A Guide To Describe The Occurrence and Mitigation Of Switching Transients Induced By Transformer And ~~Breaker~~ Switching Device Interaction

1.0 Overview

1.1 Scope

This Guide addresses the application of transformers in the presence of oscillatory switching transients. These oscillatory transients are typically produced by the interaction of the ~~breaker~~switching device, transformer, load, and system. This Guide defines operating conditions that may produce switching voltages damaging to the transformers insulation system. It discusses the electrical characteristics of the system source, ~~breaker~~switching device, transformer, and load and the nature of their transient interaction. It outlines several mitigation methods. Two examples are included.

This Guide recognizes that many devices and/or system operations, in addition to ~~breaker~~switching devices~~s~~, can produce the oscillatory transient waveforms addressed in this guide. The focus of this Guide is on the transformer-~~breaker~~ switching device interaction as a result of several reports of transformer internal winding failures.

This guide focuses only on mechanical switching devices and do not cover semiconductor switching devices.

1.2 Purpose

When a transformer is switched into or out of a system, the transient voltage produced at the terminals of the transformer may contain a high frequency oscillatory component. When this oscillatory terminal voltage has a frequency component near one of the natural frequencies of the transformer and is of sufficient magnitude and duration, permanent damage to the transformer internal insulation structure may result.

The purpose of this Guide is to provide aid in the recognition of conditions and applications where transformers are subjected to terminal oscillatory switching transients that may produce internal winding voltages damaging to their internal insulation structure. This will be accomplished by developing necessary expressions that characterize this interaction. This guide will also characterize the transformer, ~~breaker or interrupting device~~switching device, system, and load during this type of event. Screening methods will be presented which help to determine if a potential concern exists. Finally, several mitigation methods are outlined.

1. 3 Overview

Recent attention has focused on the transient voltage interaction of ~~the~~ a switching~~breaker~~ device and transformers due to a number of transformer internal winding failure reports. The conditions causing the event ~~is~~ are of considerable practical interest because the transformers that failed had passed all standard induced, high potential, and impulse voltage tests called out in ~~the~~ transformer standards. Additionally, these transformers were further protected with lightning arresters. It is appreciated that this phenomena is not limited to transformers but any device containing a resonant characteristic, e.g., shunt reactors, motors and generators are vulnerable. It has been understood for some time that switching events can generate transient voltages on the terminals of the transformer~~ that are of both aperiodic and oscillatory form~~. These transients voltages can be damped, oscillatory, triangular or exponential and can occur as a combination of these forms. Generally, these transient voltages ~~of oscillatory form~~ are~~ of a lower magnitude than the aperiodic waves and normally~~ below the arresters maximum ~~continuous operating voltage (MCOV)~~protective levels. Because of this, it was felt that these ~~oscillatory~~ wave forms could not produce any damage to the insulation structure of the transformer. However, even with a much lower magnitude these oscillatory switching voltages have the potential to produce very large internal voltages if the oscillatory frequency is near one of the winding natural ~~frequency~~frequencies. These facts were brought to the attention of the industry in a paper by Musil, et al.[11] The authors suggest that the internal transformer insulation may well be overstressed when an oscillatory voltage is applied at the winding terminal, even if the voltage magnitude is below the surge arrester protective level.

This situation was brought to the attention of the IEEE PES Transformers Committee and the Working Group on Switching Transients Induced by Transformer/Breaker Interaction was formed. This application guide is the product of the work of this group.

1. 4 Definitions

1. Transient Recovery Voltage (TRV). The voltage transient that occurs across the terminals of a pole of a switching device upon interruption of the current.

2. Terminal Voltage. The voltage appearing between the excited terminal of the transformer and ground.

3. Resonance. The enhancement of the response of a physical system to a periodic excitation when the excitation frequency is equal to a natural frequency of the system. When a component is excited with an oscillatory excitation and that excitation coincides with ~~the~~ one of the natural frequencies of the transformer a condition of resonance is encountered.

4. Re-ignition. A resumption of current between the contacts ~~(poles)~~ of a switching device during an opening ~~-~~operation after an interval ~~of~~ following zero current of less than ¼ cycle at normal frequency. ~~If a switch breaks down and current conduction is re-established within half a cycle of current interruption. If the breakdown occurs later it is called a restrike.~~

NOTE: re-ignitions are normal part of the interrupting process. Usually they cannot be avoided when contacts separation in the switching device happens close to a current zero. They are avoided only in case of slow rising TRVs (capacitive loads), with resistive loads or if controlled switching is used (see 8.2).

5 Restrike: A resumption of current between the contacts of a switching device during an opening operation after an interval of zero current of ¼ cycle at normal frequency or longer.

~~5~~6. Current .Chopping. Phenomenon where the current is forced to zero prior to its natural zero crossing by the complex interaction of the arc within the switching device and its parallel capacitances.

Note: This phenomenon creates a negatively damped oscillation causing the current to be interrupted prior to current zero. Part of the instability is caused by the cooling mechanism of the switching device. Current chopping is not solely caused by the switching device but from an interaction between the system and the switching device. Also observe that the theory does not apply to vacuum switchgear.~~When an arc suppression device in the circuit breaker drives the current to zero abruptly and prematurely ahead of a normal current zero.~~

~~6~~7. Snubber. ~~A device composed of a series combination of a surge capacitor, resistor, and fuse used to reduce the magnitude and frequency or the transient recovery voltage and terminal voltage.~~ A device composed of a combination of a capacitor and a resistor to reduce the magnitude and frequency of the transformer transient terminal voltage. A snubber circuit may include a fuse for protection.

~~7~~8. Natural Frequencies. The frequencies at which the circuit will oscillate if it is free to do so. These are the frequencies of energy interchange between the capacitances and inductances of a system. These frequencies are determined by the system of interest alone and are independent of the event causing the transient.

~~8~~9. Power Factor. The ratio of total watts to the total root-mean square (R.M.S.) volt-amperes of the load.

10. Synchronized (or controlled) switching: Operation of a switching device in such a manner that the contacts are closed or opened at a predetermined point on a reference voltage or current wave.

2.0 System Configurations of Concern

Systems of concern are those having a ~~breaker~~switching device and transformer in close proximity with the transformer unloaded or very lightly loaded. These system conditions have shown the capability of producing transient voltages at the transformers terminals containing high frequency oscillatory wave forms. When these oscillatory transient terminal voltages are near the transformers natural frequencies, large internal overvoltages may result. Systems that are ungrounded or grounded through a high impedance may also produce voltages of concern.

Winding failures have been reported with ~~breakers~~ switching devices located on either the high or low voltage terminals of the transformer.

Systems that are solidly grounded or effectively grounded with high power factor loads tend not to produce high frequency oscillatory waveforms of sustained duration. Additionally, systems with very large capacitive components between the ~~breaker~~ switching device and transformer tend to produce oscillatory terminal voltages with frequencies below the transformers resonant frequencies and as such tend not to produce high internal voltages.

IEEE C37.010-1999 paragraph 5.17.1 discusses a special consideration for switching transformers noting that power systems, transformers, and breakers form a dynamic system during switching. On occasion this interaction requires some method to mitigate the transient voltages containing high frequencies. ~~C37.06.1-2000, A Guide for High-Voltage Circuit Breakers Rated on a Symmetrical Basis Designated "Definite Purpose for Fast Transient Recovery Voltage Rise Time" address the issue of very fast transient recovery voltages.~~

3.0 Transformer Characteristics

All transformers possess a frequency dependant impedance characteristic. Therefore, the relationship between the voltage applied to the transformer terminals and the voltage developed within a transformer winding is dependent upon the frequency content of the applied voltage wave and the specific impedance characteristic of the transformer. Each unique transformer design has a correspondingly unique impedance versus frequency characteristic. This section of the guide defines commonly encountered terms which are used to describe these frequency sensitive response characteristics. Additionally, the relationship between the voltage at the transformer terminal and within the transformer windings will be outlined.

3.1 Impedance Versus Frequency Characteristics

The steady-state and transient behavior of any transformer, for any applied voltage, is established by the location of the zeros (natural frequencies or eigenvalues) and poles of the impedance function and their respective mode shapes (eigenvalues). The zeros of the terminal impedance function coincide with the natural frequencies of the circuit, by definition. McNutt, et al,(A12) defines terminal resonance as having a condition of terminal current maximum and a terminal impedance minimum. In a physical system there are an infinite number of resonances. Normally only the first three or four are of practical importance. Terminal resonance also corresponds to series resonance.(A13-A15) Terminal anti-resonance is defined as having a condition of terminal current minimum and a terminal impedance maximum.(A12) This is also referred to as parallel resonance.(A13-A15) McNutt, (A12) defines internal resonance as an internal voltage maximum and internal anti-resonance as an internal voltage minimum. There are a number of excellent texts and papers on the theory of resonant response of electrical networks.(A2,A11,A12,,A16,A17) This discussion will not repeat this work but will present only sufficient information to show the influence of resonance on the transient response of windings. The mode shape of a winding is the steady state voltage distribution within the winding when it is excited at one of the natural frequencies.

The natural frequencies and mode shapes of a winding can be determined either by measurements or calculations. Annex B outlines the method for determining the natural frequencies and mode shapes by computing the eigenvalues and eigenvectors of the system matrix, [A]. Other methods are outlined in the references.

Figure 1 in Annex B presents a cross section of a single leg of a three phase transformer that will be used to illustrate the issues at hand. The low voltage is a helical wye 13.8kV/$\sqrt{3}$ rated at 110kV BIL for both the X_1 and X_0 and the high voltage is a 115kV continuous disk delta rated at 450kV BIL for both the H_1 and H_2 terminals. This transformer is rated at 11MVA per phase and has a short circuit impedance of 13.8%. Figure 2 is the computed impedance versus frequency characteristic of the winding looking into terminal with all other terminals grounded. It should be observed in Figure 2 that the impedance shown at 60Hz is 166 ohms and is the short circuit impedance of this transformer. Recalling the definitions of natural frequency it is observed that the first natural frequency is at 7.88kHz, the second at 21.40kHz, the third at 35.84kHz, etc. The frequency response analysis (FRA) is an effort to understand the condition or change of condition of a transformer by analyzing the transformers frequency characteristic, both input impedance and transfer function. The primary objective of FRA is to determine how the impedance of a transformer behaves over a specified range of frequencies. Practically, there are two methods to obtain the frequency response characteristic of a transformer. The first~~,~~ method is to make physical measurements on the physical transformer winding structure. The difficulty with this is that measurements can be susceptible to error, or the location of interest may not be accessible, and that the transformer itself may not always be available. The second~~,~~ method is to model the transformer analytically, for example with an RLC network, and mathematically compute the input impedance and desired transfer functions. Either method properly applied will provide the transformers natural frequencies and damping coefficients.

3.2 Internal Voltage Developed Near Resonance

Figure 3 presents the per unit voltage observed at the center of the disk coil when H_1 is excited with a 1 per unit oscillatory input voltage. When H_1 is excited with 1 per unit voltage at 60 Hz point A will exhibit 0.5 per unit voltage. This is to be expected since point A is in the center of the high voltage winding. However, the voltage observed at point A when the excitation frequency is the first resonance, 7.88 kHz, the voltage at point A is over 100 per unit of the applied voltage. When the excitation frequency is the second natural frequency, 21.40 kHz, the voltage observed at point A is 0.25 per unit (less than the turns ratio) and when the excitation frequency is the third natural frequency, 35.84 kHz, the amplification factor is well over 100.

Figure 4 presents the voltage amplification factor observed at the ¾ point of the disk, shown in Figure 1 at point B when H_1 is excited with 1 per unit voltage.

Figure 5 presents the normalized spacial voltage distribution within the transformer when it is excited with a 1 per unit oscillatory wave form of 60 Hz, 7.88 kHz (first natural frequency), and 21.40 kHz. As expected at 60 Hz the voltage distribution is simply the turns ratio of the winding. At the first natural frequency we see essentially a half cycle sine wave distribution added to the 60 Hz distribution. However, the magnitude of the oscillatory portion is so large compared to the turns ratio distribution that the sine wave portion dominated the voltage distribution within the coil. At the second natural frequency we observe distribution of a full cycle of a sine wave added to that of the turns ration distribution. Again the sine wave portion dominated the distribution. Therefore as the number of natural frequency increases the number of half cycle standing waves on the winding increases at a rate of one half cycle for each frequency, e.g., 1st natural frequency – ½ cycle standing wave; 2nd natural frequency, 1 full cycle standing wave; 3rd natural frequency – 1 ½ cycle standing wave, 4th natural frequency – 2 full cycle standing wave; etc.

What is illustrated in Figure 5 is the relative magnitudes of voltages generated within a winding structure when the excitation voltage is fixed and only the frequency of excitation is varied. It is well known that when a coil or transformer winding is excited at or near its natural frequency, only the winding losses will limit the magnitude of the voltage generated. The damping ratio (R/X) for transformers at 60 Hz is on the order of .01 to .05. For higher frequencies, the damping ratio increases because of the skin effect of transformer winding conductors as well as increased stray losses. This additional natural damping at higher frequencies reduces the amplitude of the internal overvoltages..~~which indicates that the subsequent peaks of an oscillatory wave are 1 to .94 and 1 to .74, respectively.~~

3.3 Insulation Integrity Under High Frequency Voltage Stress

Figure 6 presents the experimentally verified log-log relationship between voltage applied and time to failure for a paper oil system subjected to a sine wave excitation. In a paper by Kaufman, [reference A22], the slope m of this curve was stated to be between 15 and 30, with 25 suggested as most typical for the systems used in power transformers. The form or relationship of this curve is valid not only for oil-paper systems, but also for most insulation systems in general. Therefore, by using the one hour induced voltage test to establish a voltage and time, and selecting an appropriate slope (m) for a class of insulation, it is possible to generate a straight line (when plotted log -log) through this point (defined by the one hour induced voltage test) and back toward the switching impulse surge time of 300 ~~µs~~µs~~econds~~ such that a reasonable representation of the transformer insulation characteristic at low frequency in the region of 1000 to 10,000 ~~µs~~µs~~econds~~ can be established. Figure 7 is a plot combining the transformer volt-time insulation characteristic used in Figure 3 of C62.2 for aperiodic wave forms and the volt-time characteristic for sine waves shown in Figure 6 with a slope of 25. The consistency between the two curves is quite good and suggests that the region prior to the BSL point at 300 ~~µs~~µs~~econds~~ can be represented as a sloped line consistent with the sine wave characteristic. To establish the time shown in Figure 7 one would use the time the applied voltage is above 90% of its peak multiplied by the number of cycles in the terminal transient voltage. Clearly, this is a very approximate approach but provides an order of magnitude for the windings insulation capability. In most instances if a winding is excited near resonance, the internal oscillatory voltage produced is the dominant voltage component.

For all type of applications (even indoor applications), ~~A~~a~~n~~ surge arrester ~~is normally~~should be ~~placed~~ connected directly to the transformer primary terminals to provide protection~~directly in front of the transformer to afford it protection~~ from transient voltages produced on the system. Curve E on Figure 7 is a metal oxide arrester protective curve established in a manner similar to that described in IEEE standard C62.2. The protective ratio is established by dividing the transformer insulation capability by the arrester protection level for the wave shape of interest. For example in Figure 7 the protective ~~level~~ ratio for a switching surge is on the order of 177 % or (0.83/0.47)~~X100~~x100.

What is of issue now is to compare the ability of a winding to withstand a standard full wave to that of its ability to withstand the voltages produced by a terminal voltage of oscillatory wave form. Figure 8a contains a plot of a standard 450kV BIL full wave *(NOTE to Bob: Figure 8a the scale needs to be changed since this not a 450 kV BIL but a 45 kV BIL, make the necessary changes in figure 8a)* and an oscillatory waveform at the first natural frequency, 7.88kHz, where the peak magnitude of oscillatory wave has been constrained to 0.37 p.u. of the full wave peak (or just slightly under the arrester cut off voltage for an arrester normally used to protect a 450kV BIL transformer). Figure 8b compared the response of the disk winding center to ground for these two applied voltage waveforms. The first is a standard full wave voltage impulse test given in the factory and the second could be anticipated in a situation where a ~~breaker~~switching device would re-ignite a number of times. The factory full wave impulse voltage test corresponds to Curve A on Figure 7 at 3 ~~microseconds~~ µs and could be interpreted that if a voltage was generated to this level it would produce one failure in approximately 1000 applications of a 100% voltage full wave impulse. If the full wave impulse voltage were approximately 30% higher (3 ~~microseconds~~ µs on Curve B) one would anticipate one failure in every two applications. When the transformer is protected in a field application by an arrester the voltage seen by the transformer will be much less and for this particular example less than 50% of the full wave impulse voltage design value (~~for this example~~typical protective margin for systems rated 145 kV and below) and the failure rate due to the voltages produced by a lightning surge ~~the full wave~~ within the winding structure will be miniscule. For higher system voltages the protective margin is normally much lower and can be as low as 27% for 800 kV systems. For special applications like Static Var compensators or HVDC substations, the protective margin can be as low as 20%.

Alternately, when an oscillatory voltage near resonance is applied to the transformer winding it is possible to generate large internal overvoltages even if the applied voltage is limited by the arrester. Figure 8b shows an example of the computed internal voltage at the disk winding mid-section as a function of time. This voltage is limited only by the internal damping of the winding structure, the load, and the frequency spectrum of the applied wave form. If the frequency is near one of the windings natural frequencies, modest damping, is present and is applied for several cycles, it is anticipated that high internal voltages will be produced. It can been seen that in approximately 6 cycles the oscillatory wave form produces voltage stresses similar to a 100 % full wave impulse voltage and within~~in~~ 10 cycles, the oscillatory excitation produced an overvoltage greater than what one would anticipate the insulation structure would be designed to withstand.

NOTE to Bob: The way that the simulation is described is not realistic of any system conditions. The TRV oscillatory mode is not a constant voltage oscillation but a an exponential decaying sinusoidal excitation and normally last for less than 10 cycles (mainly where the capacitance is low and the frequency high enough). Does the simulation shown in figure 8b) consider an exponential decaying sinusoidal excitation as applied in service condition? I do not know if you can simulate an exponential decaying sinusoidal excitation but this will be more realistic of service conditions.

3.4 Methods to Obtain Required Performance Characteristics

Before the transformer is constructed an estimate of the impedance versus frequency and its internal amplification factors can be obtained by building an analytic model (lumped parameter model) of the transformer. Using this model one can compute its transient response (both terminals and internal) along with its impedance versus frequency characteristic. References A2, A12-A17 contain substantial information about building these predictive models. It should be pointed out that all models are at best an approximation and are limited in accuracy by the assumptions necessary to accomplish their construction. However, even with these constraints one would expect the model to predict the impedance versus frequency characteristic within 10 % up to 500 kHz.

Once the transformer is constructed it is possible to make low voltage transient voltage measurements. Additionally, the impedance versus frequency of a winding can be determined. It is often difficult to determine amplification factors by measurements because the physical location of interest is in general not available for inspection or measurement.

4.0 Supply Characteristics

The source and its transmission system can be represented as a network of inductances and capacitances. The separation between the source and the transformer and ~~breaker~~ switching device of interest and the complexity of that transmission system will determine the complexity of this network equivalent. For a stiff source close to the transformer a single series inductance (representing the source and lines) and a single shunt capacitance to earth (representing the line capacitance) should be adequate. For more complex supply systems, for example an overhead transmission line and cable system, a network of series inductances and shunt capacitances would be constructed to represent these abrupt transitions.

5.0 Load Characteristics

5.1 Loads of Concern

If the transient voltage produced by the system has a~~n~~ significant oscillatory component at a frequency near one of the resonance frequencies of the transformer it may induce voltages within the winding structure that produce stresses greater than the safe operating limit of the transformers insulation structure. It is recognized that in most of the switching related failures one or more of the following conditions exist:

1. The transformer was unloaded or lightly loaded, or,

2. The load was highly capacitive, e.g., connected to the transformer with long cables or ~~smoothing~~ filter capacitors on the secondary, or

3. The load is highly inductive, or,

4. Switching in ungrounded neutral systems.

The switching duty may also be a concern. A frequently switched transformer (e.g. daily switched) has more risks to encounter a problem. It should be recognized that even with some or all of the above conditions present the occurrence of an event that will produce the excessive voltages that cause destructive results can not be predicted with certainty. In each instance detailed analysis is necessary to predict with certainty that a switching event can produce an oscillatory voltage wave form containing a frequency near the resonance and that this will lead to destructively high internal overvoltages.

In general, systems of concern are those having a ~~breaker~~ switching device and transformer in close proximity with the transformer unloaded, very lightly loaded, or heavily loaded with a capacitive or inductive load. These system arrangements have shown the capability of producing transient voltages at the terminal of the transformer containing frequencies much higher than the system nominal frequency and occasionally near one of the resonance frequencies~~y~~ of the transformer. System neutrals ~~s~~ that are ungrounded or grounded through a high impedance may also produce overvoltages of concern.

Systems that have produced winding failures have had the ~~breaker~~switching devices located on either the high or low voltage terminals. Switching operations on the load side of the transformer could also induce failures in the primary side of the transformer.

5.2 Loads of Less Concern

Systems that are normally not of concern are those ~~that are~~ having their neutral solidly grounded or effectively grounded and connected to high power factor loads. These systems may produce transient voltages at the terminal of the transformer, of a large magnitude and appropriate frequency, but the load provides substantial damping and the transient decays rapidly.

Additionally, systems with ~~very~~ relatively large capacitive components between the ~~breaker~~switching device and transformer ~~will not generally exhibit the breaker re-ignition and~~ are generally not of concern. In this situation the capacitance will tend to lower the frequency of the transformer terminal transient voltage and produce the same effect as a snubber capacitor.

6.0 ~~Circuit Breaker~~Switching Device Characteristics

Switchgear is the general term covering switching and interrupting devices. Switchgear performs two important but different functions. The first is to perform routine switching operations such as disconnecting or isolating apparatus for a variety of system requirements. The second is to interrupt current flow under abnormal or fault conditions to prevent excessive damage ~~or~~ and to confine difficulty to the smallest part of a system. ~~Circuit breakers~~Switching devices are ~~switchgear~~ capable of not only interrupting normal load and fault currents but are also capable of reestablishing the connection within the ~~circuit~~ system very quickly. Therefore, the function of a ~~circuit breaker~~switching device ~~-~~is both of opening and closing a circuit.

When a ~~circuit breaker~~switching device interrupts the flow of current several basic activities are involved. The first is the mechanical separation of the ~~breaker~~ contacts. This mechanical separation of the ~~breaker conducting~~ contacts establishes an arc since this mechanical separation would not normally ~~taking~~ take place at precisely a current zero. This arc will remain until the load or fault current passes through a normally occurring current zero. All alternating current switching devices~~ac circuit breakers~~ take advantage of these naturally occurring current zeros to interrupt the normal flow of current. When the flow of current stops a transient recovery voltage will appear ~~between~~ across the ~~breaker~~ switching device ~~poles~~terminals. This voltage is referred to as the transient recovery voltage (TRV) and its shape and magnitude are determined by the system characteristics within which the ~~breaker~~switching device is located. The increase of distance between contacts and other processes are used~~Normally some process or mechanism is used~~ to increase the dielectric strength between the contacts to ensure that the dielectric strength between ~~the pole faces~~ the terminals increases faster than the build up of the transient recovery voltage.

There are several methods for interrupting current and the most effective method will depend upon the ~~circuit~~ system ~~voltage and current~~application. Air, oil, SF_6 (~~Sulfer~~ Sulfur Hexafluoride), and vacuum are all ~~dielectrics~~ interrupting media commonly used in commercial switchgear. Vacuum and SF_6 ~~SF breakers~~ switching devices are used today, routinely, at medium voltages. For high voltage applications, the SF_6 circuit breaker is the most predominant technology offered today. ~~and appear to~~ All these technologies may exhibit (depending of the interaction with system parameters) ~~the most~~ potential for premature current interruption (current chopping) and/ or re-ignition which can produce an additional oscillatory voltage on the transformer terminals.

6.1 Volt-Time Profile as a Function of ~~Breaker~~ Switching Device

A ~~high~~ transient recovery voltage is impressed across the ~~circuit breaker~~switching device contacts when it interrupts the flow of current. If this transient recovery voltage exceeds the dynamic dielectric withstand capability of the switching device contact gap ~~between the breaker contacts~~ a re-ignition or restrike ~~may~~ occurs. This re-ignition or restrike will allow current to flow again until the dynamic dielectric withstand capability of the switching device is sufficient, in some cases multiple re-ignitions or restrikes may occur. This current will have a power frequency component and a component of much higher frequency determined by the ~~circuit~~system components. Multiple re-ignitions or restrikes produce repetitive applications of the oscillatory voltage waveshape to the transformer terminals. Some switching devices are able to interrupt at one of the current zeros of the high frequency current following a re-ignition or a restrike. In such cases, the TRV frequency content is the same but the amplitude of the TRV will be higher since the di/dt of the high frequency current is much higher than the di/dt of the power frequency current. In addition the transformer terminals will be subjected to additional frequencies produce by the repetition rate of the re-ignitions or restrikes.~~This current wave form will often pass through a zero and stop flowing. Once again a high recovery voltage will be impressed across the circuit breaker contacts. This voltage will~~

~~have the form of the previous transient recovery voltage and if it exceeds the withstand capability of the breaker contacts a re-ignition will occur again.~~

There are two major components in this interaction. The first is the transient recovery voltage produced across the ~~breaker~~ switching device contacts when the system current ceases to flow. An example of this is shown in Figure 9. The second is the volt-time profile of the ~~breaker~~ switching device contacts as they part. This is a function of the mechanical design of the ~~breaker~~switching device, the speed of the ~~mechanism~~contact, the ~~dielectric~~ interrupting medium, and the statistical ~~nature~~ dielectric and mechanical behavior of the device. A typical volt-time characteristic of a vacuum circuit breaker is shown ~~for a vacuum breaker~~ in Figure 10 (see reference)..

6.2 Re-ignition

Figure ~~11~~ 12 combines Figure 9 and 10 and illustrates the voltage that can be produced on the terminals of the transformer.

7.0 System Voltage Response

7.1 Transient Recovery Voltage

The system of interest is made up of a source, high side switching device (circuit-breaker)~~breaker~~, transformer, low side switching device (circuit-breaker)~~breaker~~, and the load. Under normal operation the source looks like an inductor and its stray (shunt) capacitance to ground can be ignored. The switching device (circuit-breaker)~~breaker~~ under normal operation looks like a short and the transformer can be represented as if it were an inductor. The load can assume any form depending upon the machine or system being supplied. What is of interest is not the steady state characteristics of the system, but how the system responds to the act of the switching device (circuit-breaker)~~breaker~~ interrupting the circuit (interrupting the current from the supply or energizing the system). In this case each of the components, e.g., source, stray capacitances, transformer, ~~breaker~~ switching device and load must be considered in view of their respective high frequency characteristics. Specifically, what is of interest~~ed~~ is the voltage magnitude and shape applied to the terminals of the transformer when the ~~vacuum~~ switching device~~breaker~~ opens the circuit. Normally the voltage wave form is a damped, exponentially decaying sine wave which is discussed in detail in reference [A2]. Figure ~~12~~ 13 presents a typical lumped parameter model of this type of system arrangement.

In the simplest case the ~~breaker~~ switching device opens separating the system into two parts, the supply side and the load side. On the supply side of the ~~breaker~~ switching device, the voltage will ~~simply~~ be the power frequency voltage superimposed to the TRV associated with the source side characteristics (the source side TRV is normally a small part of the system voltage).~~(at steady state)~~. On the load side terminal of the ~~breaker~~ switching device a transient voltage will be established by the redistribution of the energy trapped in the ~~magnetic structure~~ inductance of the transformer and connecting leads or bus bars, capacitances, and load. The magnitude and the duration of the load side voltage is function of the load characteristics (inductance, capacitance and resistance). If the current is chopped, the amplitude of the transient load terminal voltage is increased for inductive loads (suppression peak overvoltage) and decreased for capacitive load, the load not being charged to the peak of the source voltage. ~~The magnitude of the voltage and its duration depends upon the magnitude of the current chopped by the breaker.~~ Ideally, the interruption takes place at current zero. If this is the case, and the load is purely resistive, only the system voltage and the source side TRV will be seen across the poles of the ~~breaker~~switching device.~~ The breaker will be able to withstand this voltage and the circuit will have been separated without event.~~

If the system is inductive or capacitive, then a TRV of higher magnitude and frequency may be~~will be~~ seen. If this frequency and/or voltage is ~~great~~ high enough it may cause the ~~breaker~~ switching device to re-ignite or to restrike. If the system of interest ~~is~~ has its neutral ungrounded, the TRV amplitude ~~may be~~is

~~substantially~~ larger because of the first-pole-to-clear factor which is greater than 1,0 (typically 1,5) and the risk of having re-ignition or restrike may be increased (A2).

7.2 Post Re-ignition and Subsequent System Voltage

Complex interaction between circuit characteristics and arc behavior of switching devices may cause the current to be interrupted before a normal current zero (current chopping). Typical worst case situations, circuit, transformer and load characteristics interaction with arc quenching, may lead to typical chopped current of less than 5 A for vacuum and SF6 technologies and up to tens of amperes for air-blast switching devices.

~~The modern breaker can be very aggressive when it interrupts. In general, the current will be chopped (in other words the vacuum breaker will cut or chop the current before it passes through a normal current zero). This "chopped" current may be on the order of 1 to 5 amperes.~~ This act of prematurely interrupting the current can leave a substantial amount of energy trapped in the equivalent ~~magnetic structure~~ inductance of the transformer. The resultant energy contained in the ~~magnetic structure~~inductance of the transformer must go somewhere and ~~normally~~ is transferred into the stray capacitances~~ive~~ and magnetic circuit ~~structure~~ of the ~~transformer~~ transformer, ~~and~~ ,adjacent cables and apparatus and system. As discussed before, Figure 9 illustrates a TRV where the current is interrupted at a natural current zero whereas Figure ~~13~~ 12 illustrates the same TRV when a small current is chopped by the ~~breaker~~switching device. The main effect of current chopping is the increase of the TRV peak. ~~This circuit will take on a slightly different form depending upon whether the breaker is on the high or low side of the transformer.~~ The frequency of ~~this~~ the transient voltage is the same whether the current is chopped or not and is a function of the inductance of the transformer and connecting cables or busbars and the ~~shunt~~ stray capacitances of the transformer, a~~and~~ ~~a~~djacent equipment and system. References A2 and A23 list the appropriate equations to determine the frequency of this transient voltage. This transient is always damped and the damping is a function of the high frequency losses in the cables or busbars, transformer, and load. While very interesting (and complex) it does not affect our analysis because we need only be concerned with the initial rate of rise of the transient. The initial rate of rise is a function of the TRV peak voltage and the frequency.

The above discussion assumes that the ~~breaker~~ switching device can withstand the TRV. Switching devices are extensively type tested to prove that they can interrupt fault and load currents with the standardized TRV values associated with the various making and interrupting test duties. If the system TRV exceeds the dynamic dielectric strength (due to the high frequency and/or magnitude of the TRV) of the contact gap of a switching device, a reignition or restrike will occur~~If the voltage increases too quickly (due to the high frequency and/or magnitude of the TRV), the breaker will flashover or re-ignite~~.. Under this condition the voltage across the ~~breaker~~ switching device drops near to zero (an arc voltage is present) and current starts to flow again through the ~~breaker~~switching device. This post re-ignition current is composed of two components. The first is the power frequency current at 60Hz. The second is ~~the~~ an higher frequency current caused by the transfer of energy from the load side capacitances (which may be charged to a high voltage from the energy trapped in the equivalent inductance of the transformer) back to the source side capacitances. This is normally at a much higher frequency than the power frequency (on the order of 50 kHz to ~~500kHz~~1000 kHz). The magnitude of the high frequency current is generally of the same order as the 60Hz component. As such the resultant sum of the 60Hz current and the high frequency current will pass through zero many times ~~based on the high frequency component~~before the natural power frequency current zero. When the current passes through zero (or near zero) the ~~breaker~~switching device ~~wil~~may~~l~~ interrupt again (since it has continued to open mechanically and its dynamic withstand voltage is increasing) or have to wait until the next power frequency current zero ~~(since it has continued to open mechanically and its withstand voltage is increasing)~~. The subsequent current interruption will initiate the process all over again. This sequence will continue until the dynamic dielectric withstand capability of the interrupter contact gap exceeds the applied TRV~~not stop until the breaker builds up a large enough withstand voltage to withstand the TRV~~. This process may take several milli~~-~~seconds and the transformer may be subjected to ~~hundreds~~ several ~~of repetitions of this~~ repetitive chopped voltage waveshape. See Figure ~~11~~ 12 for an example of an interruption with four re-ignitions. It is this resultant voltage waveform (its frequency spectrum and voltage magnitude) that has the potential to do damage within the transformer. Reference [A8] provides an excellent picture of this phenomenon.

The magnitude and frequency of the transformer terminal voltage is caused by the interaction of the ~~breaker~~ switching device dynamic withstand voltage characteristic and the TRV resulting of system parameters. The ~~breaker~~ switching device withstand voltage characteristic is a function of the switching device design and technology (mechanical speed gas pressure, contact material, ~~at which the breaker opens and the materials the pole faces are made from~~and interrupting technology). The TRV is a function of the system parameters (R,L,C) and the possibility of current chopping which again is a function of the ~~breaker~~ switching device characteristics. The resultant voltage produced at the transformer terminal is then a function of the ~~breaker~~ switching device characteristics, (including current chopping behavior) ~~the current it chops~~, and the total system electrical characteristics (~~supply~~source side components, system parameters in between the switching device and the transformer, transformer, and load) ~~electrical characteristics~~. The two major frequencies of interest then are the frequency of the transient recovery voltage (TRV) and the frequency spectrum ~~produced when the breaker has re-ignited~~associated with the re-ignition or restrike repetition rate. References A2 and A23 provide expressions for both of these frequencies.

The important issue is to ensure that the combined effects of the source and load side TRV responses do not produce differential voltage in excess of the dynamic dielectric withstand capabilities of the switching device.~~The "critical" portion of the system action is the actual breaker voltage versus time withstand characteristic.~~ This is shown in Figure 10 as a single sloped line. This characteristic is discussed at length in reference [A9]. Looking at Figure ~~10b~~ 11 (this is Figure 9 of reference [A9]) it is observed, as an example, that ~~the~~a typical MV vacuum breaker will have a voltage withstand capability that can vary between 3 and 15kV as time zero grows to a withstand value between 5 and 60kV in one millisecond depending upon the interrupter contact material and design ~~and~~ together with the statistical behavior of the dynamic voltage withstand and re-ignition border.~~the statistics of the devise.~~ Clearly, this may result in ~~provides~~ a large variability in the performance of the ~~breaker~~switching device. The specific volt-time characteristic of a ~~breaker~~ switching device exhibits on a given interruption ~~is~~ is statistical and should reasonably be expected to vary somewhat in shape and magnitude. As such, the pattern of switching device~~breaker~~ withstand and re-~~strike~~ ignition is a matter of probability along the border delimiting withstand and re-ignition. If the switching device characteristics and systems parameters (TRV) are such that resulting transient voltage applied on transformer terminals may excite one of the resonant frequencies of the transformers.~~With the proper breaker characteristic it is possible to obtain a periodic voltage at the resonant frequency of the transformer.~~

7.3 Transformer Internal Voltage Response

Figures 8a, 9, ~~11~~12, ~~13~~14, ~~17a~~18, and ~~20~~ 21 contains several sketches of the types of transient voltage that would be impressed on transformer terminals. The variables that effect these terminal voltages are ~~the transient recovery voltage characteristic of the breaker (~~the ~~breaker~~ switching device dynamic volt-time characteristic as shown in Figure 10~~)~~, the impedance characteristics of the transformer (as illustrated in Figures 2, 3, 4, 5, ~~18,~~ and 19) and system (as illustrated in Figures ~~12~~ 13 ~~and15~~and16).

For the majority of the time this condition will pose no problem to the transformer in service. This is because the TRV produced and the subsequent re-ignition transients will neither be of a great enough magnitude nor at one of the ~~a~~ resonant frequenc~~y~~ies of the transformer winding. However, the reason for concern is simply that all complex electrical equipment possess impedance versus frequency characteristics, which are not linear. In other words, a voltage of 50% in the center of a winding at 60Hz is to be anticipated, but at higher frequencies the observed voltage may be much lower or (unfortunately) much greater than normal turns ratio voltage. If a transformer (or motor, or reactor~~or capacitor,~~, etc.) were excited by a periodic voltage at one of its resonant frequencies one would expect to see internal voltages develop within the winding structure much greater than those seen during normal operation (or even factory tests). As such these periodic voltages, if near resonance, can produce voltages within the winding structure that will fail a perfectly sound transformer insulation structure designed to withstand production induced and impulse voltage tests.

The saving characteristic in most instances is the sharpness or narrowness of the resonance. Unfortunately, with a statistical ~~breaker~~ switching device dynamic voltage withstand characteristic, delimiting the withstand/re-ignition border, the same ~~breaker~~switching device and transformer can produce a sweep of frequencies and as such increases the probability of having a voltage applied to transformer terminals at a frequency close to or equal to one of the resonant frequencies of the transformer and thus producing internal over-voltages. Additionally, it is quite possible for the transient voltage to last for many cycles (of the high frequency) thereby providing time for the voltage to build within the winding. For the prevailing conditions it is a very real possibility that a voltage of periodic shape of modest magnitude could produce dangerously high internal voltages.

8.0 Mitigation Methods

There are several methods of reducing peak internal voltage response of a transformer when its terminals are subjected to an oscillatory transient voltage. As in most engineering designs, cost and performance are major concerns. As a result often the most cost effective and robust solution for MV voltage applications is a simple R-C snubber. For HV application, controlled switching is generally the most suitable and economical solution.

8.1 Resistor-Capacitor Snubber

This solution is normally limited to MV applications. Snubber networks used for this particular application generally consist of a series connected capacitor (including its parallel discharge resistor), and resistor~~,~~. A fuse may be used for protection. ~~and fuse~~ (see Figure ~~14~~15). The purpose of the capacitor is to ~~make the period of the TRV greater to~~ decrease the frequency of the load side TRV (reduction of the rate-of-rise) in order to reduce the probability ~~number~~ of switching device~~breaker~~ re-ignitions. This will also have the effect of lowering the frequency applied to the transformer terminals. If the modified frequency is then much lower than one of the resonant frequencies of the transformer, this will ~~and~~ effectively remove the problem of high internal voltage amplification. The amount of capacitance needed to accomplish this is generally on the order of 0.25 to 0.50 µF. The exact value needs to be calculated knowing the internal resonant frequencies of the transformer and system parameters. The addition of this capacitance will increase the capacitance of the load system and transformer by approximately two orders of magnitude and therefore reduce the load side ~~high frequency~~ TRV by approximately a factor of 10. This reduction in frequency will ~~effectively~~probably move the applied voltage out of the frequency range of the transformer’s resonance frequencies.

The magnitude of the resistance is not critical but should be on the order of 5 to 25 ohms (normally a resistance value close to the surge impedance of the system is recommended). Too low values may result in TRV amplitude factor exceeding the switching device capabilities. Too high values will result in over-damped TRV but with higher resistor losses. The selection is a balance between ~~damping~~ the resulting amplitude factor (during the transient) and resistor power losses at normal operation. Successful applications have used a time constant, $\tau = 1/RC$ of approximately 10 µs~~econds~~. The purpose of the resistor is first to reduced the amplitude factor of the resulting TRV (without resistor, the amplitude factor would be close to 2.0 since the snubber capacitance is much higher than transformer stray capacitances) and to reduce the inrush transient current when the system is energized. The resistance must be of the non-inductive type, and be rated to carry the losses produced by ~~of~~ the steady state current determined by the size of the capacitor. It should also be recognized that the system will generally have some level of harmonics and normal practice is to increase the current by a factor of 1.3 to account for this. It is recognized that as the capacitance becomes larger the resistance must also become larger and the entire system becomes more expensive. The strategy is to lower the TRV’s frequency approximately by an order of magnitude and should be below the first resonant frequency of the transformer. Any more than this is of little practical value and will unnecessary increase the snubber costs..

The use of a fuse is optional. If it is desired it must be rated to withstand the steady state current (and harmonics) of the system and operate ~~with the loss of~~ in case of~~the~~ a capacitor failure.

It is also ~~recommended~~ needed that the transformer be protected with a dedicated arrester appropriately sized even for indoor applications.

8.2 Other Mitigation Methods

~~Breakers~~ Switching devices equipped with ~~pre-insertion~~opening resistors ~~resistors~~ are one method to reduce the magnitude of the load side TRV. This has been shown to be an ~~very~~ effective method ~~at~~ for high-voltage applications~~high voltage,~~. ~~however~~However, ~~at modest~~for medium voltage~~s~~ applications it adds substantially to the cost of the ~~breaker~~switching device. Such switching devices were used and offered in the past. Today, this solution is generally not offered by switching device manufacturers unless special requests. In addition, the use of opening resistors showed that the reliability of the switching device is somewhat reduced compared to a switching device not having such resistors. Moreover, there is substantial ~~the~~ added operational costs for~~of~~ maintaining the ~~switcher~~ interrupter which inserts and removes the resistors.

~~In rectifier and HVDC systems the application of capacitors and tuned filters provide var support and low impedance paths to ground for harmonic current. The presence of substantial shunt capacitance, generally far in excess of the shunt capacitance of the transformer, has the effect of lowering the natural frequency of system response by an order of magnitude. As such the presence of the shunt capacitance and/or filters serves to minimize the potential for high frequency oscillatory voltages on the terminal of the transformer.~~

The presence of resistive loads can provide a damping effect on the switching induced transients, thus preventing or substantially reducing dangerous voltage excursions within the transformer ~~structure~~windings. It is therefore recommended that as much resistive load as possible should be maintained on the circuit when switching operations are performed.

The use of ~~synchronized~~ synchronuous (or controlled) switching is also an effective method for eliminating re-ignitions or restrikes and thus reducing the risk of having repetitive oscillatory transient voltage. Synchronized switching allows to separate the arcing contacts of a switching device at a suitable time, relative to current zeros, so that re-ignitions or restrike are not possible (operations with medium arcing times). It ~~normally would not be~~ is at present the most economical mitigation method for high-voltage applications.~~but if available for other reasons would provide an effective mitigation strategy.~~

Nonlinear resistors or metal oxide varistors connected across portions of a transformers winding structure are also a method for dealing with high internal voltages caused by external oscillatory excitation at one of the transformers resonance frequencies. This can effectively address the concerns at one frequency ~~by~~ but should not be considered as a complete solution for all natural frequencies.

9.0 Examples

9.1 Example A

9.1.1 System

The system of interest is shown in the Figure ~~15~~16. The circuit breaker between the supply system and the feeder of interest is a~~n~~ SF6 circuit breaker and was closed during the failure. Supply is through a long cable feeding a vacuum circuit breaker.

Between the vacuum circuit breaker and the transformer is a short length of cable. The transformer is a 3 phase dry type 12 kV unit with two primary windings connected in parallel and two independent low voltage windings each designed to feed separate loads. The transformer was unloaded at the time of failure. Figure ~~16~~ 17 is a diagram of the transformer windings. The transformer was being energized when an improperly set relay instructed the vacuum circuit breaker to open. The transformer failed from the center of the high voltage winding to both ends of the delta. Location of the failure is shown in Figure ~~16~~17.

9.1.2 Failure Mode

There were no lightning or switching events in the area during the period in question. It is most unlikely that the unit~~s~~ failed due to insulation failure caused by a system transient voltage (lightning or switching surge) since the unit~~s~~ ~~were~~ was protected with lightning arresters and would have a protective margin of over 100 %. Additionally, the locations of the failure do not suggest an impulse type failure mode.

Ferro-resonance might have been the reason for failure since the transformer was unloaded. However, the flashover locations and the voltages that were required are substantially greater than the two or three per-unit voltage that would be observed in a ferro-resonant event. Additionally, there was no record of audible noise which normally exists with a ferro-resonant event.

The most likely scenario causing this failure was that during this switching operation an oscillatory transient voltage was generated on the high voltage terminals of the transformer while interrupting the ~~energization~~ magnetizing current. The frequency of this oscillatory transient voltage coincided with one of the internal resonance frequencies of the transformer, producing voltages within the winding structure greater than the insulation strength of the transformer. These unacceptably high overvoltages were caused by the unfortunate condition where the frequency of the transient oscillatory voltage (a product of the circuit breaker, system, transformer and load characteristics – Figure ~~17~~18) and the internal resonance of the transformer (a function of the transformer geometry and material characteristics – Figure ~~18~~19) coincided.

Several additional comments are of interest.

First, in this example, the transformer of interest was a new 75 kV BIL unit and had been subjected to and passed the 75 kV standard 1.2x50 ~~microseconds~~ μs full wave impulse factory test. The winding failure locations were not in the locations where one would anticipate a normal impulse winding type failure, e.g., to be near the line terminals rather than across great portions of the winding (e.g., center of the disk to the winding ends for example).

Secondly, the ability of the transformer to withstand factory impulse voltage tests does establish a basis to compare the “electrical strength” of the unit. Figures ~~19~~ 20 and 21 compare~~s~~ the internal transient voltage produced by applying a 75 kV full wave impulse to the voltage generated by applying a sinusoidal voltage waveform bounded to the arrester protective level.

Third, with an arresters present on the high voltage terminal (without the snubber) it is doubtful that the unit would have survived a situation where the breaker had multiple reignitions.

Fourth, the magnitude and frequency spectrum of the periodic voltage produced at the transformer terminal is a function of the circuit breaker, transformer, and system characteristics. This resultant current-wave form is a function of the circuit that surrounds the circuit breaker and the transformer. Each system is unique. There are three major frequencies of interest in this system, e.g., the frequency of the ~~basic~~ load transient recovery voltage or $f_L = \frac{1}{2\pi\sqrt{LC_L}}$ (for this system it is approximately 25.0 kHz). In the IEEE C37.015-1993 (IEEE Application Guide for Shunt Reactor Switching - reference A25) this is called the load side frequency. The second frequency of interest is the frequency of the system immediately after the circuit breaker has re-ignited (for this system on the order of 500 - 1000 kHz). This is generally referred to as the second parallel frequency and can be approximated by $f_{2P} = \frac{1}{2\pi}\left[\frac{C_L + C_S}{L_B C_L C_S}\right]^{\frac{1}{2}}$. The third frequency is the main circuit frequency, $f_m = \frac{1}{2\pi}\left[\frac{L_S + L}{L_S L(C_S + C_L)}\right]^{\frac{1}{2}}$ and this in on the order of 100 kHz. Figure ~~12~~ 13 provides the basic circuit diagram for the three frequencies.

Fifth, a critical portion of the system action is determined by the circuit breaker's dynamic voltage withstand versus time ~~withstand~~ characteristic. The circuit breaker characteristic is discussed in reference A.9 including the dynamic volt-time characteristic that could reasonably be expected for circuit-breaker interrupter contacts made of CuCr. Looking at Figure ~~10b~~ 11 (Figure 9 of reference A.9) it is equally reasonable to assume that the circuit breaker could have a constant voltage withstand from 10-20 kV from 0 to 1 ~~millisecond~~ ms or alternately a characteristic that is growing from near zero (4-5 kV) at time zero to over 20 kV in less than a millisecond. The actual characteristic is statistical and could be anywhere in this range. Only tests can accurately characterize this circuit breakers dynamic volt-time response. Even with tests, the dynamic volt-time withstand characteristics will remain statistical.

9.1.3 Analysis

Figure ~~17~~ 18 contains a idealized and theoretical sketch of the saw tooth transient voltage that is developed on the high voltage terminal of the transformer due to the reignition of the ~~breaker~~switching device. For example, if the ~~breaker~~ switching device ~~where~~ was assumed to have a constant voltage withstand of 10.0 kV for the first millisecond, Figure ~~17a~~ 18 illustrates the form of the saw tooth wave that is produced. The variables in this diagram are the ~~transient recovery voltage characteristic of the breaker (~~switching device~~breaker~~ dynamic volt-time characteristic – assumed in this case to be a constant 10 kV, could realistically be from 5 to 15 kV) and the ~~base~~ load side oscillating frequency of the transformer and load side system ~~and transformer capacitance~~ (approximately 26 kHz for this system, f_L). Additionally, we will assume that the transformer terminal exhibits no voltage escalation and as such has the form shown on Figure ~~17~~ 18 with a peak magnitude of $17.6kV = \frac{12kV\sqrt{2}}{\sqrt{3}} \times 1.8$. $\frac{12kV}{\sqrt{3}}$ is the line to neutral voltage for a 12.0 kV system, √2 brings it to its peak value, and 1.8 is the K or ~~overshoot~~amplitude ~~value~~ factor. ~~for a nominal x/r ratio system from the IEEE C57-1200.~~

Therefore, with the circuit breaker dynamic volt-time characteristic – assumed in this case to be a constant 10 kV for the first millisecond, ~~withstand characteristic at 10kV~~ and with a ~~terminal transient~~ load side oscillating frequency of 25 kHz and a TRV magnitude of 17.6 kV peak, it would be possible to generate a saw tooth periodic voltage of approximately 166 kHz. Alternately, if the circuit breaker has a voltage withstand characteristic of 12 kV then the frequency of the voltage applied to the transformer terminals would be approximately 120 kHz. If the breaker volt-time characteristic increases the sawtooth frequency developed ~~frequency~~ will decrease. If the voltage across the circuit breaker escalates (as discussed in reference A.10) the frequency and magnitude will become larger. It is within the capability of this system to generate frequencies in the range of 50 to 250 kHz with magnitude considerably larger than the system voltage. This process of current chopping and reignition can last well over a millisecond (see Reference A.8 Figure 1) and as such may produce a sustained oscillatory voltage on the terminals of the transformer. The above description is given as a theoretical example for a better understanding of the phenomenon involved. In reality, the situation is much more complex because of the statistical re-ignition behavior of the switching device. In case of multiple re-ignitions, the time in between each re-ignition and the TRV voltage peak just prior to each of the re-ignition will vary and this will produce a wide range of frequencies.

Figure ~~18~~ 19 contains the impedance versus frequency of this transformer. The resonances are defined as the points where the impedance is small and the anti-resonances are defined where the impedances are large. Note that there is a very sharp resonance at 119.5 kHz, a second at 208.4 kHz, and a third at 279.6 kHz. Associated with each of these resonances are internal amplifications within the winding structure (in fact with all frequencies of excitation). Figure ~~18b~~ 19 contains a calculation of this amplification factor across half of one of the disk (from the input terminal to the tap break) in the high voltage winding. At 60 Hz the voltage expected, when 1 per unit voltage of oscillatory wave form is applied, is $10^{0.30} = 0.5$ per unit. This is the turns ratio voltage. However, if 1.0 per unit voltage is applied at a frequency of 119.5 kHz (the first resonance) the voltage seen within the transformer is $10^{1.98} = 95.5$ per unit or about 200 times greater than that expected at 60 Hz. Therefore, what is of concern is the form and duration of the oscillatory voltage applied to the transformer terminal and the transfer function to the point of interest in the winding.

Recognize that these transformers (all power transformers) were designed and tested with wave shapes and voltage magnitudes called out in the transformer standards. The performance and insulation characteristic of a transformer in the 50-250 kHz range is not normally considered by any transformer manufacturer. The saving characteristic in most instances is the sharpness of resonance (as shown in Figure ~~18~~19) and the fact that the ~~breaker~~ switching device is not opened and closed routinely. Unfortunately, when the ~~breaker~~ switching device opens and reignites it produces a sawtooth transient voltage that sweeps through a wide band of frequencies (because of its increasing voltage withstand characteristic and statistical behavior) and as such may approach the frequency near or at one of these transformer resonant frequencies.

For this example ~~system~~, it was a very real possibility that a voltage of periodic form (close to 119.5 kHz, or 203.4 kHz, or 279.6 kHz) of magnitude greater that system voltage (limited only by the arrester cutoff level) could be applied to the transformer terminal. This periodic external excitation would then generate within the high voltage winding (at the point of failure) a voltage many times greater than that applied ~~in~~ during factory tests. This amplification is limited only by the small losses at or near resonance and will grow 5 to 50 times greater than the terminal voltage (see reference 10 and 11).

Figure ~~19~~ 20 contains the computed voltage responses of this transformer for sine wave excitations of 17.6 kV at a frequency of 119.5 kHz compared to the response of the unit to a standard full wave impulse voltage. These computations produced voltages within the winding great enough to cause failures.

The fact that the unit was often switched on and off probably contributed to the failure. Since this is a statistical type of event the fact that the transformer was subjected to many switching operations substantially increased the probability of having the failure and the potential for this type of failure since tracking within the insulation structure may have occurred on previous switching events prior to failure. Additionally, it is possible that a voltage escalation took place up to the arrester cut off which would act to exacerbate the situation.

9.1.4 Mitigation Method

This situation was addressed by installing an RC snubber to the terminals of the transformer.

1~~-~~. Capacitor. The installed capacitor was a ~~¼~~0.25 ~~micro-farads~~µF per phase or about 15 kVAR in a 3-phase arrangement. The BIL should be at least 110 kV. At 60 Hz the capacitor will carry about 0.75 ~~amps~~A r.m.s.. At 60 Hz the capacitor will look like a ~~-j~~10,6~~10.~~ ohms capacitive reactance.

2~~-~~. Resistor. A series non-inductive resistor of 25 ohms per phase was installed. The steady state power requirements are ((1.3x0.75)^2)x25=25 watts. If the capacitor fails in short circuit the full phase to ground voltage will be across the resistor, therefore, approximately 319 ~~amps~~A ~~rms~~r.m.s. will pass through it to ground. As such in one cycle the resistor will have to absorb ((319)^2)x25/60 =42361 joules.

   This snubber was fused. If the capacitor fails and if a fuse is present it will blow and have to be replaced. Alternately, if the capacitor fails and no fuse is present, the resistor will blow in a few cycles and have to be replaced. Either way the capacitor is not available to protect the transformer and will have to be replaced in a timely manner. The installation of a fuse is a preference issue.

3~~-~~. Fuse. A fuse for this system should be rated for 15.5 kV ~~rms~~r.m.s., a continuous current rating of greater than 2 ~~amperes~~A ~~rms~~r.m.s., and a time response of 0.008 seconds at approximately 300 ~~amperes~~ A r.m.s..

9.2 Example B

9.2.1 System

The system of interest is a supply to an uninterruptible power supply (UPS) for computer back-up and is shown in the Figure ~~21~~22. The circuit breaker between the 12.47 kV source and the feeder of interest is a vacuum circuit breaker and during the time of failure was opened and closed numerous times during system testing. Between the vacuum circuit breaker and the transformer is 60 meters of shielded cable. The transformer is a 3 phase 3000 kVA dry type 12.47 kV (95 kV BIL) unit with delta primary and 480 V grounded-wye secondary. The high voltage delta winding was constructed of continuous wound line on end disk with four 2.5 % taps for de-energized operation in the center of the high voltage winding. At the time of the failure the transformer was loaded with 5 UPS harmonic filters. The low voltage winding was sheet wound construction. The high voltage winding of the transformer was protected with 18 kV distribution class arresters and a series current limiting fuse.

9.2.2 Failure Mode

This installation experienced four identical failures in the high voltage winding structure during a two year period. The failures occurred on essentially new transformers during switching operations while testing of the UPS system. Failures were from the center of the disk to ground and from tap-to-tap in the center of the disk. Even with the terminals of the high voltage winding protected with properly sized arresters, voltages of damaging magnitude were measured in both phase to ground and tap-to-tap within the high voltage winding during both closing and opening operations of the breaker (see Figures ~~22~~ 23 and ~~23~~24).

9.2.3 Analysis

In a factory test with a 95 kV BIL full wave impulse voltage excitation, the voltage seen tap-to-tap is 2.4 kV peak. The 18 kV rated arrester limits the terminal voltage on the delta winding to approximately 45 kV so during an impulse event in the field one would expect a tap-to-tap voltage of 1.2 kV. During a staged switching event with a terminal voltage of 30 kV peak, the tap-to-ground voltage was measured at 75 kV peak and the tap-to-tap voltage was measured at 65 kV peak. The 65 kV is approximately 27 times as large as the voltage proof tested in factory tests and 54 times what one would expect with the system protected with an arrester. Clearly, these voltage are in excess of the transformer design capability. These transient overvoltages were attributed to the internal resonance of the transformer winding. The tap-to-tap failures in the center of the coil are at the second resonance and the tap-to-ground failures in the center of the coil are at the coils first resonance (see Figure 5)

The field measurements ~~produced~~ shown also 65 kV peak ~~also~~ and demonstrated that the transient voltages were very sensitive to the transformer load. Very large voltages were observed with a load of 5 UPS harmonic filters, but as the number of filters were reduced, the magnitude of the transient overvoltages decreased. With a simple resistive load no damaging transient overvoltages in the center of the coil were observed. With the transformer completely unloaded, no damaging transients were observed.

9.2.4 Mitigation Method

An RC snubber was installed at the terminals of the transformer to solve this situation. The installed capacitor was a ~~¼~~0.25 ~~micro farads~~µF per phase or about 15 kVAR in a 3-phase arrangement. The BIL should be at least 110 kV. A series non-inductive resistor of 50 ohms per phase was installed. This snubber was protected with a current limiting fuse.

With the snubber installed the tap-to-ground voltage was reduced from 75 kV to 10 kV (87 % reduction) and the tap-to-tap voltage was reduced from 65 kV to 1.2 kV (98% reduction).

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A.3 Standards

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[A24] IEC 62271-110 "High-voltage switchgear and controlgear – Part 110: Inductive load switching"

~~[A24] IEC 1233 Technical Report, "High-voltage Alternating Current Circuit Breakers – Inductive Load Switching," 1994-07~~

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[A26] C37.011-2005 IEEE Application Guide for Transient Recovery Voltage for AC High-Voltage Circuit Breakers

Annex B (Informative) Natural Frequencies – Analytic Methods to Compute Impedance Versus Frequency Characteristics of Transformers

The terminal resonances for a system can be determined by taking the square root of the eigenvalues of the system matrix, [A], shown in the state variable representation for the system shown by equation B1.1.

$$\left[\dot{q}\right] = [A][q] + [B][u]$$

$$[y] = [C][q] + [D][u]$$

with:
[A] - State Matrix
[B] - Input Matrix
[C] - Output Matrix
[D] - Direct Transmission Matrix B1.1
[q] - Vector of State Variables for System
[$\dot{q}$] - First Derivative of [q]
[u] - Vector of Input Variables
[y] - Vector of Output Variables

The impedance versus frequency characteristic requires a little more effort. In light of the previous definitions terminal resonance may be defined as occurring when the reactive component of the terminal impedance is zero. Equivalently, terminal resonance occurs when the imaginary component of the quotient of the terminal voltage divided the injected terminal current is zero. Recalling that in the Laplace domain that s is equivalent to ω with a system containing n nodes with the excited terminal node j one can rewrite:

$$\begin{bmatrix} e_1(s) \\ e_2(s) \\ - \\ e_j(s) \\ - \\ e_n(s) \end{bmatrix} = \begin{bmatrix} Z_{1j}(s) \\ Z_{2j}(s) \\ - \\ Z_{jj}(s) \\ - \\ Z_{nj}(s) \end{bmatrix} \left[i_j(s) \right] \qquad \text{B1.2}$$

The voltage at the primary (node j) is in operational form. Rearranging the terminal impedance is given by:

$$Z_t(\omega) = Z_{jj}(j\omega) = Z_{jj}(s) = \frac{e_j(s)}{i_j(s)} \qquad \text{B1.3}$$

In these equations the unknown quantities are the voltage vector and the frequency. It is a simple matter to assume a frequency and solve for the corresponding voltage vector. Solving equation B1.3 over a range of frequencies results in the well-known impedance versus frequency plot shown in Figure 2.

The amplification factor or gain function is defined as:

$$N_{lm,j} = \frac{\text{Voltage Between Point l and m at Frequency } \omega}{\text{Voltage Applied in Input Node j at Frequency } \omega} \qquad \text{B1.4}$$

Reference A16 shows this results in:

$$N_{lm,j} = \frac{Z_{lj}(j\omega) - Z_{mj}(j\omega)}{Z_{jj}(j\omega)} \qquad \text{B1.5}$$

If one is interested in the voltage distribution within a coil at one of the resonant frequencies, this can be found from the eigenvector of the coil at the frequency of interest. If one is interested in the distribution at any other frequency equation B1.5 can be utilized. Figure 3 presents an example of the amplification factor in a coil for the first three resonances.

Recall that $Z_{jj}(j\omega)$ is the terminal impedance of the transformer. By definition, $Z_{jj}(j\omega)$ will be small at resonance. As such can be large and is limited only by the magnitude of the difference between impedances $Z_{lj}(j\omega)$ and $Z_{mj}(j\omega)$. In other words, $N_{lm,j}$ is the amplification factor within the winding and can be very large (10 to 50 per-unit times the turns ratio voltage). The only limit will be the losses within the winding structure.

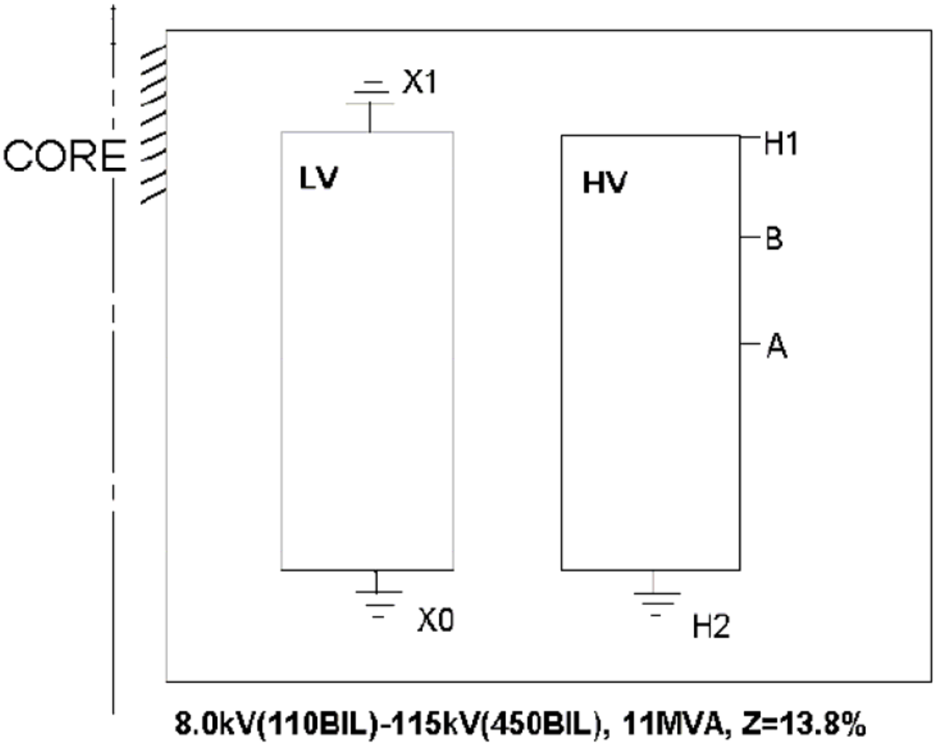

Figure 1 Cross section of two winding transformer example

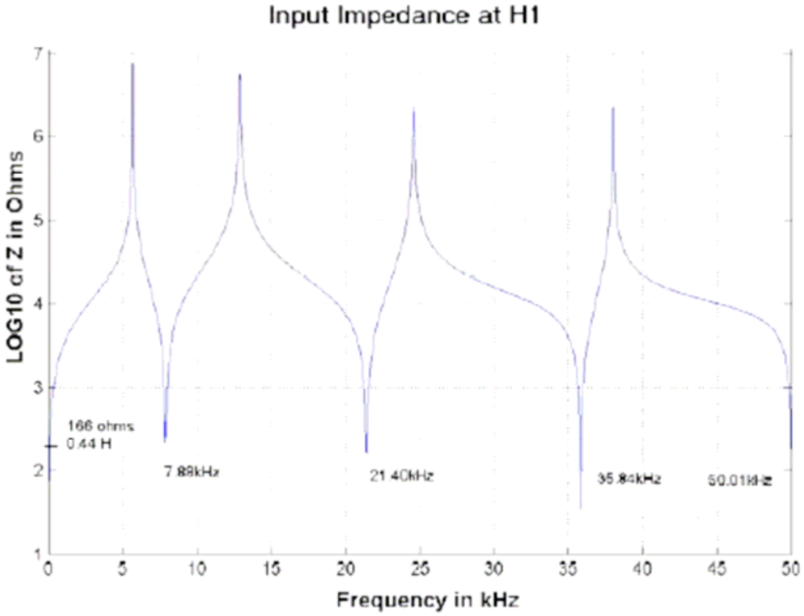

Figure 2 Impedance versus frequency example

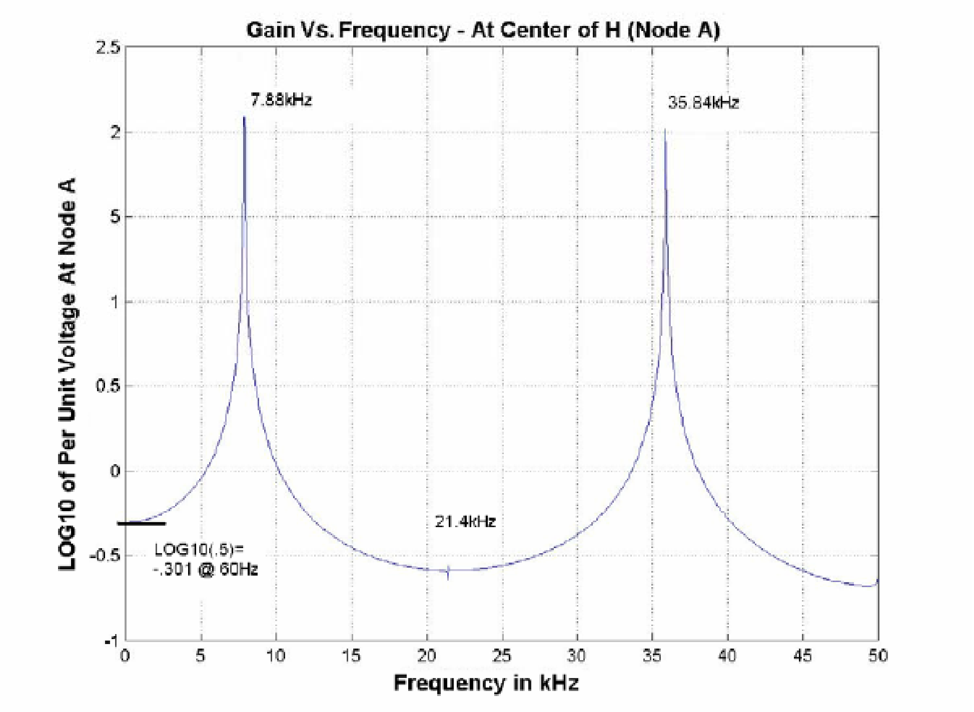

Figure 3 **Voltage at Point A (center of high voltage winding) when H1 is excited with oscillatory input voltage**

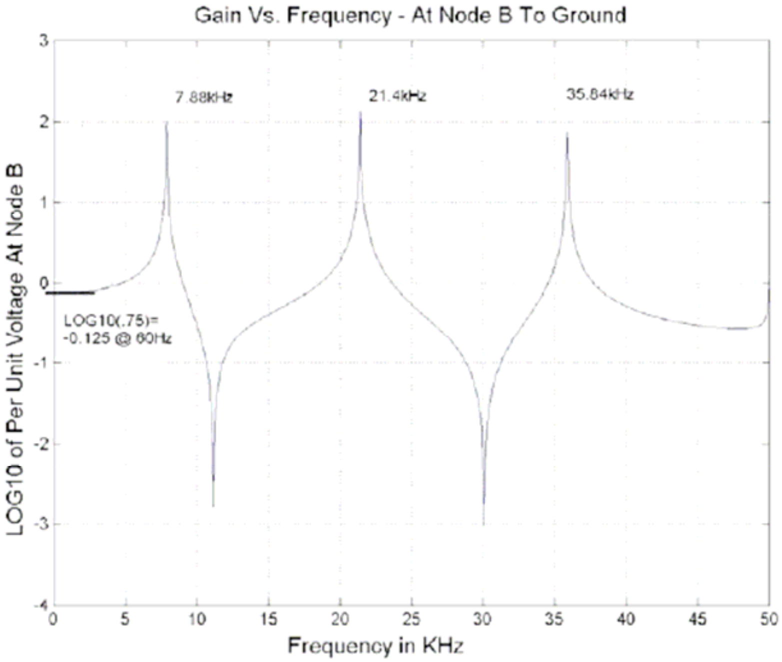

Figure 4 **Voltage at Point B (3/4 point in high voltage winding) with H1 excited with 1 p.u. oscillatory voltage**

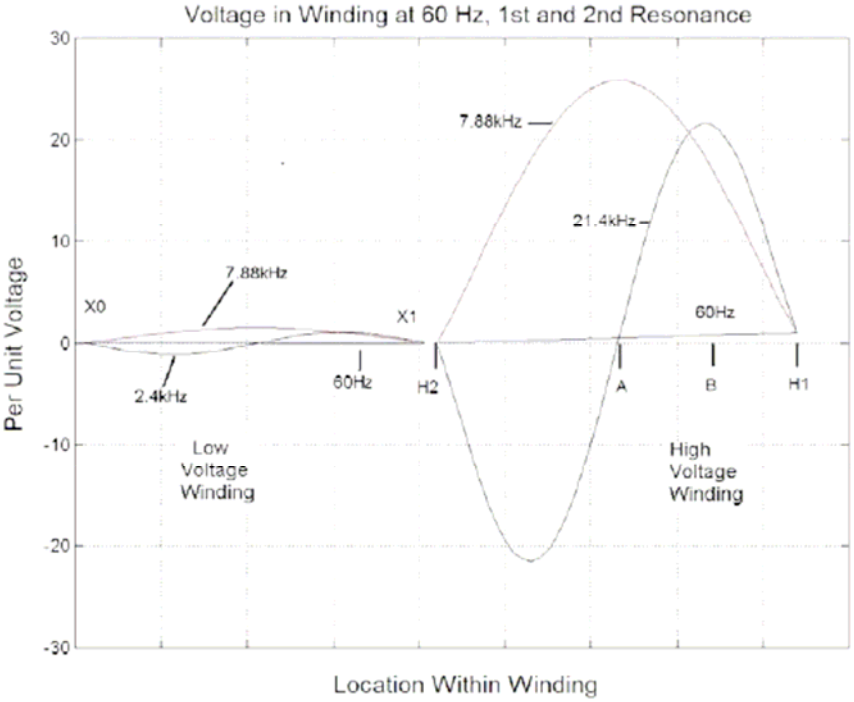

Figure 5 Normalized spacial Voltage within windings at 60 Hz, 7.88 kHz, and 21.4 kHz

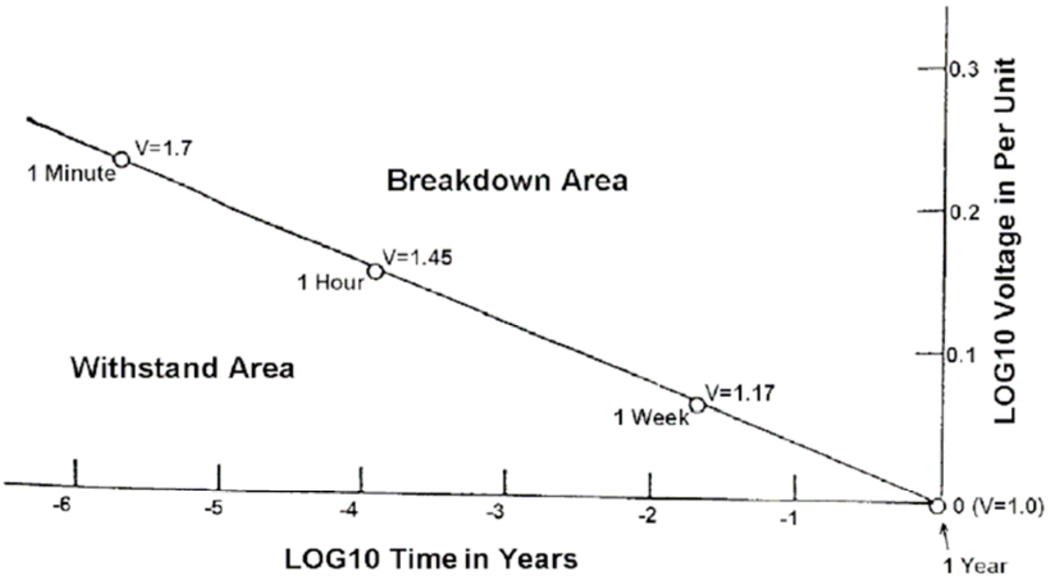

Figure 6 Relationship between applied voltage and duration for oscillatory wave to time of failure

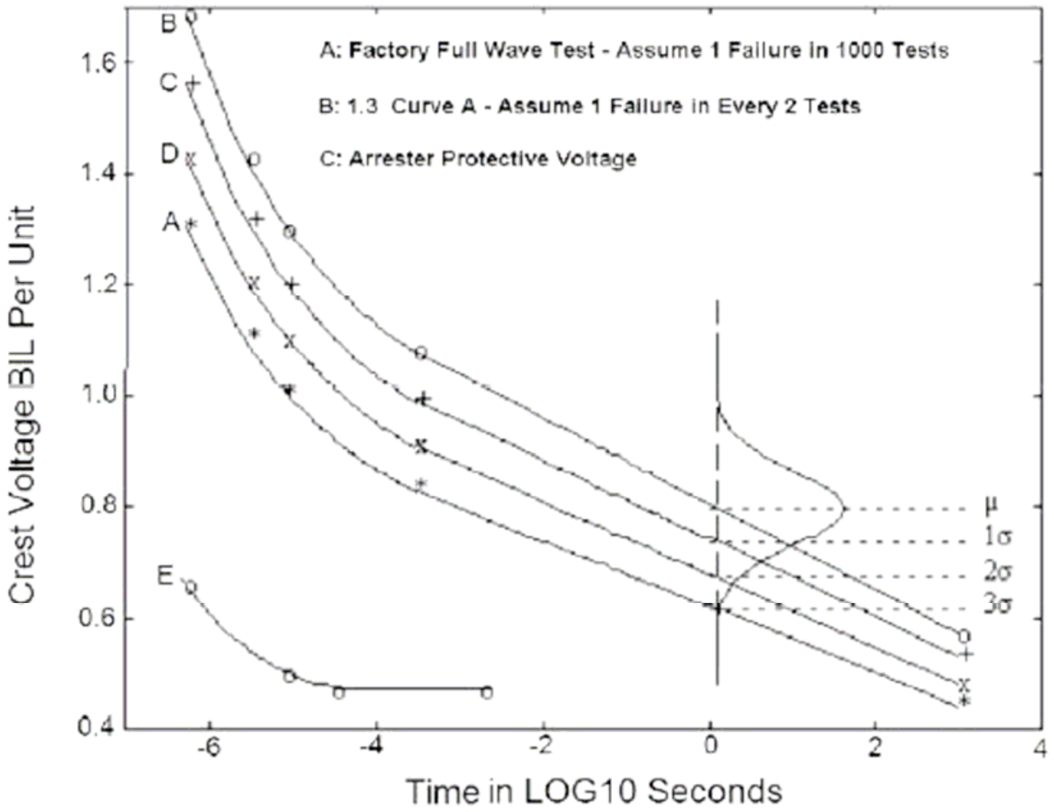

Figure 7 Transformer volt-time insulation characteristic used for arrester insulation coordination

Note to Bob: Curve C is not the protective level of the surge arrester. Curve E is. May you change the legend accordingly.

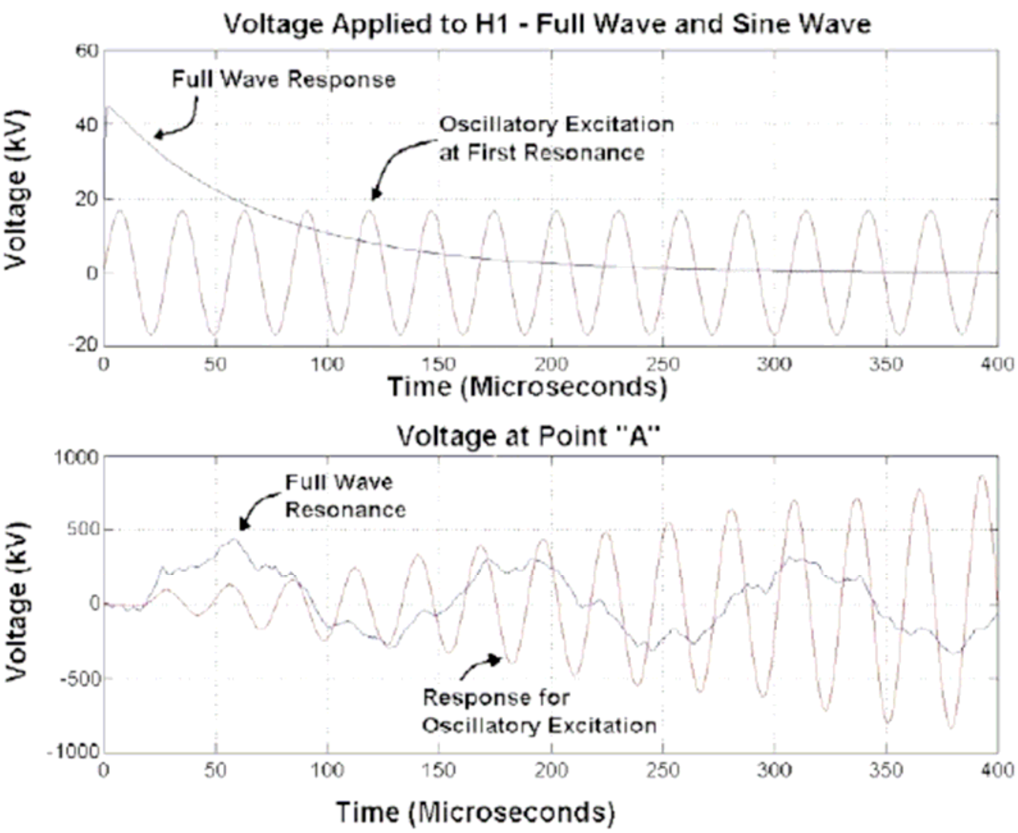

Figure 8 a. **Full wave and oscillatory voltage applied to H1. b. Response at center of high (point A) voltage winding.**

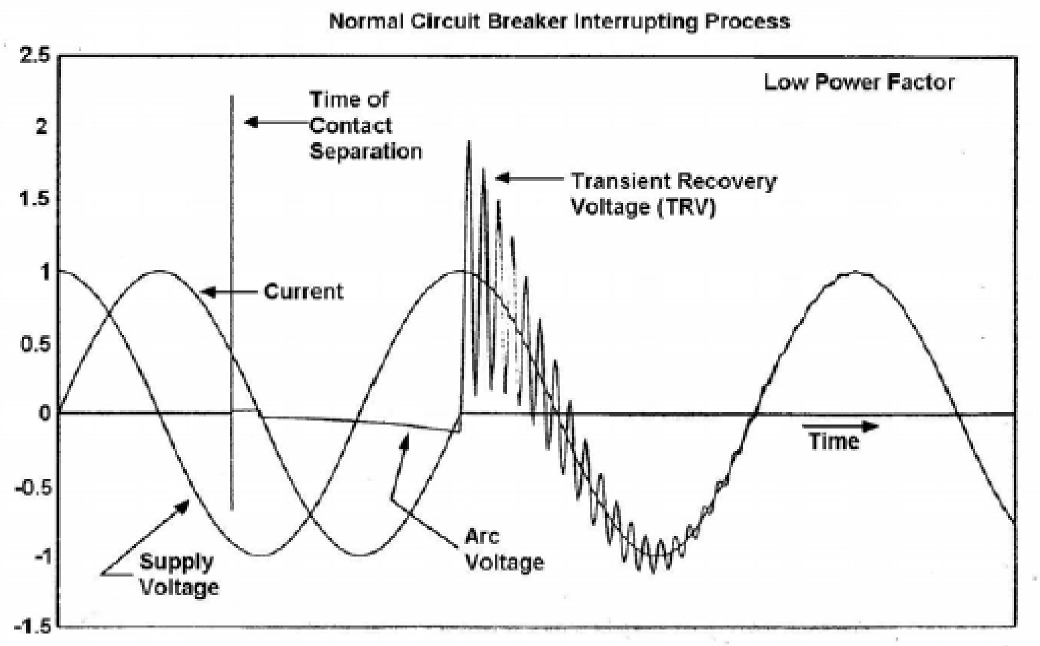

Figure 9 Normal circuit breaker interruption process

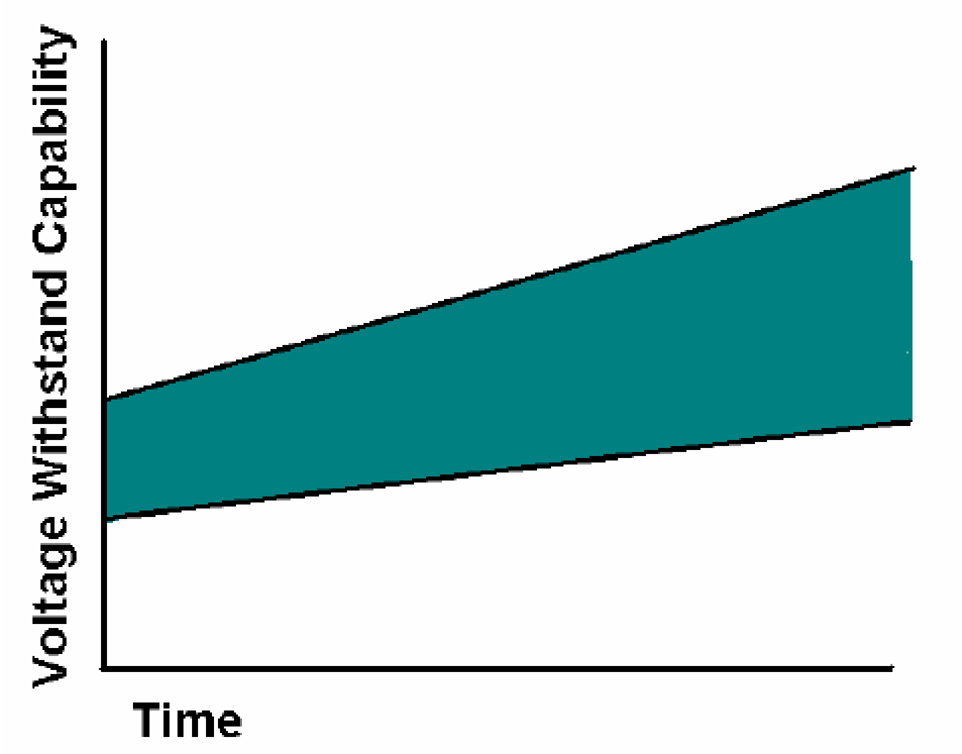

Figure 10 Example of ~~-~~ circuit ~~B~~breaker dynamic transient recovery voltage (TRV) withstand characteristic

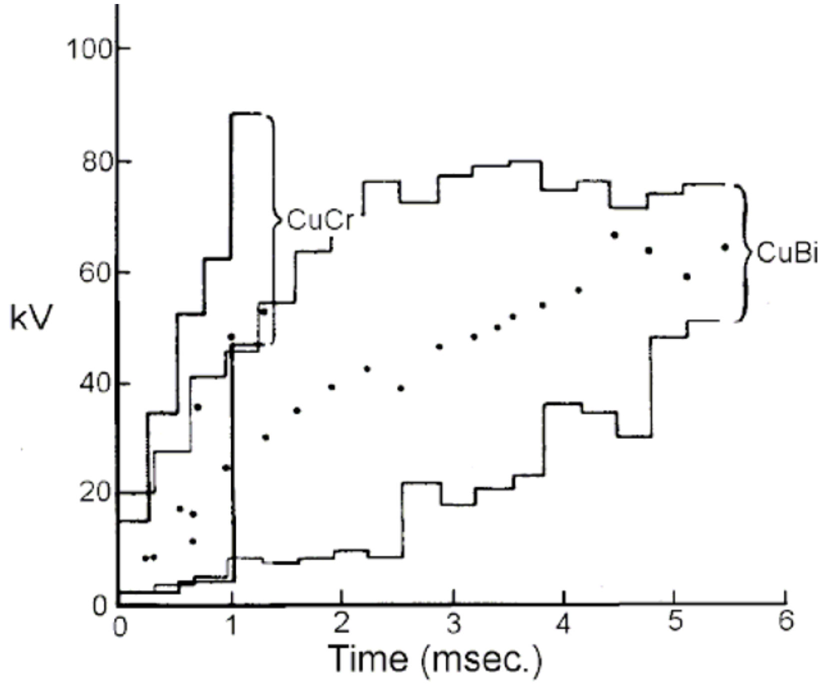

Figure 11 Comparison of breakdown data for CuCr and CuBi vacuum interrupters

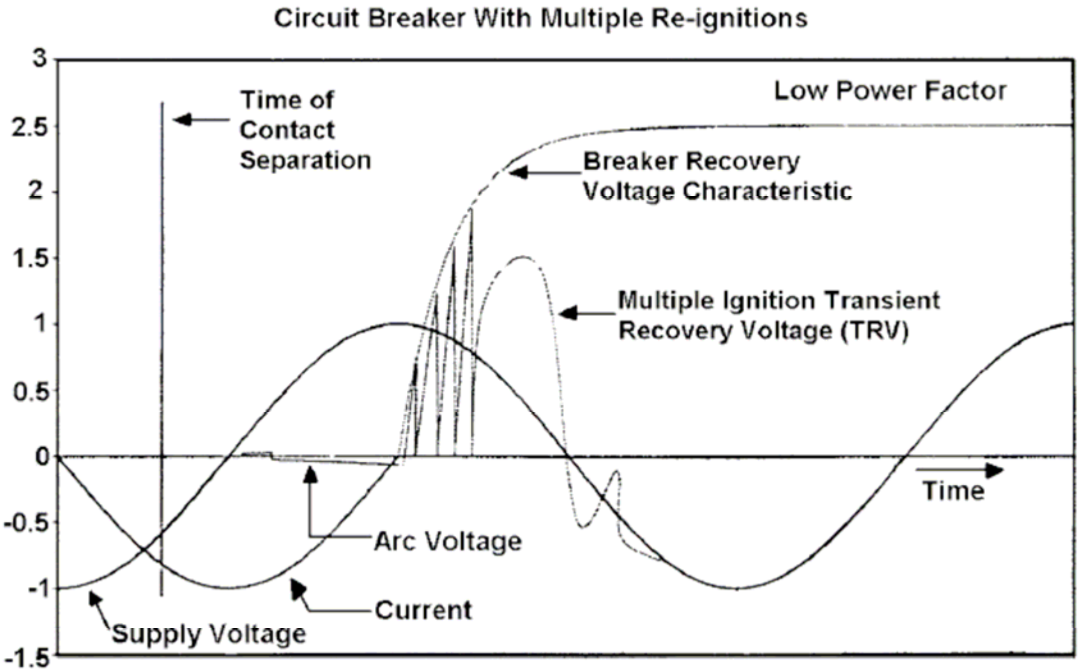

Figure 12 Circuit breaker with multiple re-ignitions

Note to Bob: The figure has to be corrected. Change "Ignition" for "Reignition"

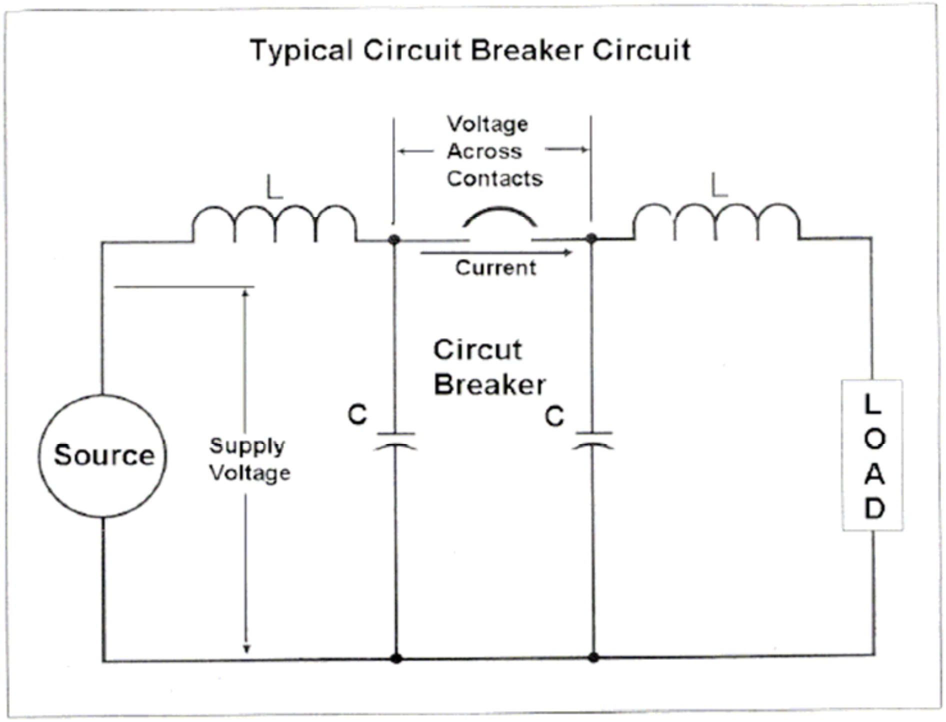

Figure 13 Typical system lumped parameter model

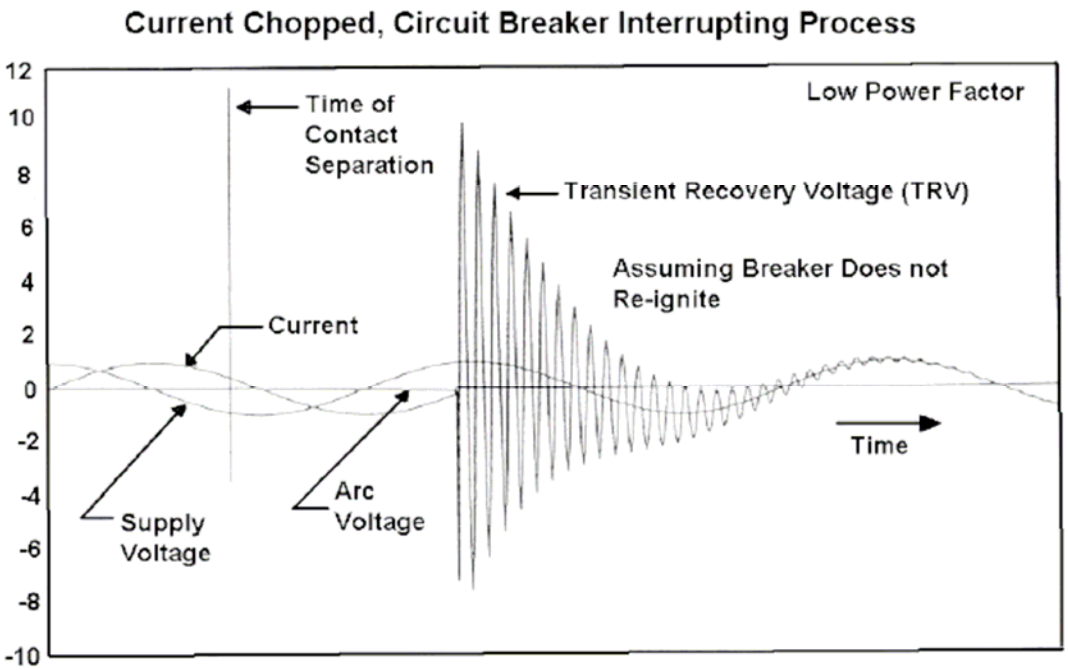

Figure 14 TRV during current chopping

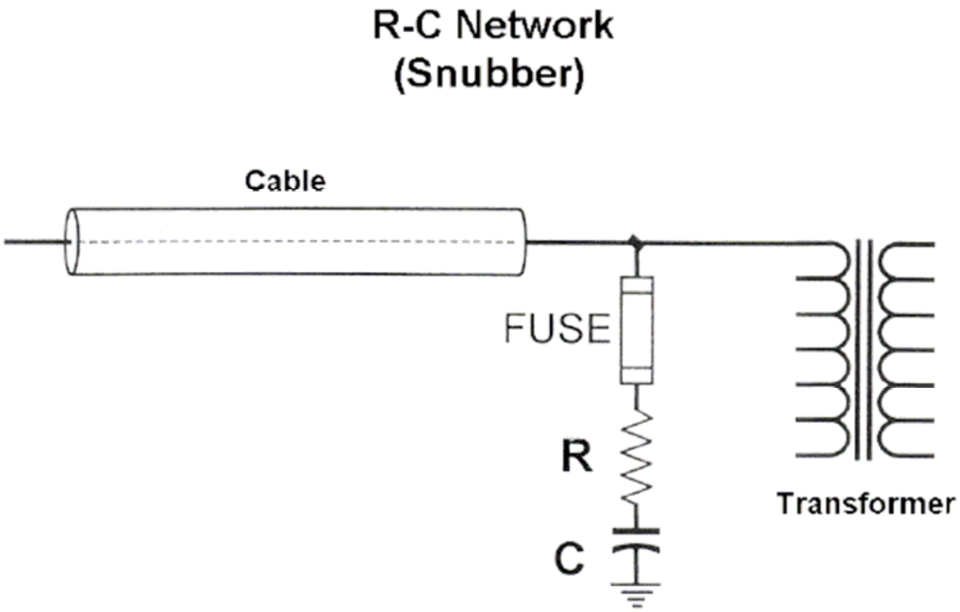

Figure 15 RC snubber network

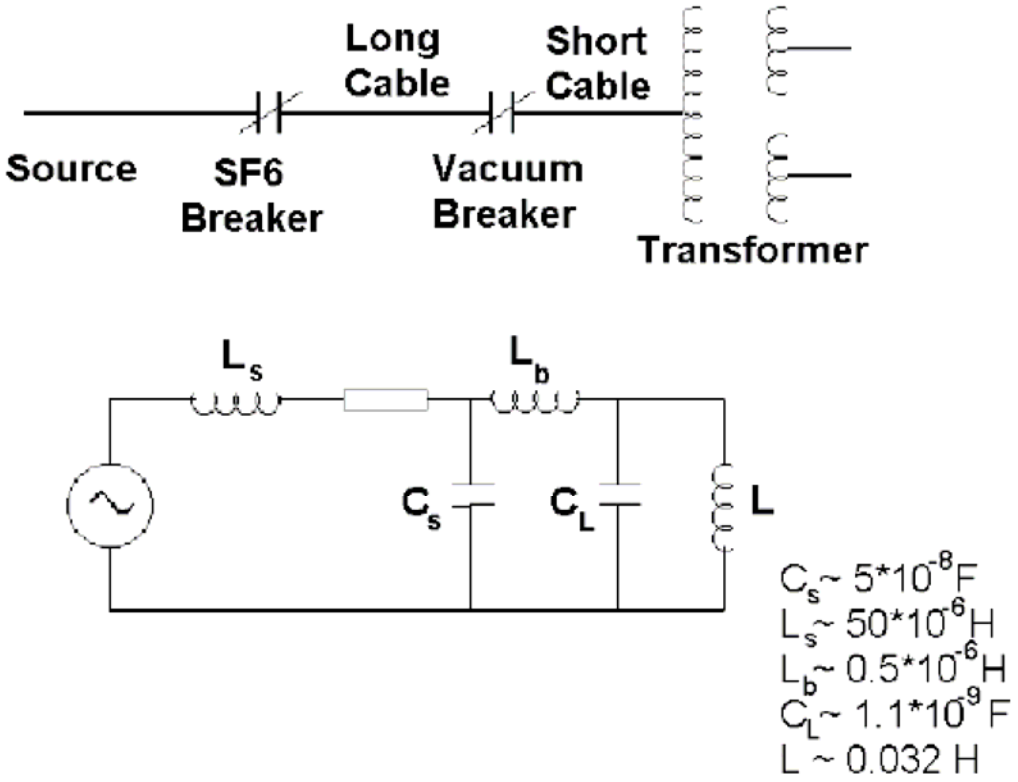

Figure 16 System Arrangement

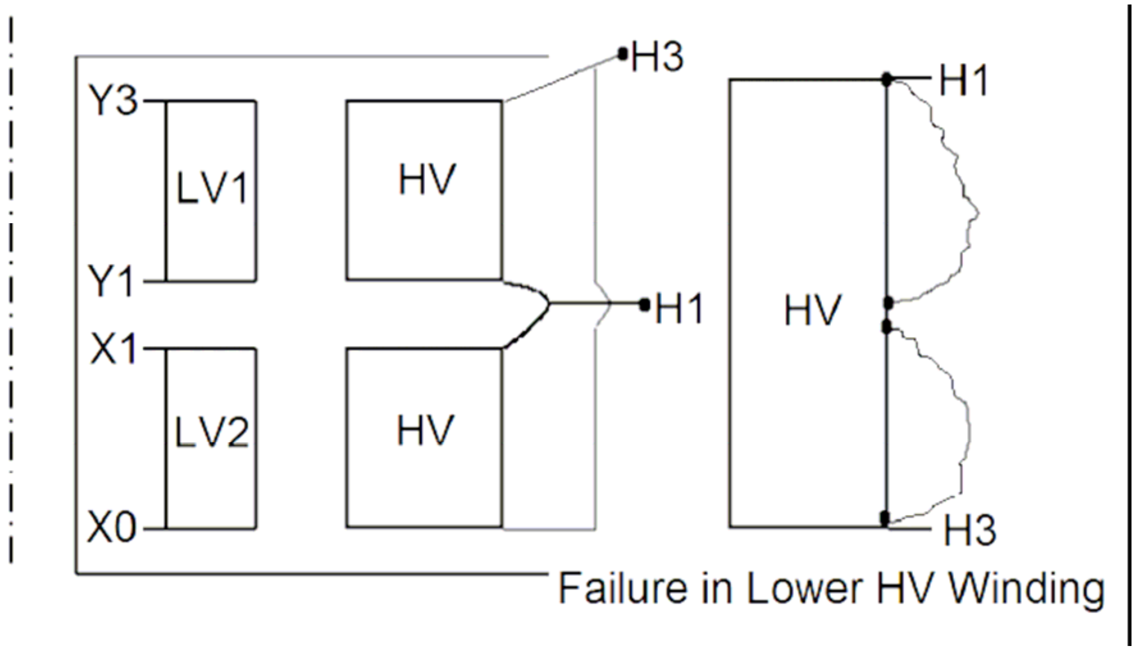

Figure 17 Transformer Cross-Section

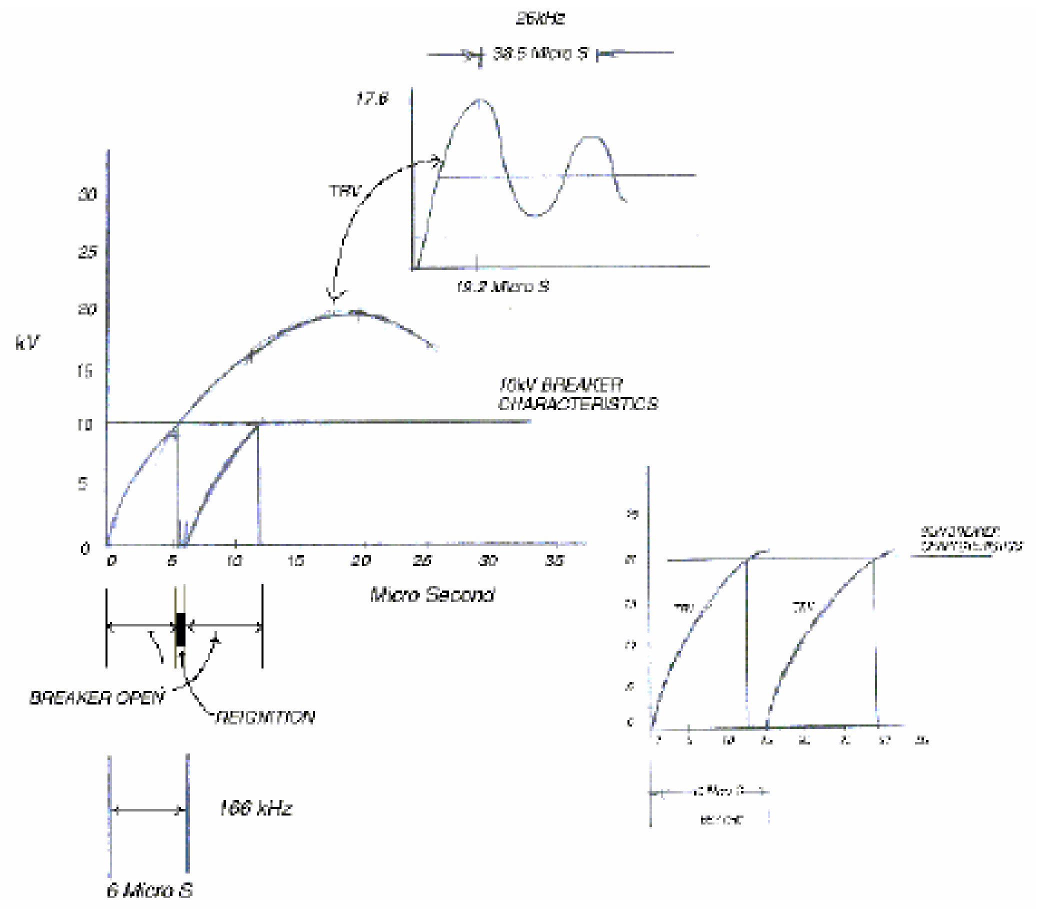

Figure 18Transformer Terminal Voltage

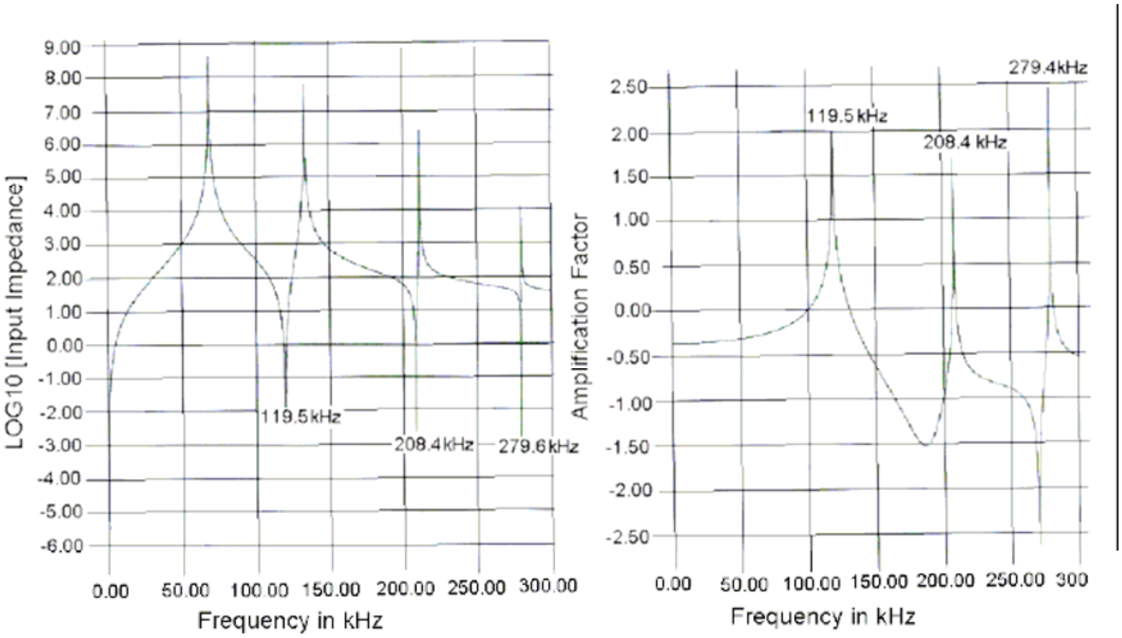

Figure 19 Amplification Factor

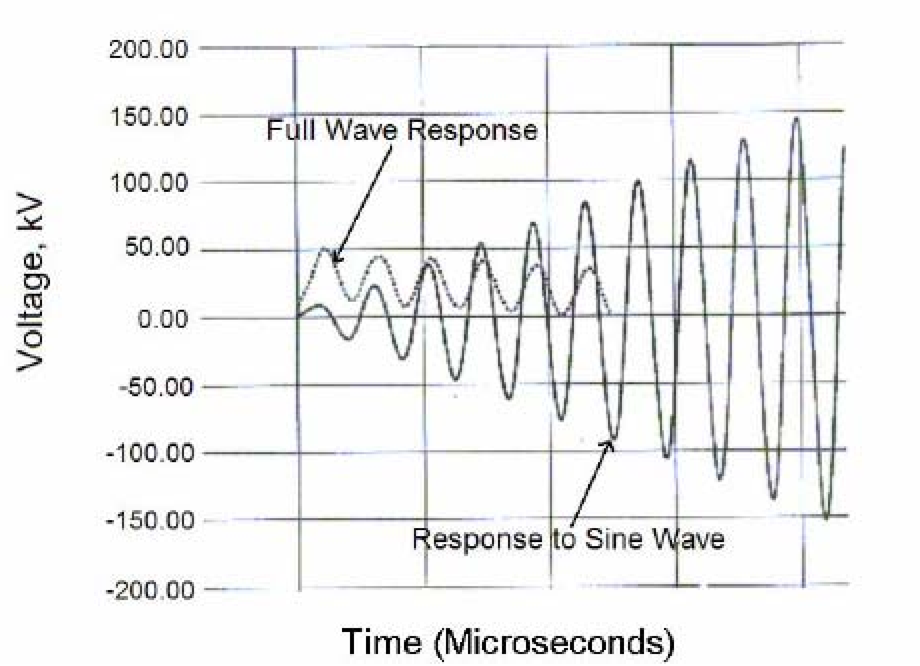

Figure 20 Compare Oscillatory versus Aperiodic Response

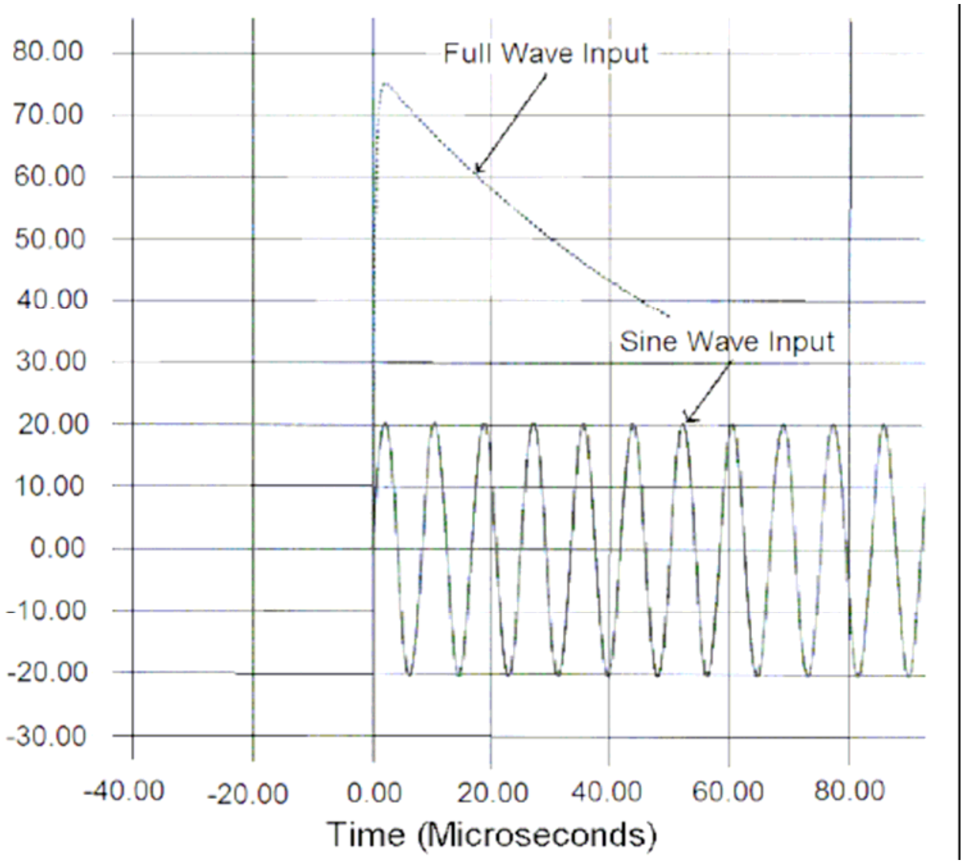

Figure 21 Applied Waves

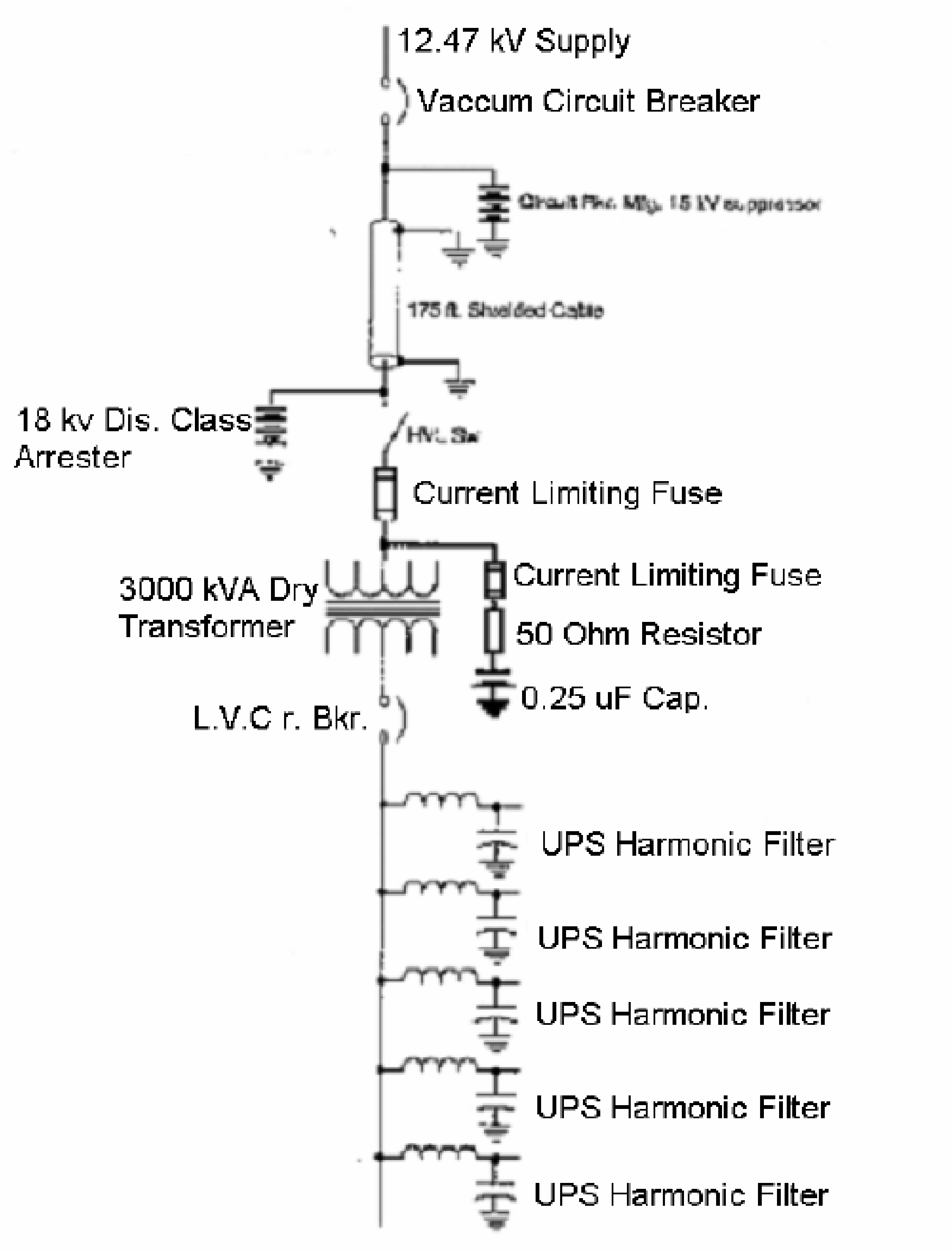

Figure 22 Circuit configuration - Example B

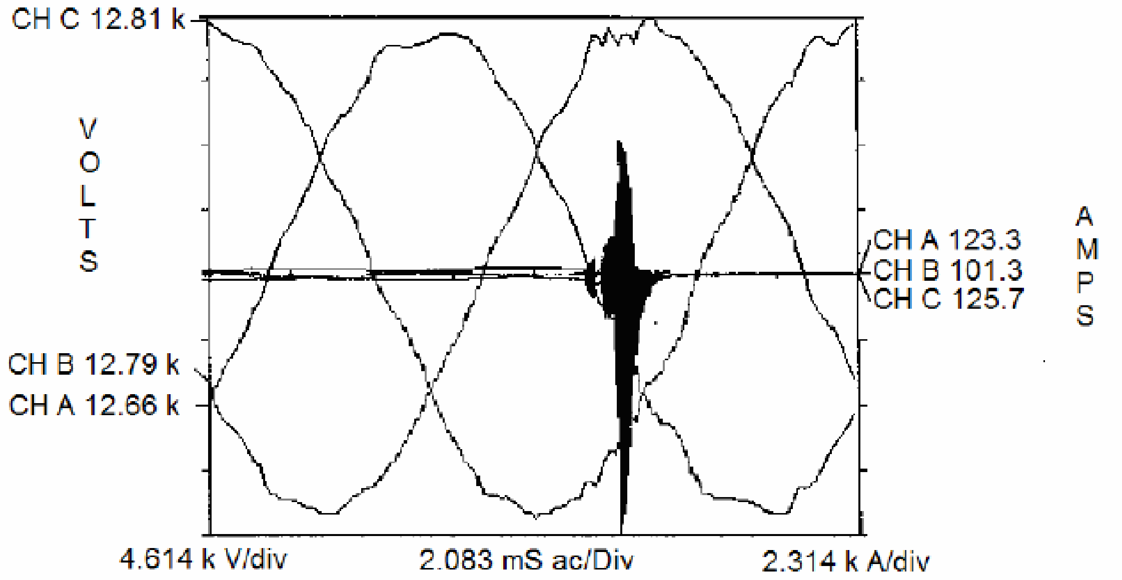

Figure 23 Transient voltages on circuit breaker opening operation

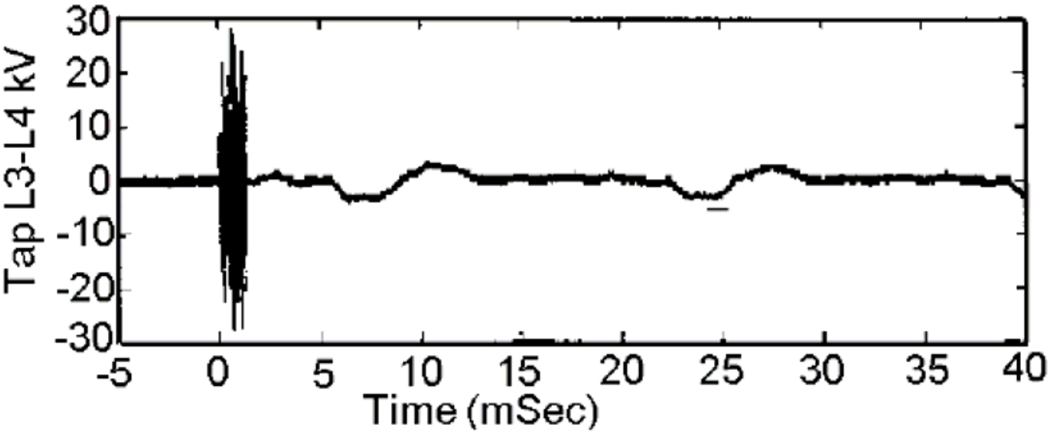

Figure 24 Transient voltages on circuit breaker closing operations