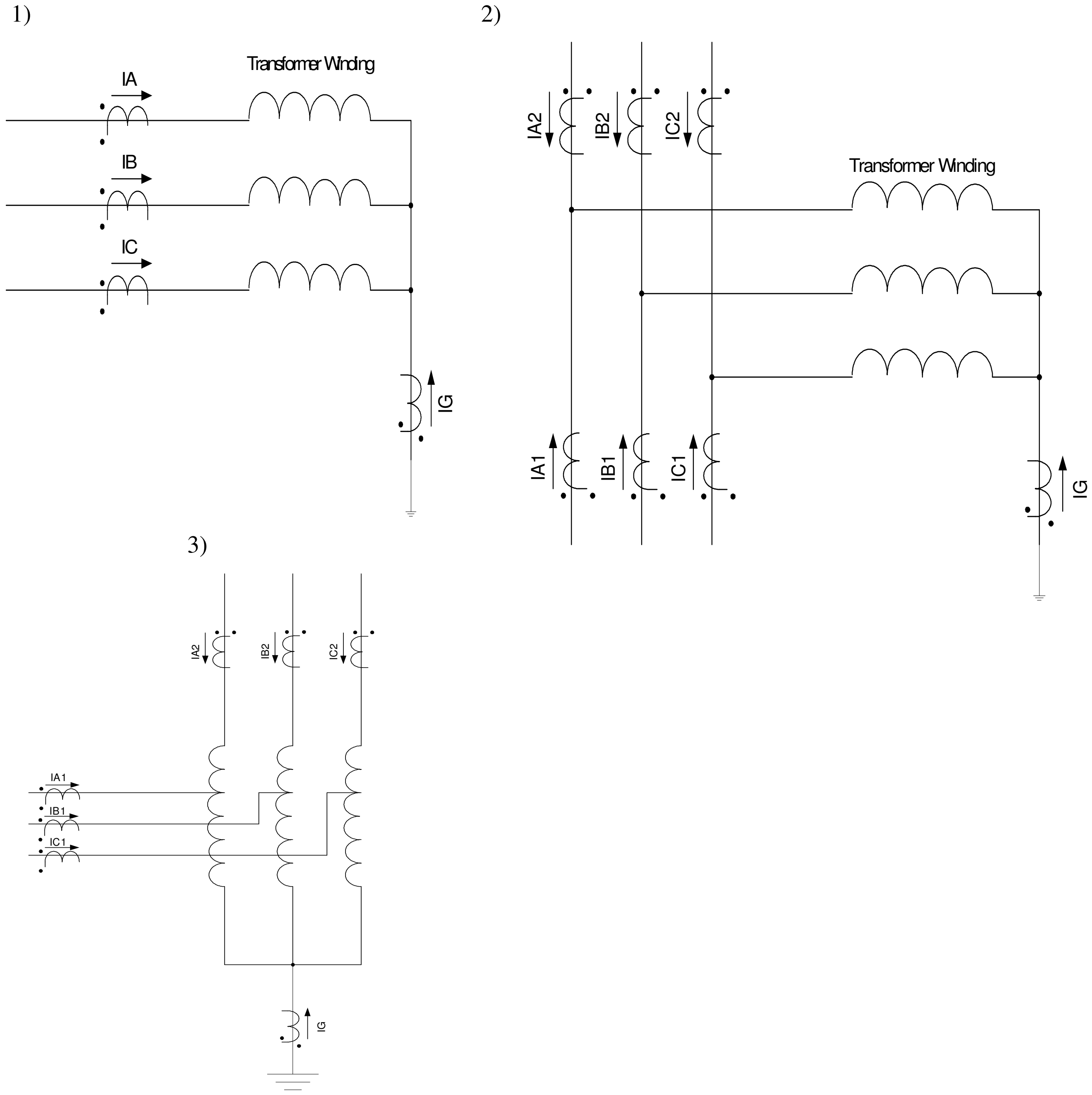

Figure 8 – Some applications of Restricted Earth Fault

The REF protection is a differential type with balancing of the neutral current (from the neutral-side CT) with the residual current (3 times the zero-sequence current from the phase CT's). Because the protection is based on the zero sequence currents, which theoretically only exist in case of a ground fault, the REF can be made very sensitive, regardless of load currents. It is the fastest protection that power transformer windings can have. It should be noted that the high sensitivity and high speed tend to make such a protection instable. Thus special measures must be taken to make it secure and block operation in the case of heavy through phase-phase or external faults.

With reference to Figure 8, REF zones of protection could be applied to wye-connected windings of power transformers in the following applications:

1. single breaker
2. multiple breaker such as double or breaker-and-a-half
3. autotransformer

It is not only external ground faults that REF should be stable against, but also heavy phase-to-phase faults, not including ground. These faults may also give rise to false zero sequence currents due to saturated line CT's. Such faults, however, produce no neutral current, and can thus be eliminated as a source of danger, at least during the fault.

As an additional measure against unwanted operation, a directional check is made between the neutral current (reference) and the calculated residual current at the transformer bushings. Such directional checks insure REF stability during power transformer inrush as well.

4.3 Ground Over-current Protection

Power transformers can have a large inrush current when being energized. This inrush current can have residual current components. The phenomenon is due to saturation of the transformer magnetic core during parts of the cycle. There is a risk that the inrush current will cause a residual current that reaches a level above the pick-up current of the residual overcurrent protection. The inrush current in the neutral point has a large second harmonic content. This can be used to avoid unwanted operation of the ground fault protection. Therefore the ground fault protection has a possibility of second harmonic restrain if the level of this harmonic current reaches a value above a set percentage of the fundamental current. New transformer core materials have a much lower impact on the second harmonic current magnitude in the neutral point current then for individual phase currents.

5. Conclusions

The old formula for calculation of peak inrush current of power transformers provides magnitudes as much as twice that calculated using the more accurate equation recently developed by ABB. This calculation accounts for a number of important transformer and system parameters that significantly impact the magnitudes and wave form of the inrush current. Accurately predicting the peak inrush current should be very critical in designing and determining the settings of the over current relaying used with a power transformer. Also, the new calculation provides the function of inrush current versus time throughout the duration of the transient as well as the magnitude of the 2nd harmonic of the inrush current. This is the parameter commonly used today to differentiate between short circuit and inrush current occurrences, hence preventing a power transformer of being erroneously removed from service by the over current or the differential relays.

Inrush current parameters (Peak, 2nd harmonic, and duration) of today's power transformers differ from those of older designs due to the use of higher grain oriented core steels, the step-lap core joint type, and higher rated design core induction values. This should have a significant impact on selecting the proper relaying protection of the transformer.

6. Reference:

[1] Elmore W A, 1995, "Protective Relaying Theory and Applications", ABB Power T&D

[2] RET670 Technical reference manual, 1MRK 504 048-UEN

[3] Electrical Transmission and Distribution reference Book, Westinghouse Electric Cooperation

[4] F.Mekic, Z. Gajic, S. Ganesan "Adaptive Features on Numerical Differential Relays", (29th Annual Western Protective relay Conference, Spokane, WA, October 22-24, 2002)

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[6] Z. Gajic, B. Hillstrom, I. Brncic, F.Mekic, I. Ivankovic "Sensitive Turn-to-Turn Fault Protection ", (32th Annual Western Protective relay Conference, Spokane, WA, October 21-23, 2005)