Challenges for Inrush Restraint when Protecting Transformers Directly Connected to Transmission Lines

Lubomir Sevov

lubomir.sevov@ge.com

General Electric Multilin, Canada

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Abstract

Energizing of power transformers in general is well discussed through number of papers, and standards. The characteristic of the inrush waveforms during magnetizing are also very well known and used to develop variety of criteria on defining mechanisms for inhibiting the differential operation function. While the existing transformer differential protection inhibiting functions perform well on energization of three-phase power transformers, they would not do so on energization of transformers directly connected to transmission lines, and particularly single-phase transformers and autotransformers. Controlled switching during energization may jeopardize 2nd harmonic inhibit function designed to block the differential protection.

The paper shows the weakness of some energization inhibiting functions, and provides a sound solution for coping with transformer differential protection in terms of stability and sensitivity for such cases.

Energizing three single-phase autotransformers and a transmission line at the same time is not trivial as one may assume. The energization is characterized by very long DC constant as related to the autotransformer and the line characteristics, unsymmetrical phase response, and distribution of less harmonic currents.

The paper includes a number of simulated test cases and discusses the results of the implemented energization inhibiting logic.

Introduction

Autotransformers are used widely in both transmission and distribution power systems, to either boost (increase), or buck (oppose, decrease) the voltage. Even though they are simpler, when compared to some transformer designs, their protection is of a high concern, due to their direct connection to the line – series winding, and solidly grounded common winding, which can be exposed to high fault currents, during system disturbances. This, in return, calls for higher insulation quality. Autotransformer failures can cause significant damage, not only to the device itself, but also to the surrounding grid, creating unwanted outages. Accordingly, high demands are imposed on power transformer protective relays. The requirements include dependability (no mis-operations), security (no false tripping), and speed of operation (short fault clearing time). The transformer energizing condition must be considered very carefully when designing differential inhibiting functions, as even though short in time, it creates stress conditions for the transformer insulation. Two are the main criteria imposed for the protective relays during transformer energization: block the operation of the transformer differential function, which otherwise would trip the transformer breaker, as the energization resembles internal fault condition, and second- maintain sensitivity on detecting internal faults. Working out to balance the two criteria, preference is always given to the security.

Typical shape of transformer inrush currents

The magnitude and shape of the transformer magnetizing currents depend on a number of factors: size and type of the transformer, the iron grain quality and the lamination sheets used for constructing the transformer core, transformer B-H curve, number of winding turns, location of the winding being energized with respect to the core (inner or outer), its cross sectional area, voltage point on wave (POW) when applied to the transformer terminals, core residual flux, etc. Nevertheless, the magnitudes of the magnetizing currents depend also on the impedance of the power system source, from where the transformer is energized. Depending on whether strong or weak source is supplying the voltage to the power transformer terminals, the magnitudes of the inrush currents can be as high as 8 to 30 times the nominal currents.

The typical magnetizing currents follow clearly the pattern of the B-H property of the transformer flux: all three phases share the flux, and their fluxes sum up to zero. They are characterized also by sharply rising peaks followed by flat portions. Figure 1 below shows typical magnetizing currents and the distribution of second harmonic throughout the energization:

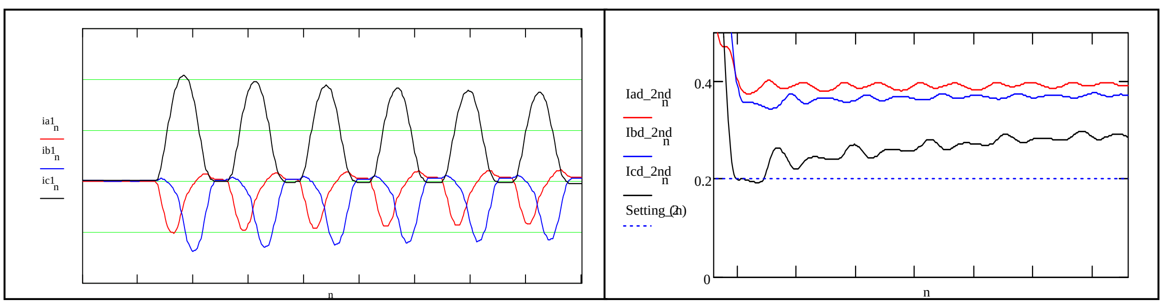

Fig. 1 Inrush currents during energization of three-phase 400MVA, 230/120kV, Yg/yg transformer

The general inrush equation for the magnetizing currents is a function of all mentioned above variables: applied voltage, total impedance including the system, point on wave, B-H characteristics, etc.

$$I_{magn} = \frac{\sqrt{2}U}{Z_T}\left(\sin(\omega t - \varphi) - e^{\frac{-(t-t_0)}{\tau}}.\sin\alpha\right).k_W.k_S \qquad [1]$$

where: U rms value of the applied voltage

Z_T total impedance under inrush including system

φ energization angle

t_0 point of time at which transformer core saturates, (function of B_N, B_R, B_S, φ)

t time constant of transformer winding under inrush

α function of t_0

K_W accounts for type of winding connection

K_S accounts for short circuit power of the system

Referring to fig. 1, the 2nd harmonic currents are accounted for more than 20% percent throughout the entire magnetizing process, hence the relays using 2nd harmonic for either directly blocking the differential protection, or added to the restraining current will effectively prevent the differential protection from operation. Some statistics show that the magnetizing currents during energization of old transformers contain higher percentage 2nd harmonic, than the ones of newly produced. The reason for this is said to be the different grain size of the iron lamination sheets by which the core is made of. The smaller the grain size, the higher the flux density and less air-gaps, hence lower percentage of 2nd harmonic current during energization. For such cases of low 2nd harmonic, additional mechanisms have been developed: adaptive lenses applied at ± 90° angle with respect to the fundamental frequency current, monitoring of the inrush current flat portions, or detection of the decaying magnetizing current peaks magnitudes. These mechanism however may also fail as can be seen further.

The typical inrush current described up to this point assumed three-phase transformer bank, energized from one winding, with the other winding open. In some power system arrangements however, the transformer cannot be energized alone, as no breaker is available on its other side, so that the energization is extended to the connected bus, transmission or distribution line. This one side of the transformer is only separated by disconnect switch, which is set closed during the energization. In the presented case Fig. 2, there are four three-phase single bank autotransformers each connected at one side of two 345kV parallel transmission lines 133 miles long. Since only disconnect switches are installed between the autotransformers and the lines, closing any of the 230kV breakers will energize the transmission line and the two autotransformers connected on its ends. The current during energization is a sum of the one following the flux within the autotransformer iron core, and the one of the line.

Characteristics of the energized System

The system consists of two parallel 345 kV lines 133.05 miles long, and have single 1780 kcmil ACSR Chukar conductor (Inner radius = 0.2185 inch, outer radius = 0.801 inch, DC resistance = 0.0516 ohm/mi). The lines are single circuit for 40.71 miles and double circuit for 92.34 miles. The lines also share a corridor with a 525 kV line.

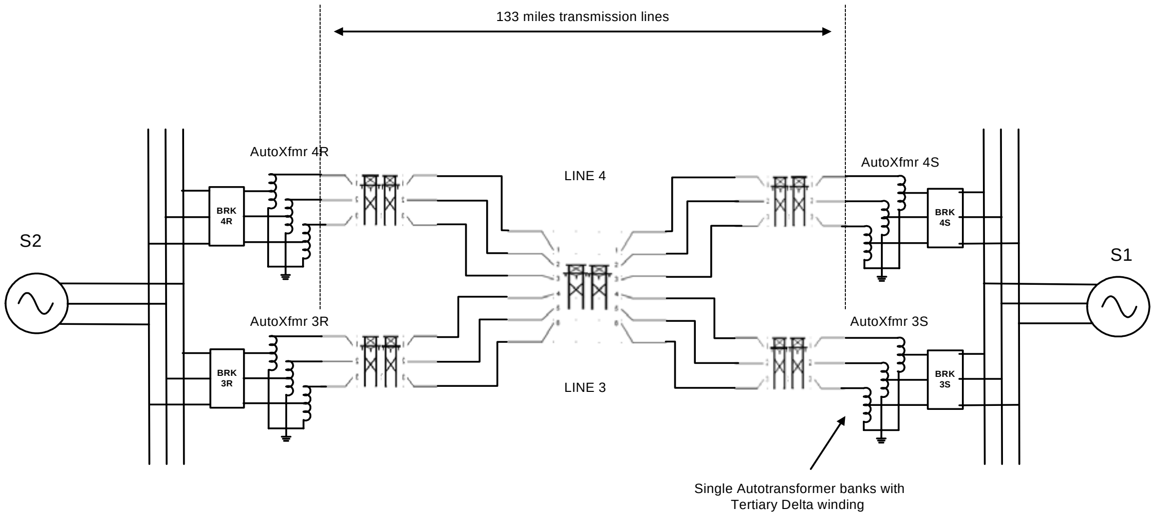

Fig.2 Double transmission line with autotransformers connected to each line end

The single circuit 345 kV towers are flat horizontal configuration, 47 feet above ground (average accounting for tower and sag), 32 feet between phases. The double circuit towers have the following layout:

3 4
2 5
1 6

The coordinates in feet, with respect to ground and the tower centerline are: 1: (-18.5, 47), 2: (-28.5, 72.5), 3: (-18.5, 98), 4: (18.5, 98), 5: (28.5, 72.5), 6: (18.5, 47)

345kV lines Impedances:

Name	Length miles	R1 (ohm/mi.)	X1 (ohm/mi.)	R0 (ohm/mi.)	X0 (ohm/mi.)	C1 (uF/mi.)	C0 (uF/mi.)	COND. TWR BUNDLE	Single or Double Cir.	Overhead Gnd Wires	Length (km)
Line 3:	133.05,	0.0609,	0.7895,	0.3469,	2.375,	0.01423,	0.00879,	Chukar K7,	DBL/SGL,	none,	214.12
Line 4:	133.06,	0.0609,	0.7895,	0.3469,	2.375,	0.01423,	0.00879,	Chukar K7,	DBL/SGL,	none,	214.14

Autotransformers Impedances @100MVA base:

Autotransformer 3R: 2 winding, Z = 0.00015 + 0.00995 pu
Autotransformer 4R: 2 winding, Z = 0.00016 + 0.00929 pu
Autotransformer 4S: 2 winding, Z = 0.00018 + 0.00959 pu
Autotransformer 3S: 3 winding, Xps = 0.01073 pu; Xpt = 0.04777 pu; Xst = 0.03124 pu

Case #1: Autotransformer- line-autotransformer energization

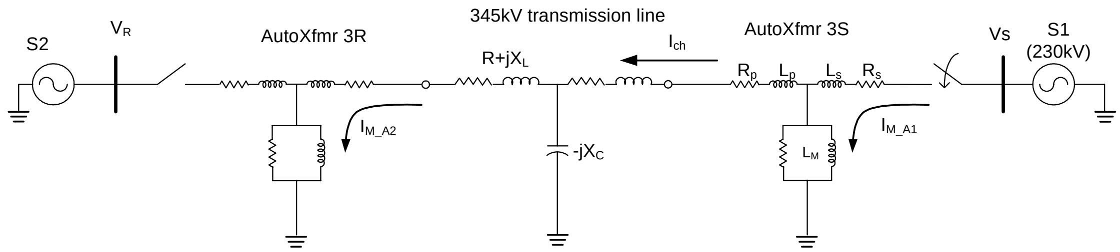

Fig. 3 Equivalent diagram of single line conductor with autotransformer bank at each end

From the equivalent diagram (Fig.3), closing the breaker from the line sending end, applies voltage Vs to the autotransformer 3S terminals and energizes the 133 miles long 345kV transmission line, and the autotransformer bank 3R at the line receiving end. Waveforms of the three-phase currents captured from both sides of autotransformer 3S during this energization are shown on Fig4. The 230kV side currents contain both: the AutoXfmr 3S magnetizing currents and the line charging currents, till the one from the 345kV side is purely charging currents. Generally, the initial (residual flux) of the autotransformer will be below the saturation flux level and accordingly the apparent magnetizing impedance will be very high compared to the in series line impedance. As a result, when the transformer is energized and the initial transformer core flux is below the saturation flux, the total supply voltage is distributed across the magnetizing branch until saturation is reached.

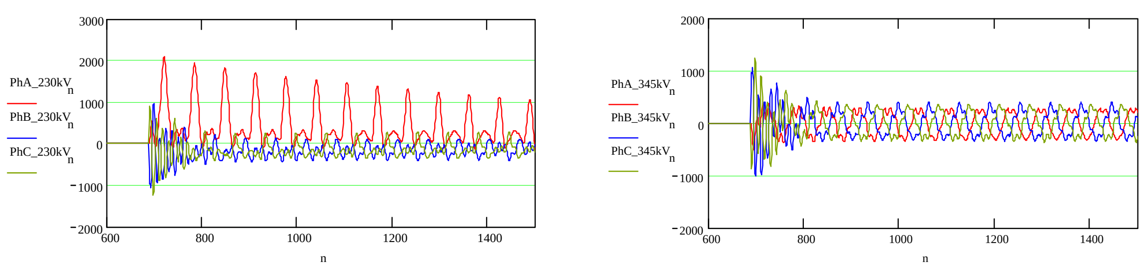

Fig.4 Currents recorded from 230kV, and 345kV sides of “AutoXfmr 3S” during breaker 3S close at zero crossing of phase A voltage

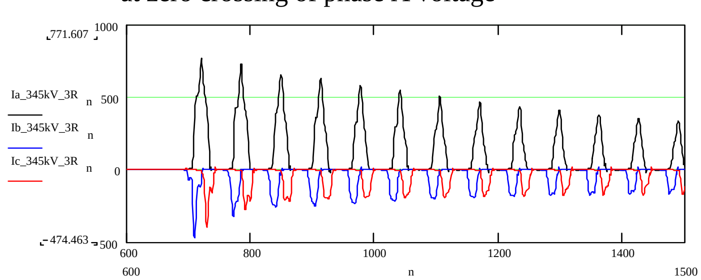

Fig. 5 Currents recorded from 345kV side of “AutoXfmr 3R during breaker 3S closed at zero crossing of phase A voltage.

During energization of a transformer at instant of voltage zero, the iron core is mostly driven into saturation, because the core flux density exceeds the saturation limit. Following saturation, the magnetizing branch can be considered as an air-core inductance, where the inrush current peak can be expressed in terms of the transformer core properties:

$$I_{pk} = \frac{B_{air} l}{\mu_0 N} = \frac{l}{\mu_0 N} \cdot \frac{A_C . (2B_n + B_r - B_s)}{A_{air}} \qquad [2]$$

where: l length of magnetic flux path in air[m]

μ_0 permeability of the air = $4.\pi.10^{-7}$[Vs(A/m)$^{-1}$]

N number of turns of the energized coil

B_{air} magnetic flux density outside saturated core[Vs]

A_C cross section area of the iron core[m^2]

A_{air} cross-section area of the air-core inductance[m^2]

B_n nominal peak core magnetization[Vs]

B_r, B_s residual and saturation magnetization[Vs]

The equation shows that, the higher magnetic flux density outside the magnetic core as opposite to the higher core flux density, will lead to higher flux saturation and higher inrush peaks. Hence, the presence of residual flux in the iron core will lead to even higher saturation currents, and higher level of 2nd harmonic.

The relationship between the residual flux and the point on wave as derived from the equation $e = n1\frac{d\phi}{dt}$ for the applied voltage e, winding turns- $n1$ and instantaneous flux- ϕ threading the winding, can be expressed as:

$$\phi_0 = -\phi_m \cos\varphi + \phi_{t0} \qquad [3]$$

where: $-\phi_m \cos\varphi$ is the steady state flux at time $t = 0$

ϕ_{t0} is the initial transient flux

φ is the angle at which the voltage is applied

It is transparent, that at angle 0° and no initial transient flux, the residual flux is at its maximum i.e. 90 degrees shifted from the angle at which the voltage is applied , and so does the excitation current which follows the same direction. On the other hand the inrush transient is reduced to maximum, if the voltage is applied at 90° degrees, and the flux is at 0° angle.

In the test from case 1, the voltage from the 230kV source was applied at phase A zero crossing, which explains the phase A inrush peaks seen on fig. 4. On this figure, all three phases currents are heavily distorted by the energization of the 345kV line with its distributed inductive and capacitive reactance defining line time constant different than the one of the transformer magnetizing. Closing of the breaker is instantaneous, so that for phases B and C the instant of energization occurs at –120° and 120° degrees respectively. Hence the magnetizing currents of these phases will be much lower than the one of phase A.

Summing up the currents recorded from both sides of “AutoXfmr 3S”, results into differential currents (Fig. 6), which appear to be the pure transformer magnetizing currents:

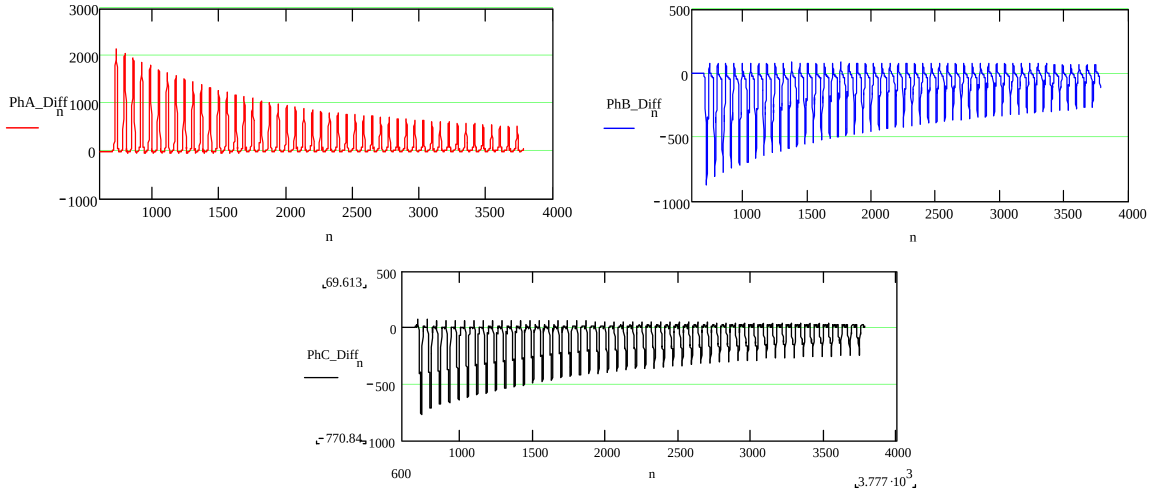

Fig. 6 Differential currents appearing as magnetizing currents for AutoXfmr 3S

Case #2: Autotransformer energization only

To compare with the magnetizing currents from (fig.6), the autotransformer was disconnected from the 345kV line, and energized from the same 230kV source S1 (Fig.7). The magnetizing currents are seen on fig. 8. Computing the 2nd harmonic per each phase showed plenty of 2nd harmonic, so blocking the differential protection would not be an issue:

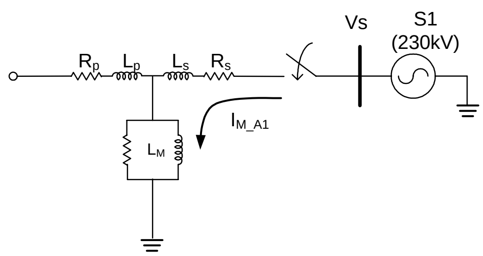

Fig. 7

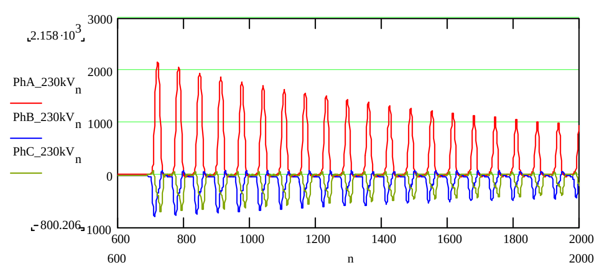

Fig.8 Autotransformer inrush currents, with 345kV winding side open

Now, comparing the currents from Fig. 8 with the differential currents from Fig. 6, gives us the right to state the following:

No matter whether the autotransformer is connected to a transmission line or not, applying the system voltage on its terminals will result in the same by shape and magnitude magnetizing currents. The wave comparison confirming this statement is shown on Fig. 9.

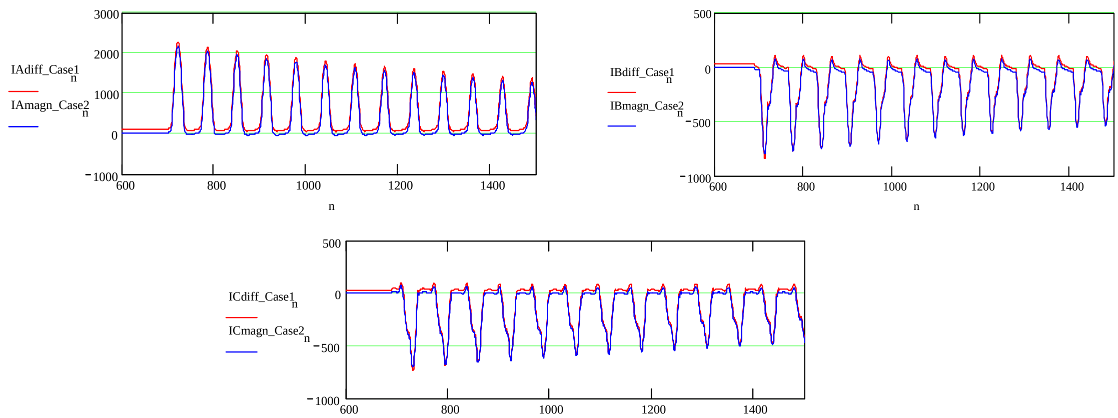

Fig. 9 Comparison of Differential currents from Case1 vs. Direct magnetizing currents of Case2

Case #3: AutoXfmr-line -AutoXfmr energized at 90° degrees voltage phase A

This test was conducted to provoke distribution of low amount of 2nd harmonic currents during energization. Phase A voltage was applied at 90°degrees POW, and the currents from both autotransformer sides recorded (Fig. 10). From fig. 11, it can be seen, , the 2nd harmonic on phase A drops below the setting of 20%, so that the differential protection may not be blocked, unless other meanings of blocking are implemented.

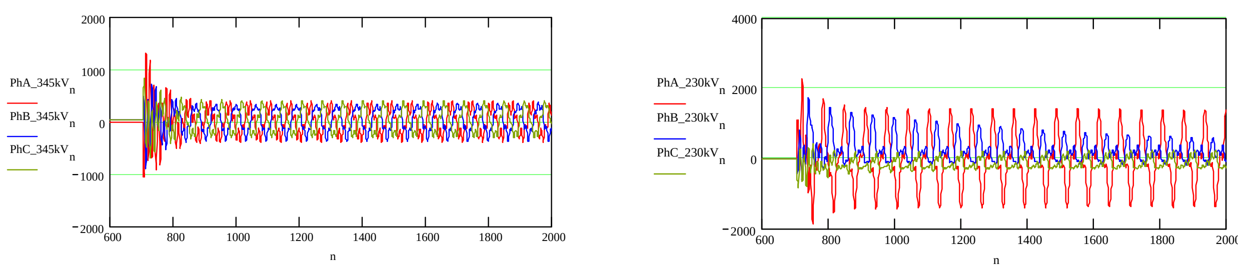

Fig.10 Currents recorded from both 345kV and 230kV sides, by closing breaker BRK_3S at 90°deg. phase A voltage

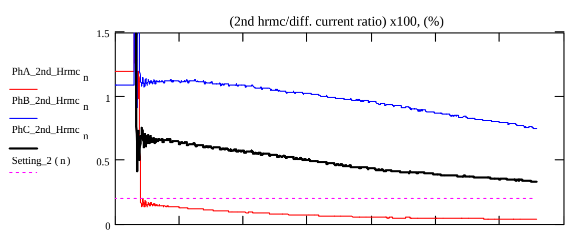

Fig. 11 Distribution of 2nd harmonic on phase A current

Case #4: Controlled switching for inrush transients elimination – good or bad

There are few known methods of breaker controlled switching that would eliminate the transient inrush current for the transformer, and therefore as stated by many papers will reduce the stress on the transformer insulation and losses. While this is true, it may however create difficulties for the protection engineer, who suppose to block the differential protection using 2nd harmonic, as during this smooth symmetrical transformer magnetization process, the 2nd harmonic, and other higher order even harmonics will be low.

Closing the breaker poles when the voltage of each phase is at maximum, i.e. 90°, -90°, and 90°, for phases A, C, and B respectively leads to no DC inrush transients, as the inrush currents following the flux sinusoid build up from point 0°degree. Figure 12, shows the transformer magnetizing currents, and the 2nd harmonic per phase. It can be seen now, that the 2nd harmonic on two phases is below the setting.

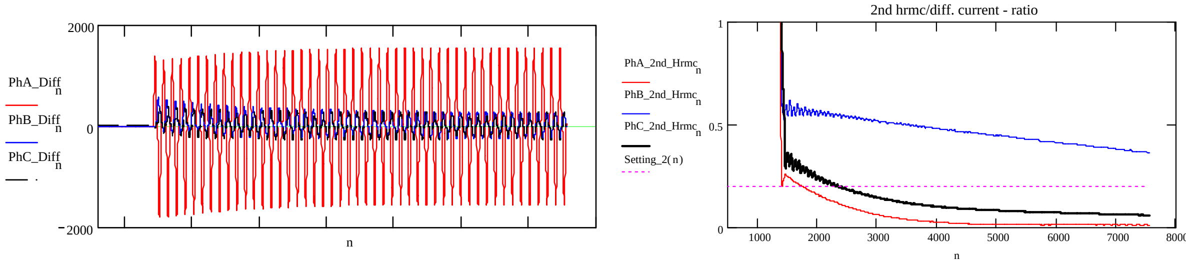

Fig. 12 Distribution of 2nd harmonic on phase A current

Depending on the applied relay, the customer may find inconvenient to apply the designed blocking mechanism, as first, they may fail to block, and second; they may be too secure, and hence may jeopardize the tripping during internal faults.

Depending on the inrush inhibiting mode and using 2nd harmonic for blocking we have:

- Per-phase blocking – cannot be used, as the 2nd harmonic on each phase is not bigger than the setting
- 2-out-of-3 blocking – cannot be used as the 2nd harmonic level on two phases is less than the setting
- Blocking based on average 2nd harmonic – cannot be used, as the average value will be lower than the setting

Depending on some other blocking philosophies that may, or may not involve 2nd harmonic we have the following:

- Adaptive lenses applied at ± 90°degree angle with respect to the fundamental frequency component to detect the penetration of the 2nd harmonic trajectory within the 20% zone – cannot be used, as the lenses blocking will lasts only few cycles. The 2nd harmonic below the setting is much longer than few cycles.

- 2nd and 4th harmonics added to the restraining current – not enough from both harmonics. Clear judgment criteria for block/permit operation cannot be applied
- Monitoring of flat inrush current segments – no such segments, as the inrush currents are symmentrical, and alter with the flux
- Monitoring the decaying inrush current peaks – involves criteria of decaying rate of change of current, which will not be triggered, when the inrush currents are symmetrical.

Restraining solution – The power of changing setting groups:

Before applying this solution it is assumed, that contact from the breaker, and voltage from the energization side between the breaker and the transformer are available. Two setting groups are used here; one configured to be in effect during the time of energization, and another one after the energization is completed. The switching between the groups (Fig. 13) is described below:

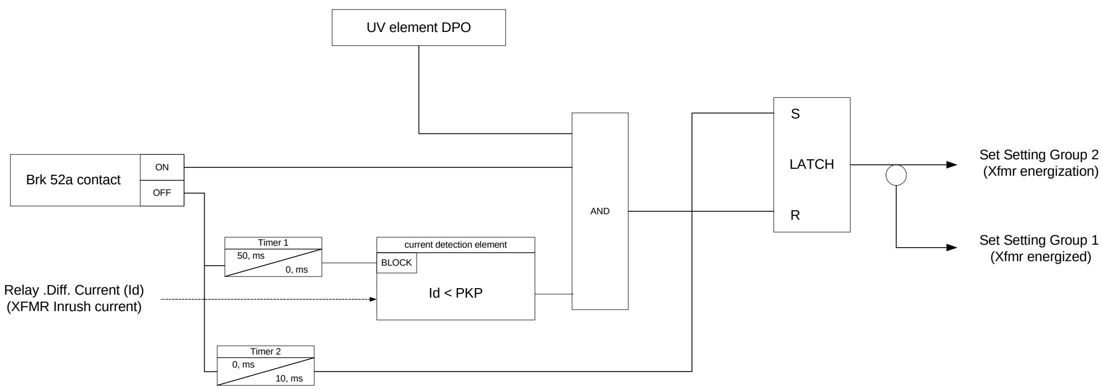

Fig.13

Upon closing of the breaker, the "OFF" status of its 52a aux. contact is prolonged for 10ms more, to assure the current detection element sees differential current bigger than the differential protection PKP setting. The pickup settings of the 87T protections from groups 1 and 2 are set the same. During the time of energization, the Latch remains "Set" (group 2 active), until the differential currents become smaller than the PKP setting, where the Latch resets. The logic switches to group 1. The 2nd harmonic threshold is set low on 87T element from group 2 to provide more secure energization.

Even though during internal faults, the differential current will be bigger than the PKP from the current detection element, and the voltage may collapse, the logic will maintain Group 1 active, as the Latch "Set" command comes only when the breaker is open (52a "OFF"). Upon 52a contact open position, the logic switches from Group 1 to Group 2, and blocks the current detection element 50ms later.

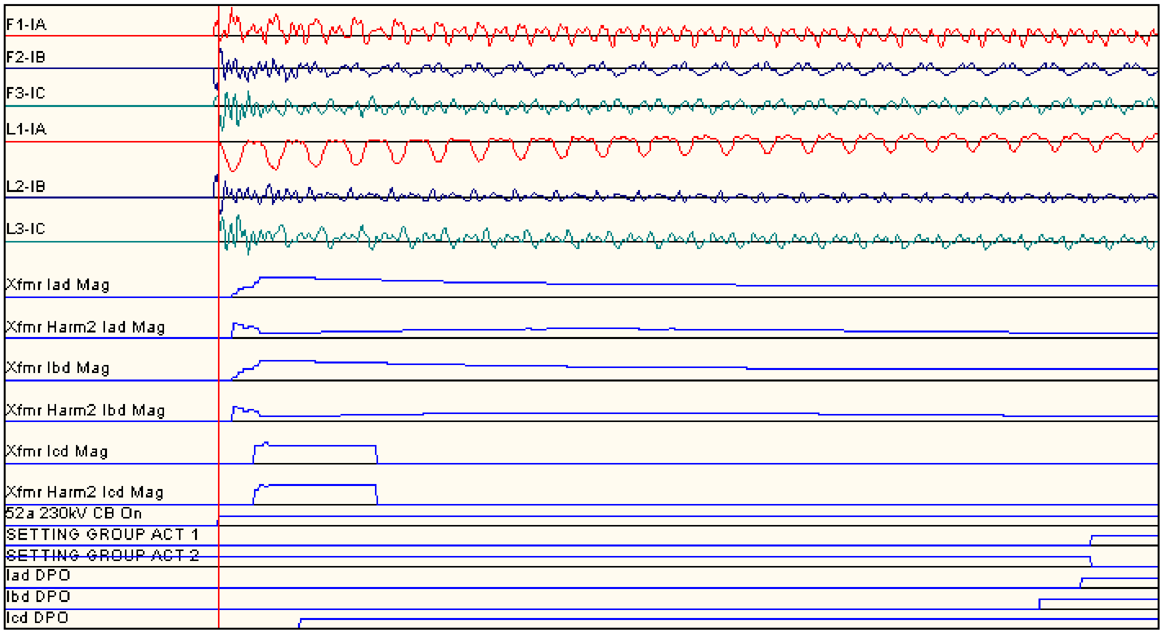

Fig. 14 Waveform playback testing the logic

The Iad, Ibd, and Icd digital signals from the recorded oscillography (fig. 14) show the inrush currents on phases A, B, and C drop below the PKP at different time. The last dropped current reverts the activation from group 2 to group 1. The group 1 is active during transformer in service.

Model of the Autotransformers - Transmission Line System

The single autotransformers and transmission lines seen from fig. 2 were modeled using ATP software, and real data from the autotransformers-lines arrangement being in service. This type of power system arrangement is not very common, but yet interesting in terms of energization. The main reason of connecting single autotransformers directly (without breakers) to the transmission lines is saving the cost on buying expensive HV breakers. It is obvious for the protective relays engineer, that fault on any of the single autotransformers connected on both sides of the transmission line, will take the transmission line out of service as well, and vise versa.

Referring to Fig. 15, the energization of interest is simulated by closing the sending end breaker BRK_3S, with receiving end breaker BRK_3R open and the other line energized (breakers 4R and 4S closed).

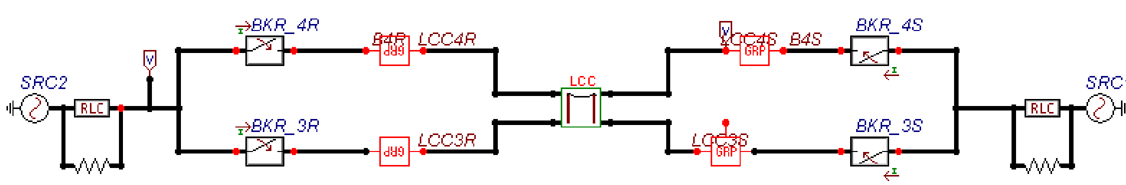

Fig. 15

Conclusions:

- Energizing of single bank autotransformers connected directly to transmission line does not create problem to the transformer differential protection unless the breaker poles closing is delayed by control switching devices.
- The unbalanced residual flux in the three single banks during instantaneous energization does not have an impact on lowering the 2^{nd} harmonic levels, as the autotransformers Delta winding provides path for the magnetizing currents to balance out the flux.
- The POW controlled breakers for smoothing the inrush currents during energization create problem for the transformer differential protections using the 2^{nd} harmonic for blocking purposes.
- Advanced relay are equipped with tools for creating logic, such that combined with detection of low 2^{nd} harmonic can be used as alternative to the known blocking methods transformer energization.

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Biography:

Lubomir Sevov received his M.Sc. degree from Technical University of Sofia, Bulgaria in 1990. After his graduation, he worked as a protection and control engineer for National Electric Company (NEC) Bulgaria. Mr. Sevov joined GE Multilin in 1998 as a relay test design engineer and in 2001 he was promoted as an application engineer in the research and development team. In 2004 he became a member of the association of professional engineers Ontario, Canada. He is a member of the IEEE – PES since 1999.

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