April 2012

Managing Transient voltage surges

The objective of this paper is to provide a basic understanding of transient voltage surges and their impact on the design and installation of distribution/power class transformers.

Definition

ANSI std. 1100-199: "*A subcycle disturbance in the AC waveform that is evidenced by a sharp brief discontinuity of the waveform. Transients may be of either polarity and may be of additive or subtractive energy to the nominal waveform.*"

In layman's terms… Transient overvoltages are short term electrical disturbances which can result in failure of electrical equipment due to overstressing of equipment dielectric systems.

Origin

20% generated from external, such as lightning, power system faults (impulse)
80% from within electrical system such as load switching, drives, motors (oscillating)

Although lightning strikes may be the most obvious, the majority originate as a result of system switching or disconnection of electrical equipment. Switching transients occur when circuit breakers open/close transformer primaries, such as automatic switching between utility services or on-site power generation. For example when a breaker interrupts current flow, an arc develops across the breaker contacts. Since the current interruption usually occurs somewhere other than the current zero crossing point, the arc will remain until the current crosses zero. The result is a voltage developing across the contacts, known as the transient recovery voltage (TRV). The level of such a surge has the potential to exceed the insulation system of the associated transformer(s).

Types

Impulse – from lightning

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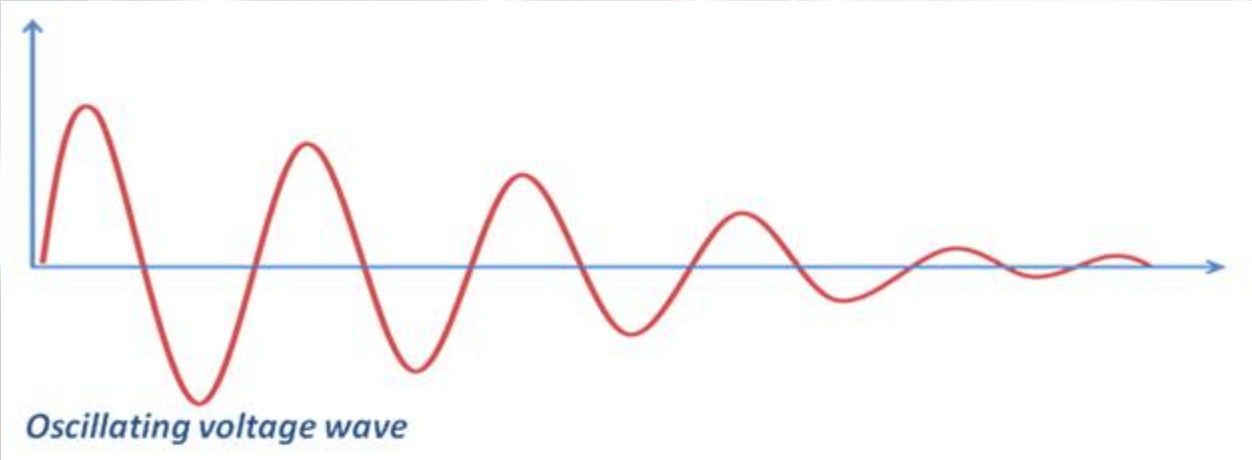
The typical signature of a lighting voltage surge reveals a single short term high frequency spike which decays to zero in as little as one nanosecond (1 billionth of a second!).

Lightning arresters are routinely installed on the transformers to manage transients originating from a lightning event. All arresters do however, have a maximum crest overvoltage rating (MCOV). Unless the electrical system is equipped to manage a surge in excess of the MCOV , the transformer could still be susceptible to damage.

Oscillating – switching



Concerns

Overstressing transformer insulation systems may lead to coil failures

Above is a photo of an actual coil failure caused by a transient voltage surge.

Transformer insulation testing 101

Transient voltage surges vary wildly in magnitude. Designing transformers to handle any and all surges without incident is not practical. IEEE standards general design and testing criteria define the electrical characteristics which each transformer must meet. The most pertinent to this paper are:

C57.12.00 – IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers

Description: Electrical, mechanical, and safety requirements are set forth for liquid-immersed distribution and power transformers, and autotransformers and regulating transformers; single and polyphase, with voltages of 601 V or higher in the highest voltage winding. This standard is a basis for the establishment of performance, limited electrical and mechanical interchange-ability, and safety requirements of equipment described; and for assistance in the proper selection of such equipment. The requirements in this standard apply to all liquid-immersed distribution, power, and regulating transformers except the following: instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, mobile transformers, and mine transformers.

IEEE C57.12.90: Test Code for Liquid-Immersed Distribution, Power, and Regulating Transformers

Description: Methods for performing tests specified in IEEE Std C57.12.00 and other standards applicable to liquid-immersed distribution, power, and regulating transformers are described. Instrument transformers, step-voltage and induction voltage regulators, arc furnace transformers, rectifier transformers, specialty transformers, grounding transformers, and mine transformers are excluded. This standard covers resistance measurements, polarity and phase-relation tests, ratio tests, no-load loss and excitation current measurements, impedance and load loss measurements, dielectric tests, temperature tests, short-circuit tests, audible sound level measurements, and calculated data.

C57.98-1993 – IEEE Guide for Transformer Impulse Tests

Description: Transformer connections, test methods, circuit configurations, and failure analysis of lightning impulse and switching impulse testing of power transformers are addressed in this

IEEE standard. This guide is also generally applicable to distribution and instrument transformers.

There are 3 standard insulation tests for liquid filled distribution and power transformers:

Hipot (also known as dielectric withstand voltage test):

A test voltage as specified by standards is applied to the primary windings with the secondary windings grounded while monitoring the resulting leakage current. The test is repeated with the voltage applied to the low voltage windings with the high voltage windings grounded. The voltage is maintained for 60 seconds. The maximum allowable leakage current is defined by standards. This is non-destructive test and is required to be performed as a 100% production line test.

Induced Potential Test:

This test is used to test the integrity of the transformer's electrical insulation. It tests the insulation of the individual windings of the transformer by applying voltages higher than rated potential between turns, layers and phases.

The induced voltage test is applied for 7200 cycles or 60 seconds whichever is shorter. The voltage applied is twice the operating voltage. Transformer core designs are such that they reach saturation slightly above rated frequency and voltage. This is done to provide high efficiencies while minimizing core material costs. To apply the required induced voltage level it is necessary therefore to utilize a higher frequency source since inductance and frequency are inversely proportional. Applying a higher frequency voltage enables the required potential to be applied without core saturation.

Impulse Test:

Impulse test requirements are necessary to simulate the occurrence of lighting and/or switching surges impressed on the transformer. ***Given the topic of this paper, this test is therefore the most pertinent.***

Impulse generator

An impulse generator is an electrical apparatus which produces very short high-voltage surges. High impulse voltages are used to test the dielectric strength of electric power equipment against lightning and switching surges.

The generator is made up of a multiple of capacitors arranged such that they can be charged in parallel to a specific voltage level, then discharged in series so as to produce an additive voltage equal to the required test voltage.

The IEEE standards detail the test values to be applied to the transformer for lightning impulse and chopped waves. These tests simulate transient surges that the transformer must be able to withstand in the field.

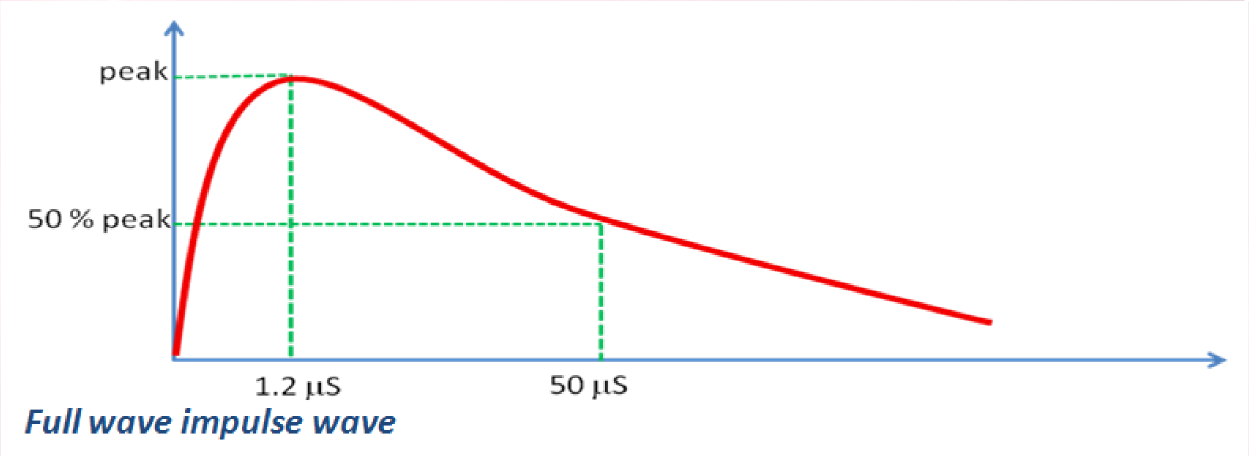
IEEE Std PC57.12.00-200x
IEEE STANDARD FOR STANDARD GENERAL REQUIREMENTS FOR LIQUID-IMMERSED DISTRIBUTION, POWER, AND REGULATING TRANSFORMERS

Table 6: High Frequency Test Tables

Lightning Impulse (BIL)	Chopped Wave			Switching Impulse
	kV Crest	Min. Time to Flashover, µs		
kV Crest, 1.2x50 µs	1.1 X BIL	Class I & Dist	Class II	kV Crest, 0.83 X BIL
Col 1	Col 2	Col 3	Col 4	Col 5
30	33	1.0	2.0	See Note
45	50	1.5	2.0	See Note
60	66	1.5	2.0	50
75	83	1.5	2.0	62
95	105	1.8	2.0	79
110	120	2.0	2.0	92
125	138	2.3	2.3	104
150	165	3.0	3.0	125
200	220	3.0	3.0	166
250	275	3.0	3.0	208
350	385	3.0	3.0	291
450	495	N/A	3.0	375

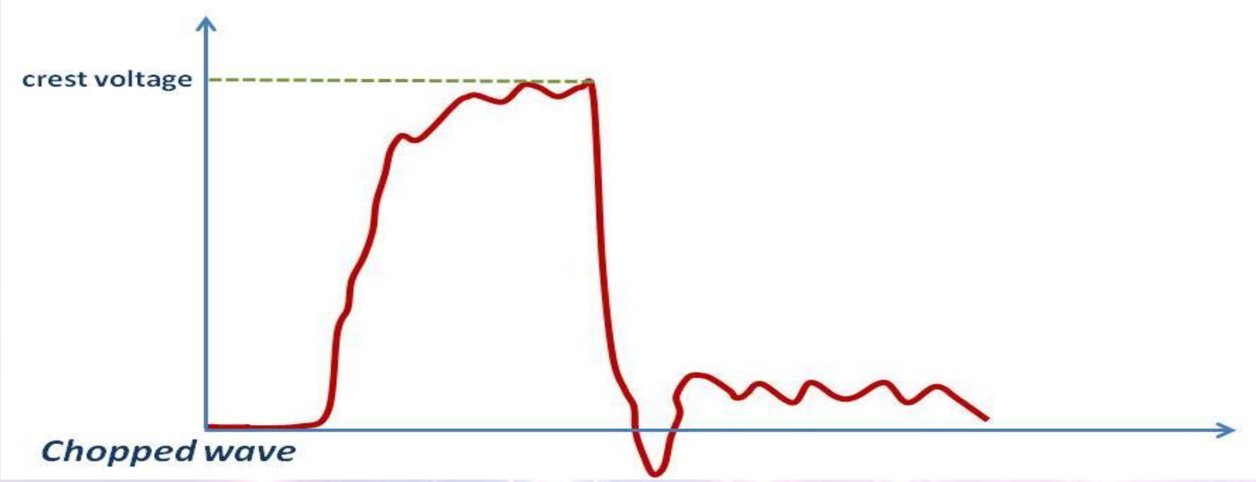
Notes: 1) Switching impulse tests are not always possible for low voltage windings
2)Class I power transformers include power transformers with high-voltage windings of 69 kV and below
3) Class II power transformers include power transformers with high-voltage windings from 115 kV through 765 kV

A full wave (lightning impulse) represents a disturbance that occurs some distance from the transformer and travels along the transmission line to the transformer. Note the similarity to the impulse lightning wave earlier in this paper.



By standards, the full wave impulse test wave must be “1.2 x 50 µs” meaning that the voltage must rise to the BIL rating (for example 95kV for 15 kV class) within 1.2 microseconds and must not decay by more than 50% within 50 microseconds (see above table 6).

The chopped wave represents a traveling wave created by a disturbance that occurs some distance from the transformer that flashes to ground near the transformer terminals.



This is determined by using impulse waves that are of the same shape as that of the BIL waveform, with the exception that the wave is chopped after 3 microseconds. Generally, it is assumed that the chopped Wave Level is 1.15 times the BIL level.

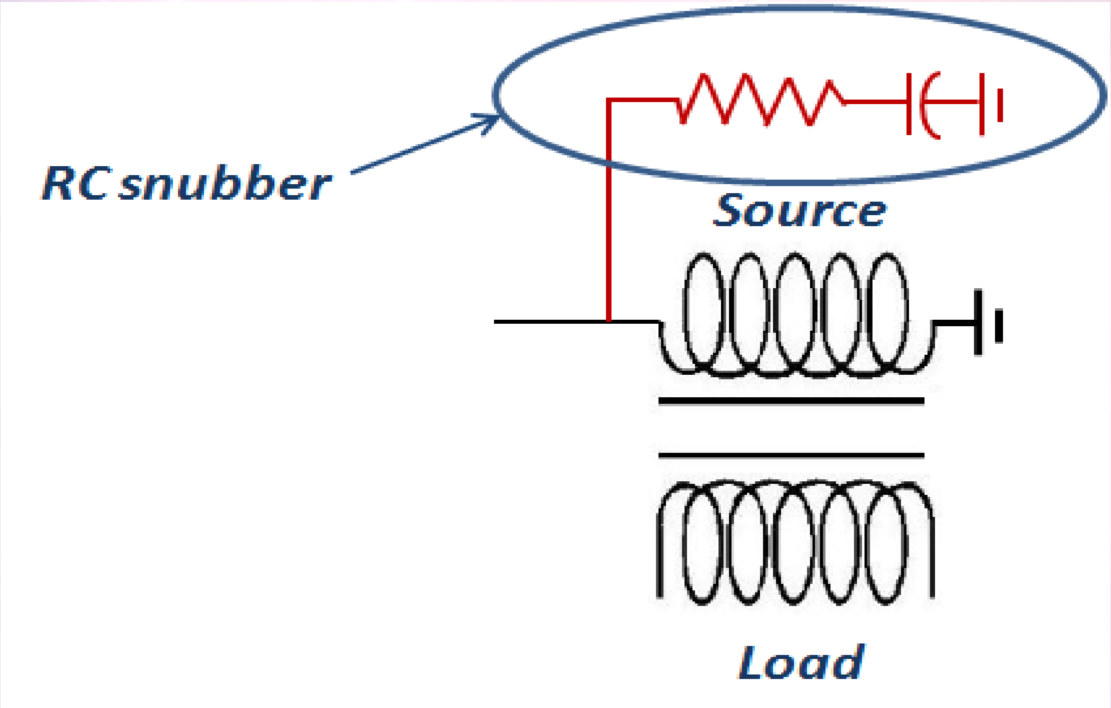
Mitigation

Transformers are designed and tested per applicable standards as modified by provided specifications. As mentioned earlier, it is not realistic to expect that a transformer be able to handle all possible fault conditions. Therefore protective products such as fuses and lighting arresters are routinely provided. To further protest the transformer, additional equipment needs to be designed and provided for the specific installation

There are several ways to reduce the effects of lightning strikes and switching transients, including transformer-winding design and series inductors. A very effective approach is the addition of a snubber circuit.

A snubber is a resistor-capacitor (RC) network that is designed for the specific system. At many installations that use medium-voltage switching, transformer damage is often attributed to lighting. However, this damage is likely caused by transients induced by switching. In a facility with on-site power generation and switching at medium-voltage levels, a power outage results in either a transfer between power sources or a transfer to the generators. The result could induce a transient that could damage the transformer. The addition of a snubber network can provide additional protection against damage.

The RC-snubber network lowers the frequency of the transient voltage applied to the transformer primary below the resonance frequency of the circuit. It reduces the development of the oscillatory voltages and provides a low impedance path to ground for the transients.



The above schematic depicts the addition of a snubber in its' basic form. It is routinely added to the primary circuit, but in some installations a snubber may also prove to be beneficial on the low voltage side of the transformer.

Snubber circuits are not "shelf items". ***They are designed for specific installations and require field electrical measurements by a qualified field engineer***. Ping tests are routinely made which allow for field simulation of transient faults on installed electrical equipment. Such testing reveals the required value levels for the resistors and capacitors to be used in the snubber.

Conclusion

Distribution and power transformers are essential links in all transmission and distribution systems. They are extremely dependable and require minimum maintenance. Compliance to applicable IEEE standards insures that the products meet stringent manufacturing and testing requirements.

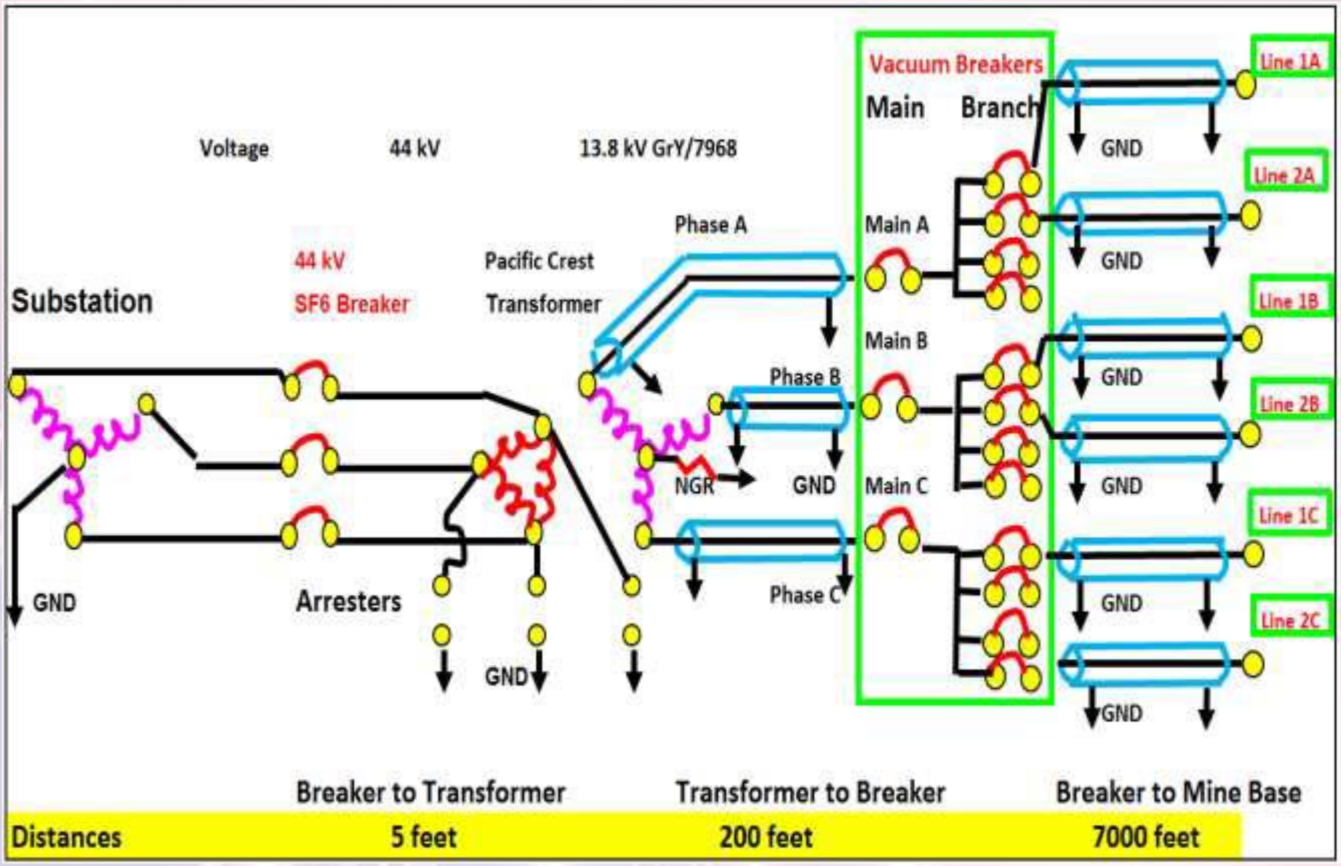
IEEE standard C57.12.90 details the routine and type tests that the transformers must meet. Products built to this standard will operate reliably in the field within “normal” environments. There are however, situations where field conditions will exceed the insulation levels of the transformers which could lead to field failures. To provide insurance against such possibilities, one should insure though field testing, that proper protection against transients is provided.

The object of this paper is to provide a ***basic*** understanding of the impact that transient voltage surges can have on distribution and power class transformers. It is important that one grasp these fundamentals in order to realize the importance that proper transformer protection plays in the installation and operation of a solid, dependable power distribution system. To further promote this knowledge, I have included excepts from a recent field service project involving 2 each 10,000 kVA substation power class transformers that had failed within weeks of being energized.

The following data shows the layout of the substation and demonstrates, through analysis, the parameters that existed which cumulatively led to a breakdown in the transformer insulation systems. It also reveals the expertise required to effectively analyze such an installation in order to ascertain the required resistance, capacitance, and inductance values necessary to design and install the appropriate snubber circuits to alleviate future disturbances.

The work was performed by Philip Hopkinson of HVOLT Inc. who was retained by Pacific Crest Transformers to visit the installation site, meet with the customer, and perform the necessary field inspections. His investigation uncovered the system conditions that led to the transformer failures and provided the data necessary to configure the appropriate snubber circuits. I have included Phil’s contact information at the end of his report.

Experts from March 19-23, 2012 field service report by Phil Hopkinson, HVOLT, Inc.



The major components in the field service transformer system

- Possible causes of failure

This is an unusual type of failure that rarely occurs in transformers that are well designed and are able to pass the IEEE Test requirements of IEEE C57.12.00 and C57.12.90. This transformer was designed to meet the Class I Power Transformer requirements that are rigorous and have a long history of excellent field performance. The station class arresters on the transformer have protective characteristics that keep normal voltage transients to within 50% of the 250 kV BIL rating of the transformer.

- Transformer Factory Tests

Both of the transformers were tested successfully at the factory to all of the requirements of Class I Power Transformers. Although not required by standards for Class I Power Transformers, Pacific Crest conducted impulse tests at the full 250 kV BIL rating prior to shipment.

- . Analysis of Potential for Resonances

Resonance inductive-capacitive circuits are conditions in which the inductive impedance at the resonant frequency is 180 degrees out of phase with the capacitive component impedance. The frequency where this occurs is called the resonant frequency.

1. Parallel resonance occurs when the inductance and capacitance are connected in parallel. In this type of circuit, resonance becomes a condition when impedance becomes infinite if there is no resistance, and current effectively drops to zero.

2. Series resonance occurs when the inductive and capacitive elements are connected in series, and when the sum of the two elements equals zero impedance. When this zero impedance condition exists, current increases dramatically and voltage across each element heads toward infinity. Clearly the series resonant circuit is the worst case. Look at the equivalent single phase transformer circuit in the figure 2 below:

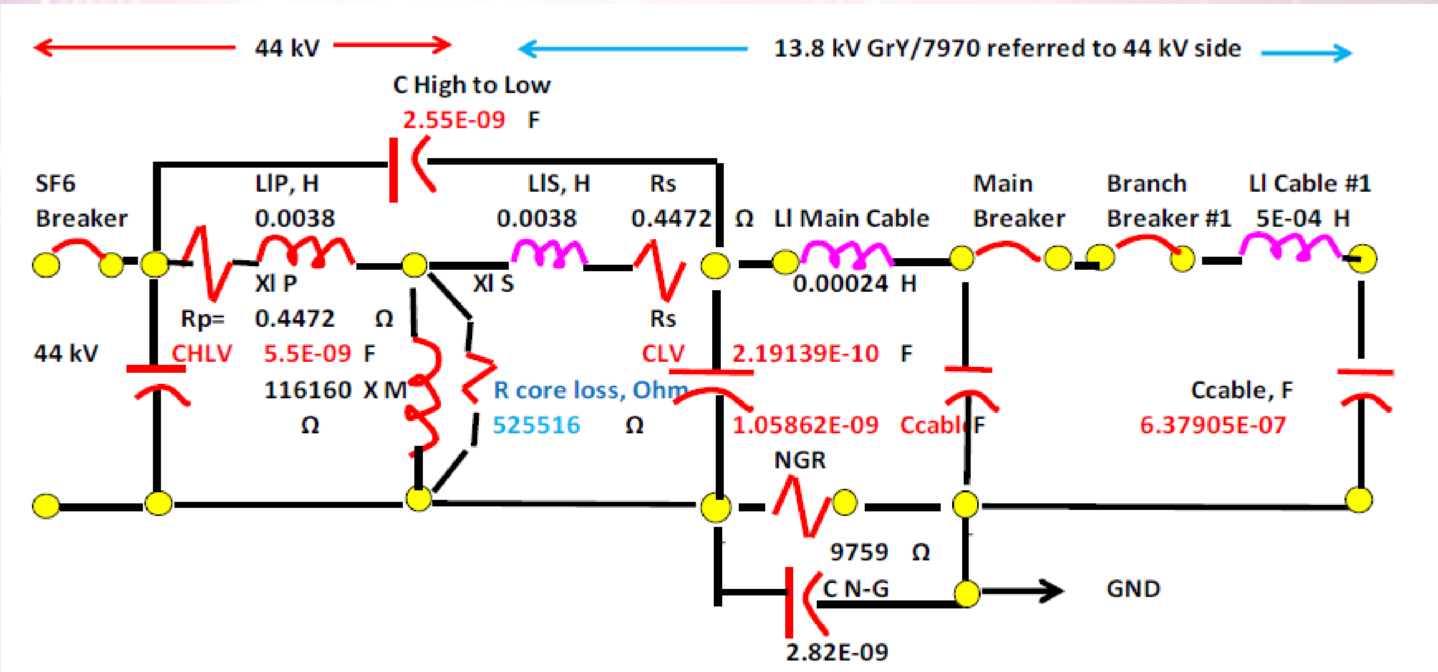


Figure 2: The single phase equivalent circuit of the transformer circuit

Note that there are multiple inductances and capacitances in the circuit. However, an extremely important series circuit exists between the leakage inductances of the transformer, additive to the leakage inductance in the 13,800 volt cable between the transformer and the Main Breaker to the shunt capacitances in the low voltage winding of the transformer in parallel with the shunt capacitance of the same transformer to main breaker cable. Table 2 below summarizes the parameters:

Table 2: Summary of Parameters				
Transformer without cables			**Transformer with cables**	
Transformer leakage inductance, H	0.0076		Transformer +Cable inductance, H	0.0079
Transformer shunt capacitance, F	2.19139E-10		Transformer + Cable capacitance, F	9.26013E-10
Resonant Frequency, HZ	**34640**		**Main Resonant Frequency, Hz**	**31458**
Surge impedance, ohm	5897		Surge impedance, ohm	2913
Surge current, amps	**7.5**		**Surge current, amps**	**15.1**
60 Hz steady state excitation, amp	0.38		60 Hz steady state excitation, amp	0.40
Damaging transients	Maybe		Damaging Transients	Maybe
			Resonant frequency on 7000 ft. cable, Hz	35074

The resonant frequency clearly is the point where many bad voltages and currents occur. This transformer with either of the combinations of 13,800 volt cables either in or switched in and out appears to be right in the range of serious resonances.

- Importance of the 13.8 kV shielded cable

Figure 2 and table 2 are significant in pointing out the importance of shielded cables in influencing system resonances and reflections. The short 200 feet of cable between the transformer and the control room has both reduced the main resonant frequency as well as introduced a very high frequency in the mega Hz range. This combination is potentially extremely damaging if the circuit is able to be excited with any of the resonant components.

- A look at the SF6 Breaker

SF6 breakers are extremely efficient interrupters as are vacuum circuit breakers. When the contacts are separated in either type of breaker, the interrupting chamber is a powerful insulator, and is easily able to interrupt small current flows prior to natural current zeros. This capability to interrupt early is attributed to a low plasma intensity that becomes unstable and extinguishes abruptly, sometimes in nanoseconds. This abrupt current interruption is called current chopping and can occur in vacuum breakers up to around 6 amps and in SF6 breakers up to 17 amps. Following such interruptions in highly inductive circuits, fast rising transient recovery voltages and reignition transients will occur. Common measurements of commutation frequencies have shown beat frequencies in the 50 kHz range. Discussions with Siemens Breaker engineering has suggested that 30-40 kHz frequencies could be expected if the currents in the circuit are able to rise above a few amps. Clearly the transformer with permanently connected 13.8 kV cables is in the range and different from the transformer alone with totally open circuited.

- Presence of the Neutral Grounding Resistor

The NGR has a resistance of 320 ohms on the 13,800 volt side of the transformer or 9759 ohms on the 44,000 volt side of the transformer. A close look at figure 25 will show that the NGR should have introduced some damping on the 13,800 volt neutral circuit. Winding failures with the NGR in place appears to suggest that damping on the 13,800 volt side of the transformer may not be able to protect the transformer.

- Summary of findings

After examining the transformer routine tests that were successfully conducted, the transformer teardown photos of S/N PQH-0181, the installation, inputs from circuit breaker experts, and the circuit parameters, it is my opinion that the Pacific Crest Transformers were not defective as shipped and received but were placed into damaging circuits at the installation and damaged by current chops, reignition transients, and circuit resonance. The extremely efficient magnetic core that is a result of the 7 step lap miter core has very little damping capability during switching. The energy efficient copper windings with low current densities are unable to provide damping either. In all likelihood, presence of the 13,800 volt cables with very low losses has worsened the damping and increased the current such that restrikes and reignitions are more harmful to the windings of the transformer.

- Recommendations

The circuit is complex with SF6 44 kV breakers, capable of injecting damaging transients into the 44 kV circuit as well as 13.8 kV vacuum breakers capable of introducing damaging transients on the 13.8 kV side. Both the 44 kV and 13.8 kV breakers open and close on the highly inductive transformer circuit containing very low damping which can result in destructive currents within the transformer. These circuits will continue to damage transformers unless sufficient damping is introduced. HVOLT Inc. regularly designs Resistor-Capacitor Snubbers, which dissipate and conduct high frequency energy to ground. In most of the transformer circuits, the snubbers are placed on the source side of the transformer. Sometimes the snubbers are placed on the low voltage side when there is clear indication that the low voltage side is responsible for failures. This transformer has a neutral grounding resistor on the low voltage side which would seem to add some protection to the low voltage such that low voltage snubbers would not be required. My experience with resistor capacitor snubbers has been especially successful to date with no failures reported over the 17 years of such use. Part of the reason for success is in the matched components that have been employed. However, a second part is attributed to ping testing where uncertainty exists. The Goldcorp case is complex with some uncertainties remaining. In this case I recommend the following:

1. I recommend that resistor-capacitor snubbers for the 44 kV side of the transformer be designed and installed. These snubbers should be successful in protecting the 44 kV windings. HVOLT Inc. can provide this service if you so desire.

2. I recommend that the snubbers be installed on both of the transformers that will be employed in similar circuits prior to any future switching.

3. I do not believe that snubbers will be required on the 13.8 kV side of the transformer as long as they are well designed and mounted on the high voltage side. The primary reason for this opinion is because the winding failures to date have both occurred in the high voltage windings.

4. Follow-up Ping Tests can be conducted, if desired to verify the elimination of damaging transients in each side of the transformer. Ping Testing requires on-site testing with a high speed oscilloscope, dc power supplies, voltage dividers, spark gaps to protect the transformer, and 2-3 days of testing for each of the switching types that can be envisioned. Successful tests occur when 100% of the reignition transients are eliminated.

5. In the event that failures do occur in the 13.8 kV windings or that ping tests are conducted and show 13.8 kV side susceptibility, then snubbers can easily be added to the transformer as well. The low voltage side snubbers will be different than the high voltage side snubbers. HVOLT Inc. will again be glad to assist if you so desire.

PACIFIC CREST TRANSFORMERS

Phil Hopkinson is an IEEE Life Fellow and long service Transformer Engineer. He received his BS in EE from Worcester Polytechnic Institute in 1966. He also graduated from GE's Advanced Engineering Course in 1970 and simultaneously received his MS in System Science (EE) from Brooklyn Polytechnic Institute. From 1966 to 2002, Phil held numerous design and engineering management assignments in the transformer businesses of GE, Cooper Power Systems and Square D Co in liquid filled, dry, and cast resin transformers of all power ratings and voltage classes. In 2001, Phil formed a power transformer consulting company, called HVOLT Inc. and since 2002 has managed HVOLT full time. He currently holds 15 US patents, is a Registered Professional Engineer in North Carolina, and is Technical Advisor (TA) to the US National Committee for IEC TC14 for Power Transformers and past TA for IEC TC 96. He has authored IEEE Transactions papers on the effects of DBPC in Transformer Oil, on Low Voltage surge phenomena in Distribution Transformer windings, panel sessions on Natural Ester Fluids at the 2006 IEEE Transmission and Distribution Meeting and the 2009 IEEE PES General Meeting, lead a panel session on High Voltage Bushing Failures at the IEEE 2010 General Meeting, has Chaired NEMA's activities and was primary author of NEMA TP-1 Guide for Energy Efficiency for Distribution Transformers. He has conducted seminars on Circuit Breaker Switching and Transformer Interaction at the

IEEE Transformers Committee in 2003 and 2007, the DOBLE International Conference in 2006, and has investigated numerous transformer failure incidents related to switching. He has chaired many IEEE and NEMA Working Groups and is heavily involved with US Energy Policy at the IEEE USA Committee and the IEEE PES

Policy Development Coordinating Committee. An important accomplishment was the issuance of the IEEE Power and Energy Society Policy on Energy and Environment (adopted by the Board of Governors in 2007) and the IEEE USA policy on Energy and the Environment issued in 2009. Phil continues to work closely with NEMA, the transformer manufacturers across the industry and the US Department of Energy on new definitions for energy efficient transformers. He also works with IEEE and the IEC to harmonize power and distribution transformer standards toward the improvement of global trade with fewer trade barriers.

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