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Differential protection for shunt reactors and power transformers - similarities and differences

Stefan Roxenborg[1] (ABB, Sweden), Stein Ingebrigtsen (Statnett, Norway)
Stig Holst (ABB,Sweden), Zoran Gajic (ABB, Sweden)

Summary

The differential protection is the main protection for shunt reactors and power transformers. The function offers an instantaneous protection for internal phase to phase and phase to ground faults. The differential protection can be of the low impedance or high impedance type.

This paper will point out some key bullets of similarities and differences for the differential protection applied to a shunt reactor (87R) or a power transformer (87T). It also provides an extra investigation on how the differential protection is affected by switching in a shunt reactor and a power transformer.

The paper is based on the Technical Brochure CIGRE B5 WG37 “Protection, Monitoring and Control of Shunt Reactors”. Additionally the inrush simulations on shunt reactors and power transformers are based on material from the ongoing CIGRE B5 WG24 “Protection requirements on transient response of voltage and current digital acquisition chain”.

Keywords

Shunt reactor differential protection, power transformer differential protection.

1 INTRODUCTION

Shunt reactors are used for consumption of the excess reactive power generated by overhead lines under low-load conditions (due to line capacitance), and thereby stabilizes the system voltage.
Shunt reactors are mainly used in transmission networks. They are quite often switched in and out on daily basis, following the load situation in the system [5, 6].

A shunt reactor has only one winding per phase and the inductance is designed to correspond to the rated reactive power by using more or less air in the core. The design is divided in gapped core and core-less reactors. The gapped core has a subdivided limb of core steel with air gaps inside the winding and no limb at all for the core less concept. Higher energy density can be achieved in a gapped core compared to an air core. Due to the air gaps the reactors has no remanence and the iron cores cannot be significantly saturated, and the reactors therefore will have a reasonably linear behavior during energizing events.

Power transformers are, in contrast to a shunt reactors, normally always in service and are only switched in/out approximately once per year for maintenance. A power transformer has also two or three windings per phase used for interconnection of different voltage levels in the power system. The power transformer is designed with a core with hardly any air gaps, and grain oriented material, which results in remanence and high impedance (high magnetic permeability and higher energy density compared to a reactor). Power transformers have a very steep no-load magnetizing characteristic with remanence and a knee point at approximately 1.2 pu voltage, followed by an almost horizontal curve, where the saturation is high.

2 INRUSH OF A SHUNT REACTOR OR POWER TRANSFORMER

2.1 *Shunt reactor inrush*

Magnetizing inrush currents occurs when energizing a reactor. The inrush current decreases slowly due to the low resistance in the reactor, with a time constant of a second, but can persist for several seconds [1-3].

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[1] stefan.roxenborg@se.abb.com

Figure 1 show the shunt reactor characteristic between peak voltage and current. For a coreless reactor it is a straight line and no saturation will exist. For a gapped core or a shell type the characteristic can be simplified with two lines, one below saturation and the other above saturation.

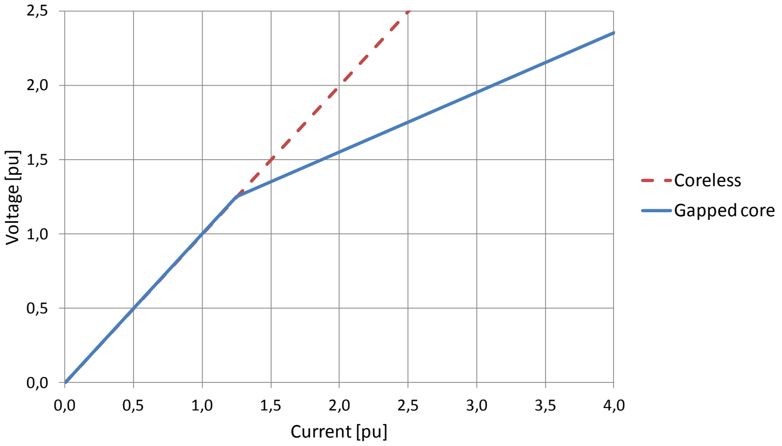

Figure 1 Shunt reactor characteristics for a gapped and air core (coreless) reactor

Based on the shunt reactor characteristics shown in Figure 1, the contents of harmonics in idealized un-damped inrush currents have been analyzed. A sinusoidal voltage has been applied to the reactor at different inception angles which results in inrush currents with different DC offset. As the damping is neglected the calculated contents of harmonics is only valid for the initial part of the inrush.

As the reactor characteristic for an air core reactor is a straight line the inrush current will be a sinusoidal current with different DC offset, see Figure 2. The inrush current consists only of the fundamental frequency and in most cases a DC offset. Except for the transient state there will not exist any harmonics. The maximum inrush peak is 2.8 times the rated current.

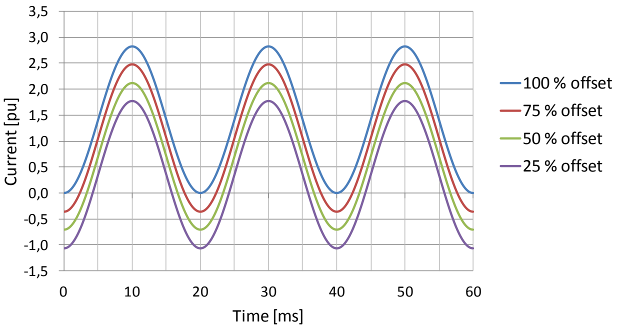

Figure 2 Idealized inrush currents for an air core reactor

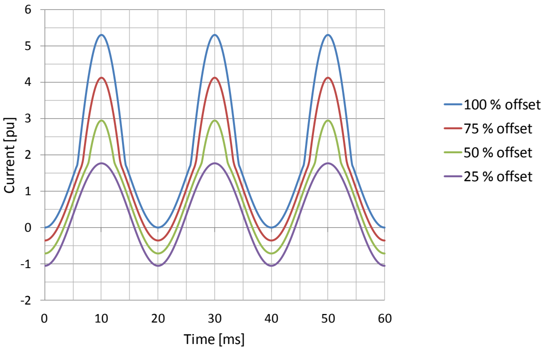

Figure 3 Idealized inrush currents for an iron core reactor

Figure 3 shows idealized inrush currents for an iron core reactor with the knee point at 125 percent of the rated voltage and the slope of the saturated part is 30 % of the unsaturated slope. The content of the harmonics in relation to the fundamental harmonic is shown in Figure 4. The second harmonic is predominant but very dependent of the degree of the DC offset. The second harmonic has been analyzed further and Figure 5 shows the relative content of the second harmonic for different offset and the peak value of the inrush.

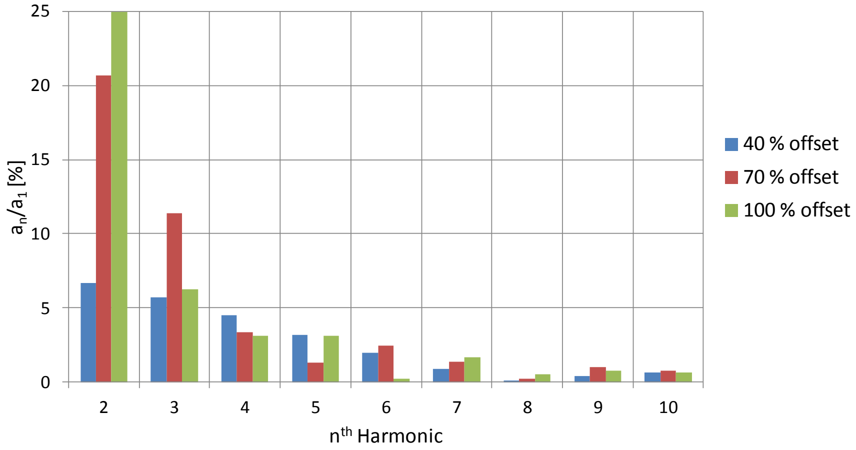

Figure 4 Example of harmonic content in an idealized inrush current for an iron core reactor

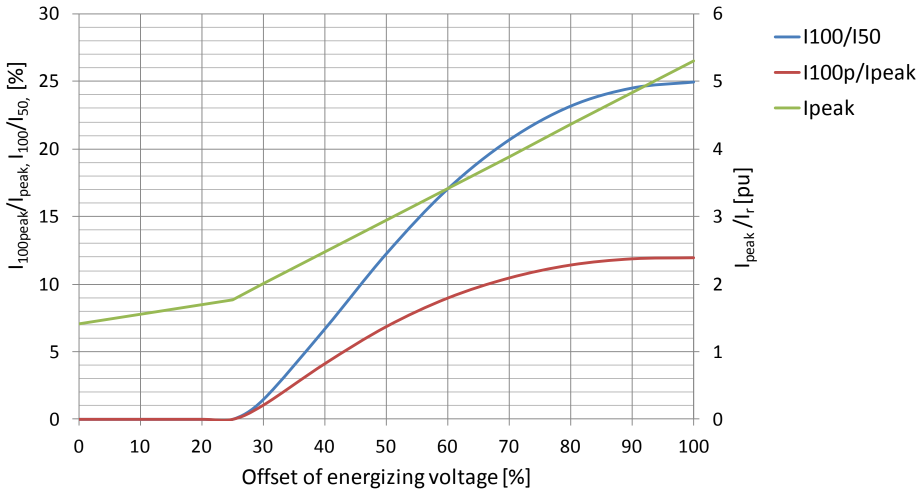

Figure 5 Example of the relative content of the second harmonic and inrush peak current for different degree of offset. The slope of the saturated part is 30 % of the unsaturated slope.

Generally inrush currents for shunt reactors and the harmonic content are smaller than for transformers. Though the level of second harmonic in many cases can be relatively high there are many cases with no or very low content of harmonics. The inrush current and the harmonics themselves will not cause any false differential current for a differential protection in contrast to the case of inrush of a transformer.

Nevertheless, the inrush condition of a shunt reactor represents a huge challenge to the low impedance differential protection. The problem is caused by the long DC-Time constant of the shunt reactor. Uneven saturation of the phase CT's can occur due to the slowly decaying DC-component of the inrush current. At the time of CT saturation, the fundamental value of the primary currents may be close to rated current of the reactor. The differential protection then operates in the sensitive part of the tripping characteristic. Even a small differential current may in this situation cause an incorrect trip by the differential protection. Some numerical differential protection offers a DC-biasing feature as a solution to this problem. With this feature, the differential protection is desensitized with increasing amount of DC-components in the measured currents.

2.2 Power transformer inrush

Magnetizing inrush currents occurs when energizing an un-loaded power transformer, due to part cycle saturation of the core. The inrush current decreases slowly, due to the resistance in the transformer and the power system source impedance, with a time constant of 100-300ms, but can persist up to a minute.

The inrush current can appear in all three phases as well as in the grounded neutral, and mostly differs in size. The magnitude of the inrush currents are in the outer winding (usually high voltage side) approximately 4-20 times, and for the inner winding approximately 2-10 times. In most cases transformers are energized from the high voltage side. The inrush currents decreases with rated power of the transformer, e.g. power transformers > 70MVA have inrush currents of 2-5 times the rated power.

Power transformers are mostly designed to operate near to the saturation level during normal operation. If the transformer is energized with no remanence and energized at maximum of the voltage wave, the corresponding flux starts at zero and the peak flux will not reach the saturation level and no inrush current will arise. However if the transformer is energized at voltage zero crossing, the peak flux will reach twice its normal maximum and cause hard saturation resulting in very large magnetization currents, further if the remanence (remanent flux) also is contributing in the same direction, the magnetizing currents will reach even higher.

The residual zero sequence current (sum of phase currents) is usually not zero during inrush on a grounded Y-side of a transformer, unless all phases are closed at the same instant of time. Phase CT:s may also be saturated by large DC components to different degree resulting in false secondary residual current.
The inrush current appears as a differential current to the transformer differential protection, due to inrush on one side and zero current on the unloaded side.
Residual, differential and neutral point - protection may mal-operate due to inrush of an energized transformer.

To study the inrush current and the harmonics in a power transformer, following no-load magnetizing characteristic with three straight lines has been used [4]. One has infinite slope and represents the unsaturated part. The other two have slopes and represent the positive and negative saturated parts.

$$i(t)=\begin{cases} I_m\left[\cos(\omega t)-\cos(\alpha)\right] & \text{for} \quad 0\le \omega t\le \alpha \\ 0 & \text{for} \quad \alpha\le \omega t\le (2\pi-\alpha) \\ I_m\left[\cos(\omega t)-\cos(\alpha)\right] & \text{for} \quad (2\pi-\alpha)\le \omega t\le 2\pi \end{cases}$$

The flux in the transformer core is above the saturation knee point for a total angular span of 2 α radians. The peak current is $I_m\left[1-\cos(\alpha)\right]$.

Figure 6 shows initially the idealized un-damped inrush current for some different α values. The content of harmonics has been analyzed and is shown in Figure 7, where the second harmonic is dominant among the harmonics.

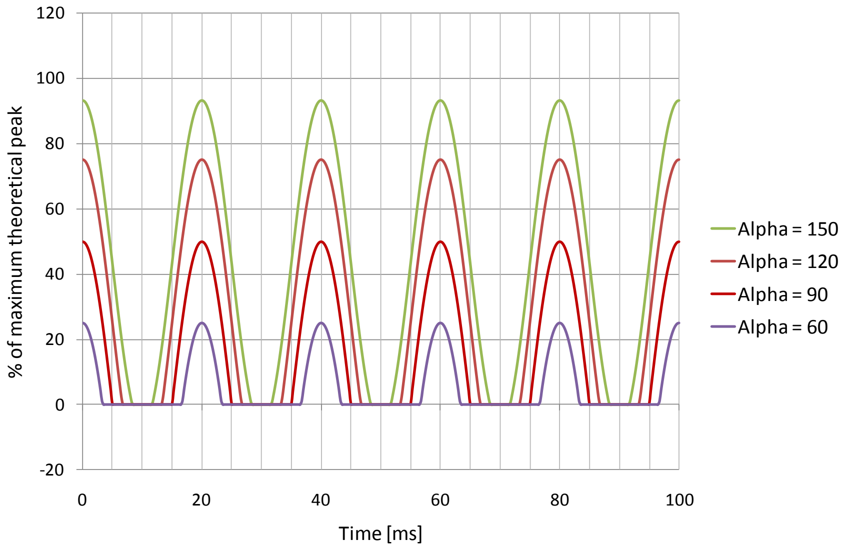

Figure 6 Idealized inrush current for different α values

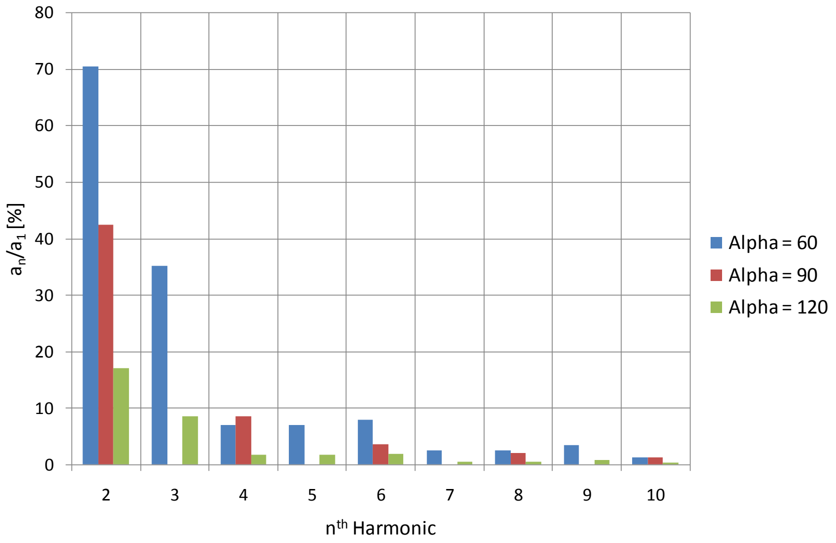

Figure 7 The content of harmonics in an idealized inrush current

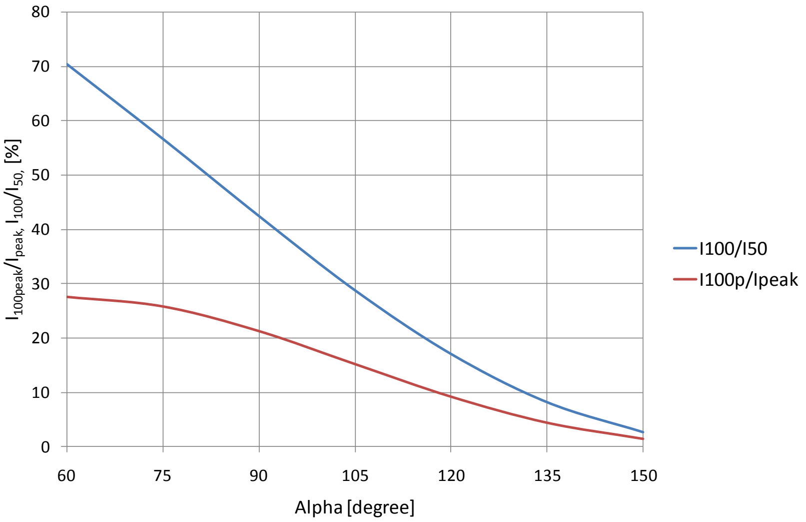

Figure 8 The relative content of the second harmonic for different α values related to fundamental and peak value of inrush current.

Further Figure 8 shows the relative content of the second harmonic for different α values. High α value correspond to high inrush currents that can be caused of high core induction or high remanence and less content of second harmonic inrush current.

We can see that often the amount of relative second harmonic current is relatively high at transformer inrush but there can also be cases with very small amount of second harmonic.

3 OVERVOLTAGE OF A SHUNT REACTOR AND A POWER TRANSFORMER

3.1 Shunt reactor overvoltage

In case of overvoltage there will be no harmonics from an air core reactor. However, for a reactor with iron core steady state harmonics arise from partial saturation in the magnetic circuit. These effects are in fact very small, and without practical importance for relaying and communication interference. Of all harmonics the third harmonic will be dominant. In the reactor neutral the third harmonics in the three phases add together and act like a zero sequence current.

If an iron core reactor is exposed to over voltage the current will be distorted and contain odd harmonics. Figure 9 shows the current for a gapped core with reactor characteristic according to Figure 1 and the knee point at 125 percent of rated voltage. Figure 10 shows the content of the harmonics related to the fundamental frequency of the current.

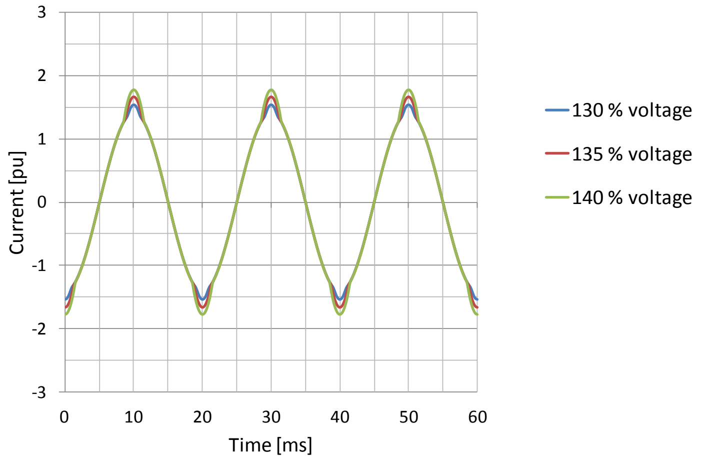

Figure 9 Shunt reactor current for operation with over voltage

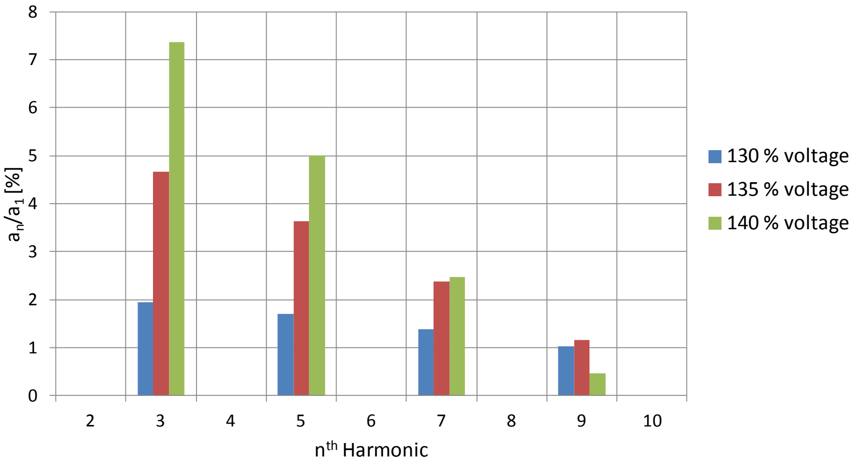

Figure 10 Harmonics in the reactor current in case of over voltage

3.2 Power transformer overvoltage

Due to overvoltage on one side of the power transformer, strong saturation occurs in the magnetic core (over excitation), resulting in high currents in the effected side, further resulting in a differential current. The differential protection must not operate on an over voltage.

A study of different over voltages on a Y-side power transformer with low zero sequence impedance and harmonics are shown in Figure 11 and Figure 12 where rated voltage is 90% of knee-point. As can be seen in the Figure 11 and Figure 12 below large 3rd,5th,7th,9th current harmonics, no even harmonics will appear, due to the balanced over voltage.

For power transformers excited on a side with high zero sequence impedance, both 3rd and 9th harmonic disappear (zero) in the phase current.

The differential protection can use the 5th harmonic as blocking of the protection for over excitation.

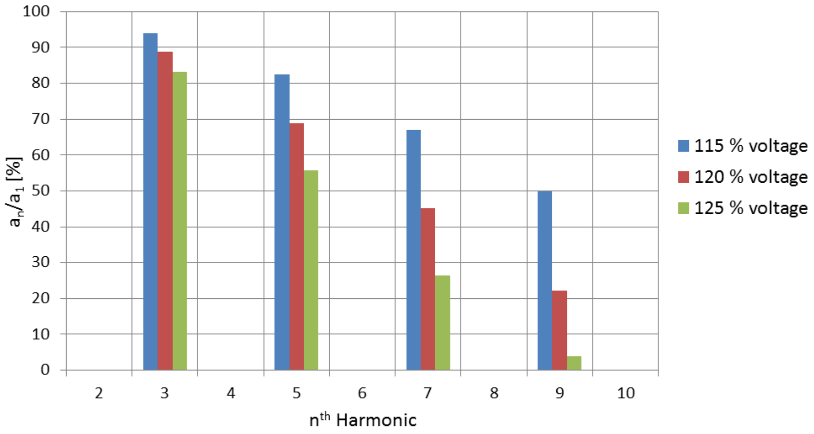

Figure 11 Harmonics generated due to different overvoltages in a Y-side power transformer with low zero sequence impedance, where rated voltage is 90% of knee-point and the harmonics is in percentage of the fundamental magnetization current.

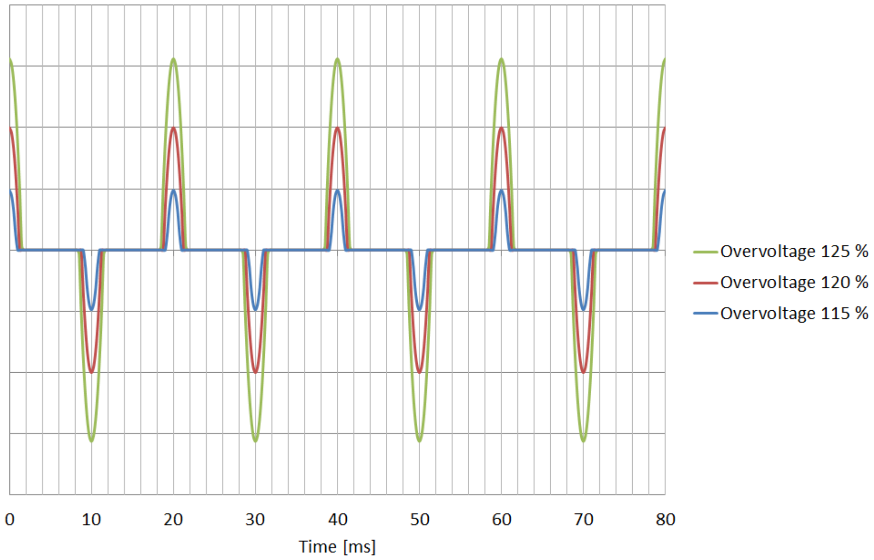

Figure 12 Magnetization current (over excitation) generated due to different overvoltages in a Y-side power transformer with low zero sequence impedance, where rated voltage is 90% of knee-point.

4 CONCLUSION

Differential currents appear in power transformers during inrush and overvoltage.
To prevent false operation of the transformer differential protection during inrush conditions, the 2nd harmonic can be used to block the protection. In general the 2nd harmonic is sufficiently large during transformer inrush for reliable inrush detection. The 5th harmonic can be used as a reliable method for blocking the transformer differential protection during overvoltage conditions.

Inrush currents in shunt reactors do not cause differential currents, but due to long DC time constants CT:s may saturate unevenly and result in false differential currents. The inrush currents in iron core shunt reactors do not always have enough 2nd harmonic content to be used for blocking of the reactor differential protection. For low impedance reactor differential protection an additional DC-biasing feature can be used to prevent unwanted tripping during inrush conditions. An overvoltage on a shunt reactor does not result in differential currents.

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