Understanding Sympathetic Inrush Currents and Their Effect on Protective Relays

Juergen Holbach, Quanta-Technology, Raleigh, NC, jholbach@quanta-technology.com
Miriam Sanders, Quanta-Technology, Ashville, NC, msanders@quanta-technology.com

Abstract

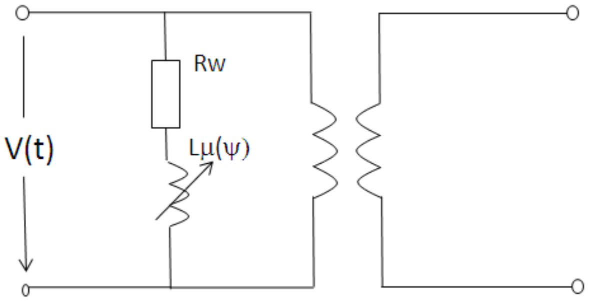
Inrush currents caused by the energization of a transformer are well know and understood by a protection engineer. Manufacturers have developed features dealing with inrush currents to stabilize differential relays and protection engineers have considered inrush currents in their coordination to avoid misoperation. The phenomena of the sympathetic inrush current that occurs when a second transformer is energized in series or in parallel to an existing energized transformer is not so well known. The inrush current caused by the energization of the second transformer causes the in-service transformer to produce an inrush current as well, the so called sympathetic inrush current. The signature of the sum of both inrush currents as well as the time constant is quite different as a usual inrush current and upstream protection relay measuring this current sum are sensitive to this current. The paper will discuss an actual operation on the 115KV side of a transformer of several distance relays on such an event and will report on lessons learned. The example is very well documented by several fault records from different relays at different locations, helping to confirm the theory of such a phenomena.

1 Introduction

During the energization of a newly installed 500kV/161kV autotransformer several distance relays operated unexpected. Because the line going to the autotransformer was still under construction, the utility energized the autotransformer from the high side (500kV) via a second autotransformer 500kV/115kV. After reviewing the relay records it was confirmed that the distance function operated with a zone 4 element for a B-G event after 20 cycles. As the current in phase B did not look like a typical inrush current it was first assumed that the transformer experienced a B-G fault. However, the fault current did not look like a typical fault current, therefore further investigation ensued. This revealed that this was a case where a sympathetic inrush current caused the operation of the distance relay. The sympathetic inrush current phenomenon occurs, if a second transformer is energized in series or in parallel to an already energized transformer. The signature of the sum of both inrush currents as well as the time constant is quite different than the usual inrush current and upstream protection relay measuring this current sum are sensitive to this current. The paper will discuss an actual operation on the 115KV side of a transformer of several distance relays on such an event and will report on lessons learned. The example is very well documented by several fault records from different relays at different locations, helping to confirm the theory of such a phenomena.

2 Fundamentals of inrush current

The inrush current produced during the energization of a transformer is well known and understood by the power industry and several papers are written about this phenomenon. For the understanding of the sympathetic inrush it is useful to review some of this material as it will build the foundation for the understanding of the sympathetic inrush current phenomena. A simplified transformer model is shown in figure 1. The core element for the inrush current consideration is the magnetization inductance $L\mu$ of the transformer.



Lµ is function of flux in transformer!

Figure 1: Simplified Transformer Model

Under normal operating conditions, the value of magnetization inductance Lµ is relatively high and can be ignored as there is only a very low magnetization current flowing through this inductance. However if the flux inside the transformer reaches the saturation point the magnetization inductance Lµ will reduce its value significantly and cause a high current. This high current is inrush current. The flux inside the transformer is an integral function of the voltage on the transformer.

Transformers are normally designed for operating voltages 10-20% greater than the nominal voltage. In this voltage range, the resulting magnetic flux values will not cause the saturation of the transformer. The value of the inductance is a function of the magnetic flux in the iron of the transformer as shown in figure 2.

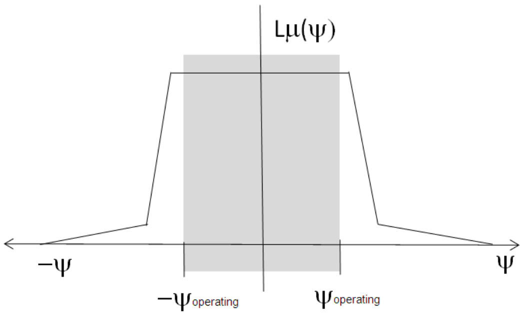


Figure 2: Magnetization inductance Lµ as function of flux

The relationship between voltage on the terminals of transformer and the magnetic flux in the iron can be described by the formula 1.

$$\Psi_{(t)} = \int V_{\text{terminal}(t)} dt + \Psi_0 \qquad (1)$$

and is illustrated in figure 3 for steady state operating conditions.

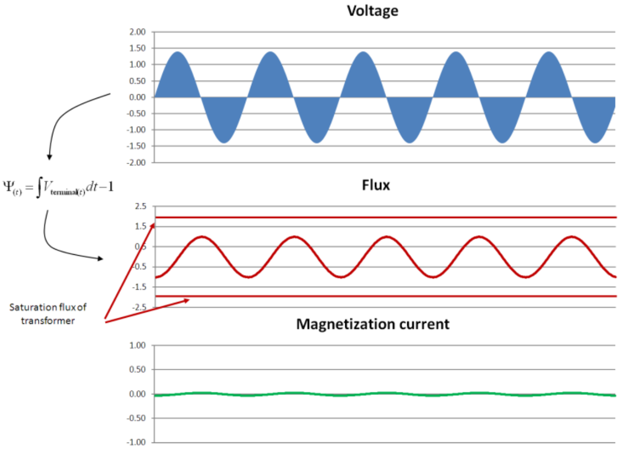


Figure 3: Relation between transformer terminal voltage, flux [pu] and magnetization current during normal operation

In this steady state operating condition, the flux value will not reach the saturation value. On an unloaded transformer only a small magnetization current can be observed.

The situation can become different if a transformer becomes energized. It now depends on the remanence flux within the transformer and the point on the voltage waveform that the transformer is energized if the transformer will exceed the maximum design flux. The remanence flux is the flux inside the transformer at the moment the transformer was switched off. The flux will not decline and stays at this value within the transformer.

Let’s consider for example the signals shown in figure 3 as an energization record and let the beginning at this record be the point in time of the transformer energization. This would be the situation if the transformer was energized at the zero crossing from negative to positive of the voltage and the transformer had a negative remanence flux value of -1 pu. In this case the flux in the transformer would be as shown in figure 3, would not reach the saturation flux and therefore not develop any inrush current.

A more critical scenario would be if the transformer is in remanence with a positive 1 pu value and the transformer energized at the same point in time as in the example before. In this case the positive voltage waveform will increase the flux above the 1 pu value (what was assumed as the maximum value during normal operation) and will eventually reach the saturation flux. At this point the magnetization inductance of the transformer is reduced o a much lower value and the magnetization current increases significantly. This current is the inrush current.

If the power system is assumed as an infinite source and the transformer is assumed as ideal and without any resistive losses the inrush current will look like shown in figure 4 and would not decline over time.

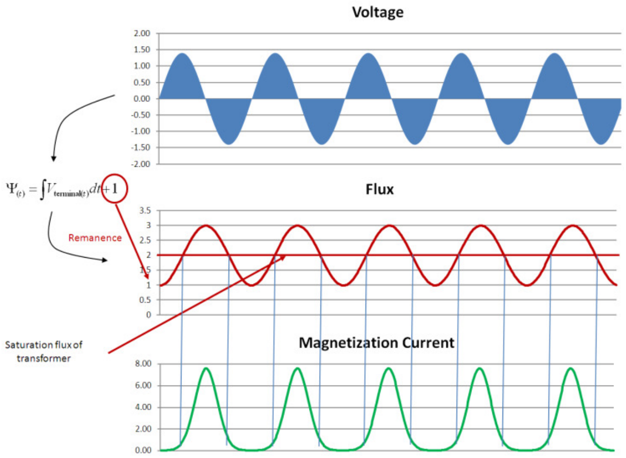


Figure 4: Inrush current show for infinite source and ideal transformer

In this theoretical case the flux would continue to swing around a positive offset of 2 pu flux.

In reality the inrush currents will decline with a certain time constant. The source impedance and the transformer resistance produce a voltage drop caused by the inrush current. This voltage drop produces an asymmetrical voltage as measured on the transformer as shown in figure 5. Based on this voltage asymmetry, the transformer remanence flux will be reduced.

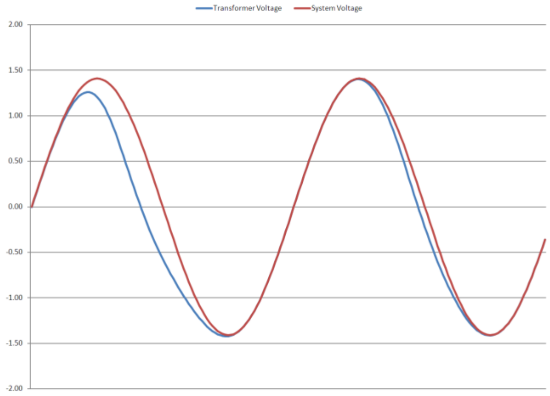


Figure 5: System voltage vs. transformer voltage

After some time the flux value will not have any offset and will swing around the zero flux value. With the decline of the flux offset value, the inrush peaks will decline in value and eventually disappear. The time constant in which this happens is mainly determined by the source impedance as explained above and the value of the magnetization impedance of the transformer as determines function of the inrush current amplitude. On transformers close to large generators and the resulting small source impedance, the resulting inrush current may be sustained for several seconds.

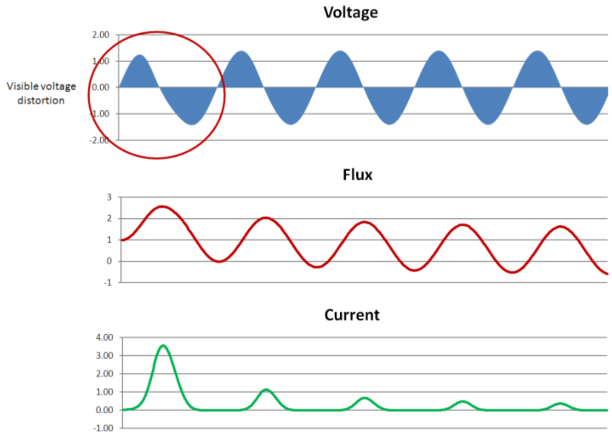


Figure 6: Transformer voltage, flux and inrush current for typical transformer energization

In figure 6 it is visible how the deformation of the voltage helps to adjust the flux offset inside the transformer. In this simulated case a very small time constant was selected to make the effect of the declining flux visible. In figure 7 an actual inrush recording is shown.

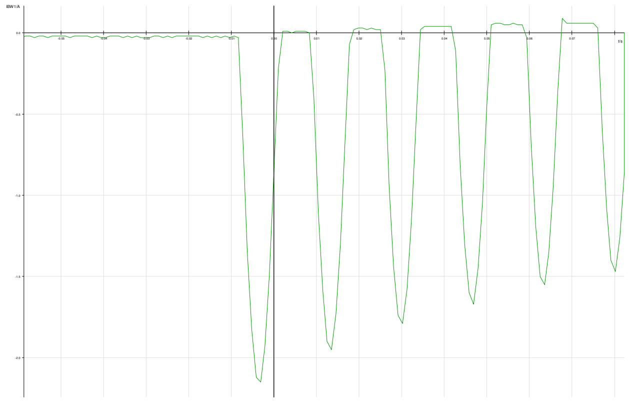


Figure 7: Inrush current recording

3 Protection setting consideration in regards to inrush current

The protection engineer needs to understand the phenomena of inrush current and consider it whenever he needs to set current based protection functions. The most important functions in this category are the instantaneous or inverse over current protection function (ANSI no. 50, 51, 67), the distance protection function (ANSI no. 21) and the current differential protection function (ANSI no. 87).

It does not matter in which application the functions are used but whenever they are used close to a transformer, the effect of the transformer inrush must be consider for the protection function with the settings selected accordantly.

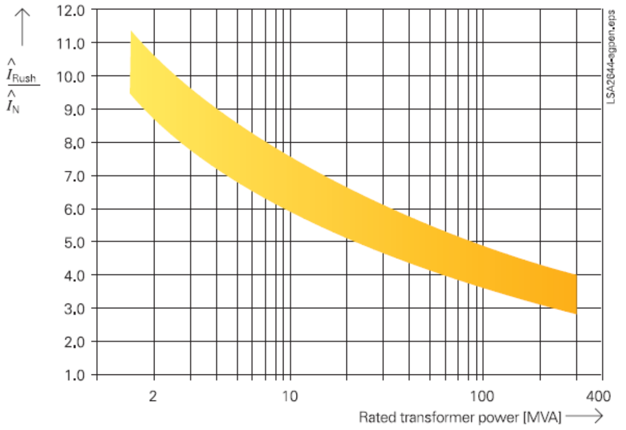
The calculation of the inrush current amplitude and time constant is not trivial but there are formulas available which give a good approximation of these values [2][3][4]. The formula below is the analytical equation described in [4]:

$$i(t) = \frac{\sqrt{2}V}{\sqrt{R_W^2 + \omega^2 L^2}} (\sin(\omega t - \phi) - e^{-\frac{R_W}{L}(t - t_s)} \sin(\omega t_s - \phi))$$

with $$\phi = \tan^{-1} \frac{\omega L}{R_W}$$

L: transformer air gap inductance
R_w: Windings resistor of transformer
V: nominal phase to ground voltage

These formulas are not very handy and the transformer air gap inductance is not always available during the setting development process. One other possibility available for the setting engineer are tables or graphics which give an estimated about amplitude and time constant in relation to the size of the transformer.



Time constant of inrush current

Nominal power (MVA)	0.5 … 1.0	1.0 … 10	> 10
Time constant (s)	0.16 … 0.2	0.2 … 1.2	1.2 … 720

Figure 8: Example graphics of inrush current [5]

An instantaneous over current element (ANSI no. 50) needs to be set above the maximum inrush current with a certain safety margin to avoid any mis-operation. It is important to understand the measurement principal of the protection function as peak value base functions will be affected divergently as function based on the RMS value. Also is it important to know whether the evaluated quantity is the RMS value or filtered nominal frequency component of the RMS value. .

The inverse over current functions must be set so that the inrush current will not affect the coordination with other protection relays. For this purpose the inrush current should be displayed on the coordination graph as shown below.

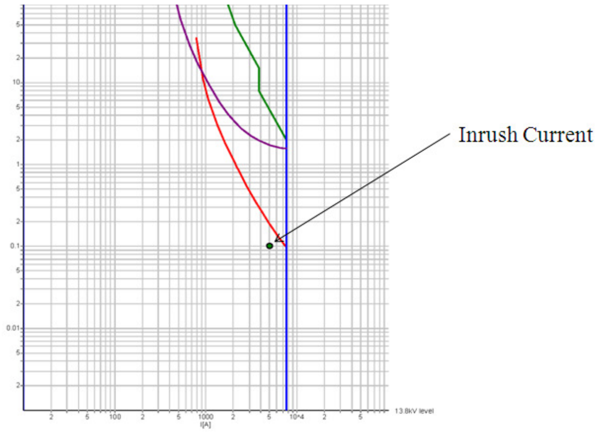


Figure 9: Coordination graph showing inrush current

Differential relays are normally not affected by the inrush current as long as the inrush currents enter and leave the protection zone. This is true for all differential applications (line, bus, and generator) beside a transformer differential relays used to protect the transformer which produces the inrush current. The differential relay will see only the inrush current on the winding from which the energization was initiated (ignoring for now the sympathetic inrush effect of a second transformer) and could mis-operate. For transformer differential relays a blocking element is needed what detects the energization and the inrush current and blocks the differential element during energization. Most manufacturers of numerical relays have for example a function implemented which will measure the second harmonics of the currents and will block the differential function as soon as the level exceeds a settable level.

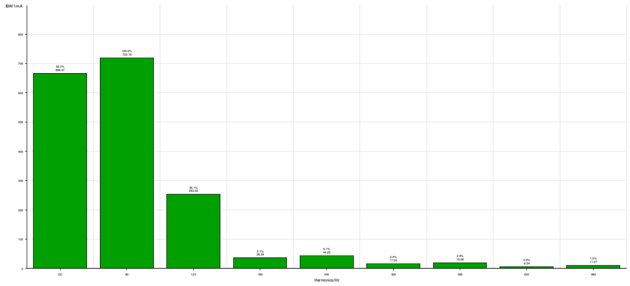


Figure 10: Harmonic content of inrush current

In figure 10 is the 2nd harmonics (120Hz for 60Hz systems) content shown for a typical transformer inrush current. In many applications a level of 20% can be considered as sufficient to detect the inrush current. However newer transformers show a lower harmonics content because of different materials used today.

The distance relay function is normally not effected by an inrush current. Only if the distance relay is used to look into a transformer does the inrush current effect need to be evaluated. Otherwise if the distance relays is protecting a long transmission line, then this line will limit the inrush current quite significantly and the effect for the distance function can be ignored. If however the distance relay is protecting a short line, the inrush current could be significant, however then the zone settings will be small enough that the effect of the inrush current will not be able to enter a critical zone (Z1). In [6] is a very detailed description given how the impedance relay algorithm is affected by the inrush current. The author shows that by filtering the 60 Hz component out of the inrush current, the amplitude will only be approximately 40% of the inrush current peak value. The author recommends to use an over current supervision for the distance protection zone to stabilize the distance element against inrush current.

4 Basics on sympathetic inrush current

The basics explained in the previous section 2 “Fundamentals of inrush currents” already laid out all the theory we need to understand the sympathetic inrush phenomena. The sympathetic inrush current is the combination of two inrush currents produced by two (or more) transformers. To illustrate the phenomena let’s consider an application as shown in figure 11. The two transformers T1 and T2 are in parallel and will be energized at different times. To simplify our model we assume no significant impedance between the two transformers as we assume them connected to the same bus. Between the bus and the source there will be the source impedance. In this case T2 is already energized and we will assume it is in a normal operation mode with or without load.

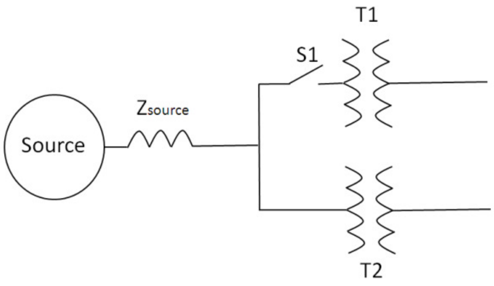


Figure 11: Parallel transformer application

In this state the flux in the transformer T2 will swing around zero but will not reach the saturation flux and therefore no inrush current is present. The voltages, the flux and the magnetization current will be as shown in figure 3 of the previous chapter.

If transformer T1 is now energized, it can produce an inrush current based on the remanence flux stored in the transformer and the voltage wave polarity at the beginning. To discuss the worst case we will assume the transformer T1 is energized at the zero crossing of the voltage from negative to positive and the transformer T1 had a +1 pu remanence flux at this time. As already discussed, the transformer T1 will produce an inrush current when the flux reaches the positive saturation flux. The discussion of the sympathetic inrush current how the inrush current of transformer T1 will influence the flux in transformer T2.

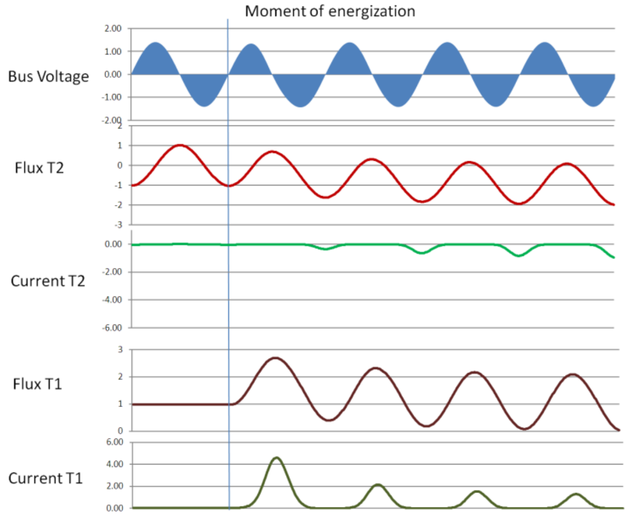


Figure 12: Flux and currents for both transformers after energization of T1

The inrush current of transformer T1 will lead to a voltage waveform distortion based on the voltage drop caused by the inrush current on the source impedance. For transformer T1 as we saw earlier this is helpful as it will help to reduce the flux offset and will support the decline of the inrush current. However transformer T2 will measure the same unsymmetrical voltage as T1 and will start to reduce its flux as well. The flux in transformer T2 with no offset will now generate a negative offset which is determined by the voltage waveform asymmetry and will trend toward the negative saturation flux. If the reduction is high enough the flux can reach the negative saturation flux resulting in transformer T2 to produce an inrush current. The inrush current of T2 will cause an asymmetry in the voltage that decreases flux inT2 transformer but increases the flux offset in T1 again .This will add to the saturation on transformer T1 in the next half wave again. This sequence can go on for quite some time with the only damping element being the resistance to the common point where both transformers are connected as this reduces the voltage distortion for the other transformer.

The inrush current produced by transformer T2 will have the opposite polarity to the inrush current produced by T1 and the peaks of the inrush currents are shifted by approx. half a cycle. This is based on the fact that in this example the flux in T1 will operate on the positive saturation flux and the flux in T2 will operate close to the negative saturation flux.

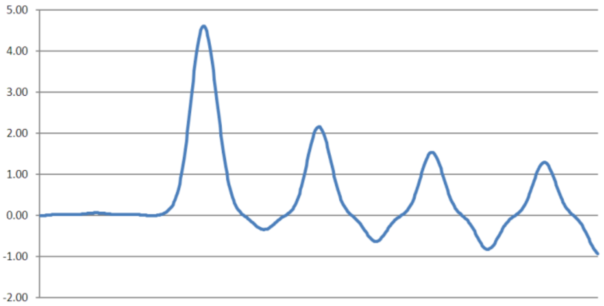


Figure 13: Current sum of I1 and I2 as seen by the source

The line feeding the bus on which both transformers are connected will see the summation of both currents as illustrated in figure 13. This is the signature of a typical sympathetic inrush current. Remarkable is that its looks almost like a fault current with a certain DC offset.
The second harmonics is less evident than in a normal inrush current.

The previous consideration can also be applied for applications in which the transformers are connected in series as shown in figure 14.

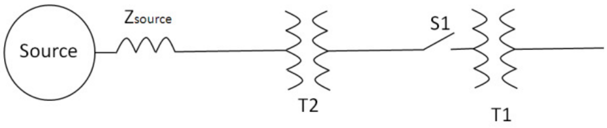


Figure 14: Recordings of distance relay on the 115kV side during trip (only B phase values)

If transformer T2 is already energized and its flux is already swinging around the zero flux (no offset) then the inrush current of T1 will cause an offset of flux in T2 and cause it to produce inrush current again.

5 Actual Event from 13th of April 2012

On Friday the 13th of April 2012 the utility tried to energize a newly installed 500kV/161kV autotransformer for test purposes. Normal practice in this utility is to energize transformer via the low side. In this case that was not possible as the 161kV line going to the transformer was still under construction. The 500kV side is connected to a ring bus on which two 500kV transmission lines are connected as well as a 500kV/115kV autotransformer. The utility decided to the energization of the 500kV/161kV autotransformer via the high side, disconnecting the 500kV lines from the ring bus and energizing the 500kV ring bus via the 500kV/115kV autotransformer.

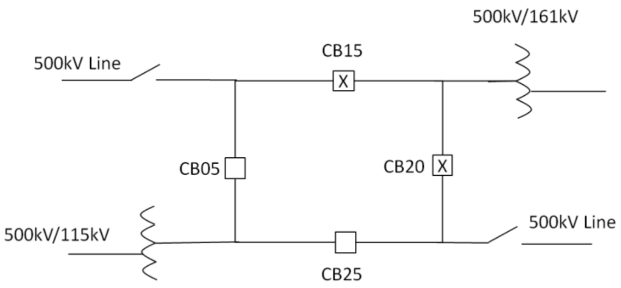


Figure 15: Configuration before energization of autotransformer 500kV/161kV

After closing of the circuit breaker CB20 several distance relays on the 115 kV side looking into the autotransformer operated. After reviewing the relay records it was confirmed that the zone 4 distance function operated for a B-G event after 20 cycles.

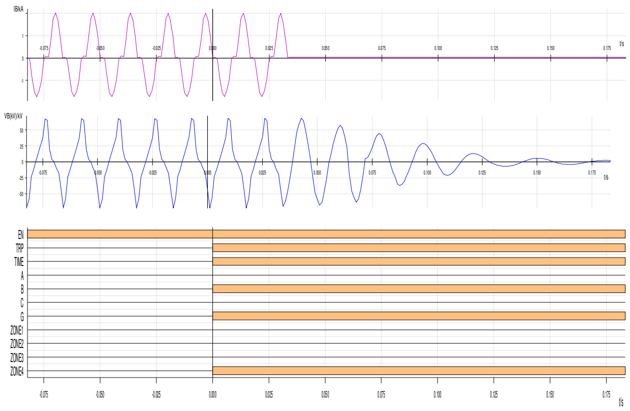


Figure 16: Recordings of distance relay on the 115kV side during trip (only B phase values)

As the current in phase B did not look like a typical inrush current it was first assumed that the transformer experienced a B-G fault. However, the degrees of voltage distortion as well as the current wave form could not be explained by a normal fault in the newly installed transformer and further investigations were requested.

A second relay which picked up on the 115kV side recorded the point of the energization revealing very helpful information for the analysis and the final.

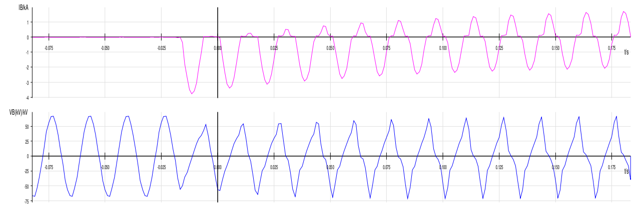


Figure 17: Recordings of second relay on the 115kV side during pick up (only B phase values)

Evident here is that the event started as a normal inrush current. The point of energization is around the zero crossing of the voltage from positive to negative and therefore we see an inrush current with negative polarity as the flux in the newly energized transformer will reach the negative saturation flux. Also evident is the voltage distortion caused by the inrush current. As we explained in sections 2 and 3, this voltage distortion will correct the negative offset of the flux value toward zero in the just energized transformer and contributes to the reduction of the inrush current. The first three cycles of the recording illustrates this. However the voltage distortion is also evident for the already energized transformer, adjusting the flux in the same way as the just energized transformer but from zero to a positive value. Therefore the transformer may reach its positive saturation flux point. After two to three cycles as we can now see that the positive half wave is increasing. The positive half-wave is the inrush current from the transformer already energized and the negative half wave is the inrush current from the transformer being energized.

In this particular event the inrush currents from both transformers reached a stable value and did not decline. This was caused by the fact that the voltage distortion caused by one half wave inrush current of one transformer offset the flux in the other transformer enough, producing same amount of inrush current in the next half wave. This sequence continued as there was no damping resistor between the transformers. The operation of the distance relay for this non-declining inrush current was desired and correct.

During the investigation of this event the advantage of numerical relays became apparent. The recordings provided data to analyze and understand what really happened. The authors can only assume that similar events have happened before but could not be easily explained as there were no recording available. The final confirmation of the sympathetic inrush phenomena was possible with the records out of the differential relays from both autotransformers. As a side note it needs to be mentioned that none of the differential relays operated, restraining on inrush currents as designed.

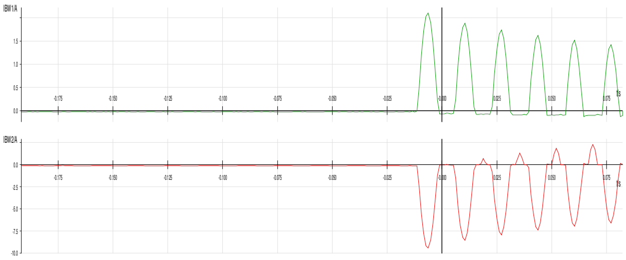


Figure 18: Recordings of differential relay on 500kV/115kV autotransformer (only B phase values)

The record of the 500kV/115kV revealed that in this case there where really two different sources for the inrush current. As shown in figure 17 at the beginning of the event, the 500kV/115kV autotransformer measures only the pass-through inrush current produced by the 500kV/161kV autotransformer as the current measured on both windings are equal but with different polarity. Only after the 3rd cycle the 115kV measurement (red) starts to produce an additional positive component which is not visible on the 500kV side measurement (green). This is the inrush current produced by the 500kV/115kV autotransformer which combines now with the inrush current of the 500kV/161kV autotransformer.

The fault record of the differential relay protecting the newly installed and energized 500kV/161kV autotransformer confirmed now that there was no fault inside the transformer as it only showed inrush current on one winding.

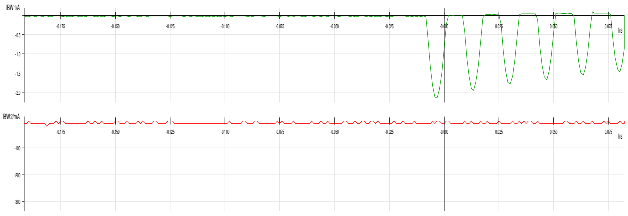


Figure 18: Recordings of differential relay on 500kV/161kV autotransformer (only B phase values)

6 Conclusion

The sympathetic inrush current phenomena is not a very common event and only occurs in applications where two or more transformers are in parallel or in series and the impedances between the transformers are small. In the described event it was caused by an exceptional operation sequence which will be avoided in the future. However there are applications as described above and the protection engineer will need to consider existence of a sympathetic inrush current. The characteristic of a sympathetic inrush current has two very different characteristics when compared to a usual inrush current

- The time constant for decay is much longer and may persist over seconds or even minutes
- Very little 2nd harmonic contents (<5%) after the two to three cycles.

In the reported event the distance protection trip was required to interrupt the current as the current did not decline with any significance over time.

7 Acknowledgment

The authors want to thank Sze Mei Wong and Gerald Breaux from Entergy for their support during the analysis of the operation and their helpful discussion during the development of this paper.

8 Literature

[1] H. Bronzeado, R. Yacamini: Phenomenon of sympathetic interaction between transformers caused by inrush transients. IEE Proc.-Sci. Meas. Technol., Vol. 142, No 4, July 1995

[2] G. Bertagnolli, Short-Circuit Duty of Power Transformers, Second Revised Edition. ABB, 1996.

[3] T. R. Specht, “Transformer magnetizing inrush current,” AIEE Trans, vol. 70, pp. 323–328, 1951.

[4] J. F. Holcomb, “Distribution transformer magnetizing inrush current,” Transactions of the American Institute of Electrical Engineers, Part III (Power Apparatus and Systems), vol. 80, no. 57, pp. 697–702, Dec. 1961.

[5] Siemens SIP · 2006, revised: Jan. 2007, E50001-K4400-A101-A4-7600, page 2-44

[6] J. Mooney, S. Samineni, “Distance Relay Response to Transformer Energization: Problems and Solutions”, WPRC 2007

9 Biographies

Juergen Holbach

Dr. Juergen H. Holbach, has more than 20 years of experience in design and application of protective relaying. He led the development project for the second generation of numerical line differential relays for a German relay manufacturer. As an application expert for transmission protection he was responsible for approval test of transmission relays with utility customer around the world. Since 2000 he works in the US as a product manager for protection relays. Juergen was one of the lead engineers on the first IEC61850 based Protection and Control, Multi-Vendor Project in the United States (500KV Bradley Station-TVA).
Juergen contributed to several working groups in CIGRE as well as in IEEE-PSRC and is the chairmen of the working group H5 “Common format for IED configuration data”. He is also member of the IEEE-PSRC subcommittees “Relay Practices” and “Relay communication”. He published over a dozen papers at the major relay conferences in North America. Juergen holds several patents in the area of protection relaying. Prior to joining Quanta Technology, he was Product Lifecycle Manager at Siemens Energy Inc. in Wendell North Carolina. He was born in Germany and graduated from the University of Berlin with a PhD in Electrical Engineering. He joined the Siemens AG in 1992 as a development engineer in Berlin Germany. In 1994 he moved to the

product management group for protection relays in Nuremberg Germany. In 2000 he joined Siemens Power and Distribution in Wendell, NC as a product manager for transmission relays. Since 2009 he joined Quanta Technology and leads the Automation group.

Miriam P. Sanders, PE

With over 30 years' experience in the relay industry, Miriam has worked with protection channels, transmission pilot relays and distribution relays. She is a Principal Advisor with Quanta Technology. Previous employers include Ametek Power Instruments, Pulsar Technologies, Inc, ABB Power T&D, Booth & Associates and Westinghouse Electric. At Ametek and Pulsar, Miriam was Product Manager for the PLC products. Miriam has published several papers on the application of Power-Line Carrier for use in protection systems. Miriam is a senior member of the IEEE, past Chairman of the Power and Energy Society's Power System Relaying Committee, and has held many positions in the organization including, Committee Vice Chairman, Committee Secretary, and Assistant Secretary, the Standards Coordinator, Chairman of the Transformer Protection Guide, member of the Power Line Carrier Practice Working Group and Transmission Line Protection Guide. She is also active in the PES's Power Systems Communications Committee and its Power Line Carrier Subcommittee. She is a registered Professional Engineer in the states of North Carolina and Florida.