Task Force to Investigate the Interaction between Substation Transients and Transformers in HV and EHV Applications for the IEEE Power & Energy Society - Transformers Committee Performance Characteristics Subcommittee

Task Force Work Summary

Abstract – **This paper summarizes the work performed by the task force to investigate potential revisions to C57.142-2010 IEEE Guide to Describe the Occurrence and Mitigation of Switching Transients Induced by Transformers, Switching Devices, and System Interaction. Although the scope of this document does not exclude HV and EHV systems, the existing document primarily includes examples and information on distribution voltage systems. A task force was formed to investigate the need to include more information in this existing document on higher voltage systems. The task force was charged with the following tasks:**

- **Establish system voltages encompassed by C57-142-2010**
- **Gather field data, reports, and literature on HV and EHV failures related to substation transients and transformer interaction**
- **Solicit input from the other technical committees on this subject**
- **Review IEC and CIGRE work in this area**
- **Recommend course of action on revision of the present guide.**
- **Recommend high level changes to the guide (if revision is needed)**
- **Prepare final paper for the Performance Characteristics SC**

In the course of this work several failure scenarios were identified. These are categorized and the failures are described. In addition, the work done in this area by IEC and CIGRE is summarized. The final recommendations to the Performance Characteristics Subcommittee are summarized and recommendations are presented for the course of action on the revision/addition of HV and EHV material to the current C57.142 Guide.

I. INTRODUCTION

During the survey for failures in the HV and EHV transformers, several cases of transformer failure were found. It should be noted that failures of these larger power transformers can be very costly and the study of these failures is often very extensive and detailed. We will not attempt to provide a detailed analysis of each failure in this paper. We will attempt to categorize the failures that were captured and identify the failures that have been related to particular power system configurations. Significant work has been performed by CIGRE in this area. This work has been published in a brochure entitled "Electrical Transient Interaction between Transformers and the Power System."[1] Upon receiving presentation inputs from several industry experts and the review of this CIGRE work, the summary of the findings of this task force are included in this document.

After reviewing the existing documented cases in the higher voltage transformers, it was clear that the existing C57.142 guide does not address the higher voltage cases that exist. Although many of the same principles exist for both low voltage and high voltage transformers, the absence of information on HV and EHV systems in the C57.142 document might lead one to believe that this problem is primarily related to low voltage transformers. From the study of the service duty cases, it is clear that these interactions are not limited to low voltage transformers. In the following sections, we will describe the general categories that cover many of the failures/interactions seen in the HV and EHV systems.

II. CATEGORIES FOR FAILURES/INTERACTIONS DESCRIBED

A. System faults and cable switching produces traveling waves with reflections that excite lightly loaded transformers to resonance

Six of the failures reviewed fell into this category. The failures were initiated by lightning induced back flashover, cable energization, and other system faults. Most of the transformers which experienced failure from these types of interactions were Autotransformers. The voltages ranged from 500kV to 765kV. Many of the failures were due to part winding resonance in the tap windings.

This type of failure is initiated by a sharp transition to ground which sets up a traveling wave. The mismatch in transmission impedance at different points on the system creates reflections that simulate an oscillating waveform with a wavelength approximately equal to four times the transmission distance between reflection points. If this oscillating waveform frequency is near the natural resonance of the autotransformer, the unit can be excited into resonance.

Even though these oscillating waveform excitations are, in many cases, well below the surge arrester clamping voltages, they still have the ability to over-voltage internal components within certain areas of the windings. In these cases, autotransformers seem particularly vulnerable in the tap winding areas. This is primarily due to the fact that fundamental frequency voltage transfer ratios do not apply in the condition of partial winding resonance. For this reason, the transformers are not protected from these damaging over-voltages by the attached surge protecting devices.

In addition, standard factory acceptance tests do not take into account oscillatory waveforms near the resonant frequency of the transformer. Most factory testing takes place with non-impulse windings solidly grounded or grounded through a terminating impedance that limits the terminal voltage increase. In the field, the terminals are loaded only by the characteristic impedance of the system to which they are connected. If the transformer is lightly loaded, it can allow these potentially dangerous resonant induced voltages to be generated.

A recording of a fault transient caused by a 230kV system fault at a distance of 3.1 miles from the measurement point is given in Figure 1.

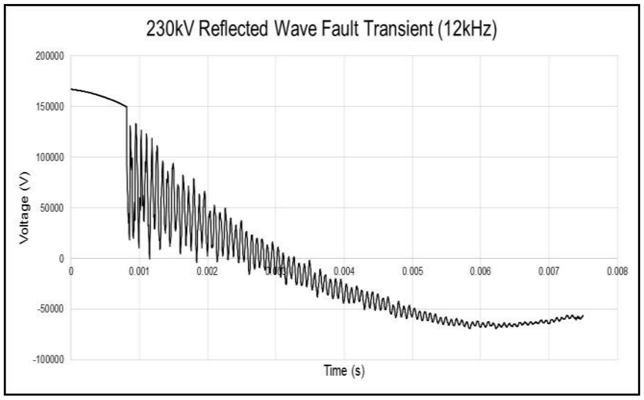

Figure 1
230 kV System Fault Transient
(Distance to Fault = 3.1 miles
Reflected Wave Frequency = 12 kHz))

The severity of a particular transient depends heavily on the loading of the transformer at the time of the transient. If the unit is lightly loaded, the probability of exciting a winding resonance is much higher.

One of the transformer failures studied during our investigation was a 500kV cable closed by a gas insulated circuit breaker. Because the prevention of all system faults is not possible, mitigation of all of these transients is unlikely. However, it may be beneficial to avoid placing capacitor banks at locations that would potentially produce reflected wave frequencies near the transformer's internal resonant frequencies.

Some of the case studies have modeled the transients produced by these reflections. Studies could be done in the planning stages when locating capacitor banks to avoid potentially hazardous distances. Manufacturers may also be able to increase insulation levels within the transformer at locations where these frequencies might produce higher voltage stress. In addition, utilities should evaluate the switching procedures, transmission cable lengths, switching device locations, capacitor bank pre-insertion resistor design, and capacitor locations as much as possible to avoid the production of dangerous frequency reflected wave transients at the terminals of a lightly loaded transformer.

Switching of large capacitive loads can also create the reflected waves in many cases. The switching of capacitors or cable will apply a temporary voltage transition to ground while the capacitance is being charged. Especially when this closing device connects the capacitive load to the system near a voltage peak, there can be traveling waves or interactions with the system that propagate from the point of closing. Depending on the cable lengths involved and the characteristic impedance of the transmission lines, there can be significant reflections that propagate to the terminals of nearby transformers. If these reflected waves excite the transformer near the internal resonant frequencies, these situations can also produce damaging voltages within the transformer. Switching cables have been known to cause these traveling wave transients.

Capacitor bank switching operations are a bit more complex and can be described in at least three different ways.

First, there is an interaction between the capacitance and the inductance of the bus that creates a damped oscillation. The transient in Figure 2 was produced by a capacitor switching event on a 115kV system. The approximate frequency of this transient was 1.1 kHz. It is typical for this type transient to be below 2 kHz in HV and EHV systems. Because this frequency is below most of the harmful resonance frequencies, it is not typical for this type of interaction to overstress the transformer.

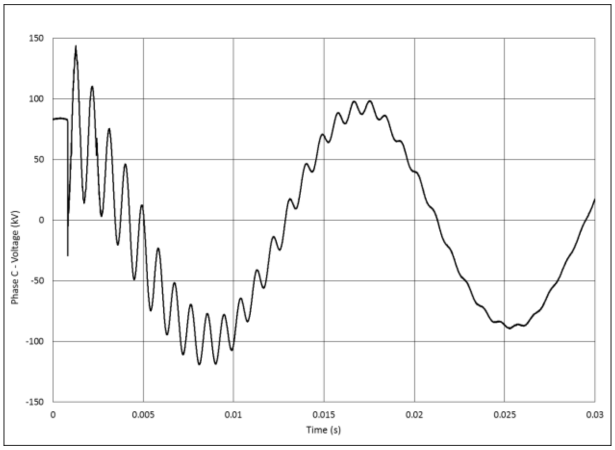

Figure 2
115kV Capacitor Switching Transient
Frequency 1.1 kHz

Second, there can be an interaction between two capacitor banks that are switched back to back. This interaction is caused by energizing an additional capacitor bank on a bus with one or more capacitor banks already attached to the bus. In this case there is a rapid exchange of energy between the capacitor banks and the loop inductance. This type of interaction causes higher frequencies that are defined by the distance between the capacitor banks and the capacitance of the banks. Although these interactions are in the frequencies which might cause resonance, the lack of significant numbers of transformer failures indicates that the duration and magnitude of the transients may not be a problem. In addition, the system loads in the circuit may not allow the transformer to reach a damaging resonant condition.

Third, there is the possibility of setting up a traveling wave caused by the rapid collapse of the bus voltage when the uncharged capacitor bank is connected to the bus. This could produce an oscillating waveform because of conditions similar to those in Figure 1. Just as in the back to back capacitor switching, this type of interaction can cause higher frequencies. However, again, the lack of significant numbers of transformer failures indicates that this type of interaction is not typically a problem.

Figure 3 is an expanded time scale of the fast collapse of the voltage in the Figure 2 capacitor switching. The voltage collapse is approximately 3-6 μs. There is a small magnitude 52 kHz oscillation that can be observed on this trace. Because this 115kV bus has multiple capacitor banks, more analysis must be done to determine if this interaction is the second or third type. The magnitude of this particular oscillation is only about 8-10 kV rms. This may not be enough voltage to cause damaging transformer oscillations. Again, this supports that conclusion that these types of interactions do not typically cause problems for HV and EHV transformers.

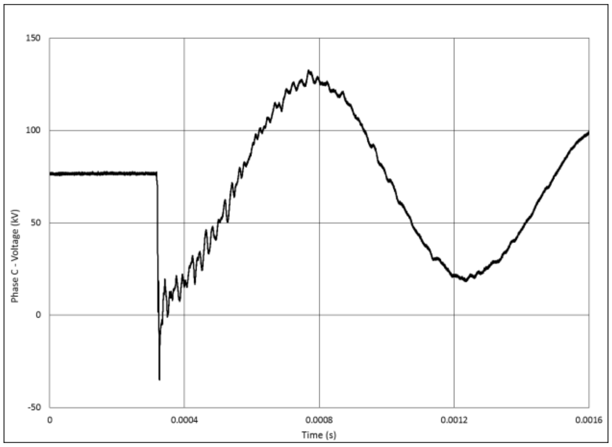

Figure 3
115kV Capacitor Switching Transient
Voltage Collapse = 3-6 μs
Oscillation Frequency = 52 kHz

This does not represent an exhaustive study on the problems caused by capacitor bank switching, but the system faults and cable switching seem to cause more significant problems in HV and EHV transformers.

B. Generator step-up transformers operating in back feed mode are excited to resonance by system transients

During the review of the failures, over twenty GSU transformer failures were found to be related to system transients. Further investigation is needed to verify that all of these were related to back feed mode, but several of the cases occurred while the units were in back feed mode. Because of the significant number of failures in GSU transformers, it was decided to discuss these units as a group. These failures occurred on units with system voltages from 230kV to 765kV.

The high transformation ratio and light loading during back feed operation makes these units particularly susceptible to resonance frequency excitation. Many of the flashovers occurred near the line terminals and between open phases on the LV windings. These failure areas lead one to believe that the failures are related to resonance within the windings. Studies have shown resonant frequencies in these units in the 10-100 kHz region on some units. The first resonant peak is often caused by a series resonance of the main gap capacitance and the leakage reactance of the three phases. In back feed mode, high frequency excitations can result in internal voltages above factory test levels without exceeding the arrestor's protection level. In some cases, surge arresters are not installed on the LV windings due to space limitations.

Several different system transient excitations were found to initiate these failures. These included switching transients, steep front lightning, bus faults, and remote ground faults. This may be due to the fact that several different resonant frequencies may be involved. The number of failures in this category seems to indicate that back feed mode is a particularly vulnerable state for these units.

One important frequency evaluation to perform on these units is the voltage transfer vs frequency from HV-LV. This analysis will identify the resonant frequencies that produce the highest voltage stress to the LV windings. High frequency modeling using potential in-service transients that would occur at these frequencies will help to determine the protection level needed in different areas of the transformer windings.

Several mitigation techniques may be used in these cases. These include increasing the winding BIL, installing LV surge protection, shunt capacitors, and snubber circuits. These methods will provide a combination of damping and increased insulation strength.

C. High frequency switching operations close to the transformer terminals excite internal resonance due to multiple re-ignitions and restrikes

The review of failures indicates that more than seven failures have been attributed to transients occurring in this category. Switching operations can produce many restrikes and re-ignitions. If the frequency of these transients is near the natural frequency of the adjacent transformer, this can excite these frequencies and be the source of damaging voltages within the transformer windings.

When disconnect switches are very near the terminals of the transformer, the line impedance does little to dampen the high frequency voltages that reach the terminals of the transformer. In particular, when frequent or abnormal switching operations occur, significant stress can be placed on the transformer's insulation structure. Many of these failures occurred in autotransformers, instrument transformers, and regulating transformers. Data from all cases has not yet become available, but several of the failures in these units occurred in the tertiary windings. As in many other cases, the problems have been observed in very lightly loaded situations where transformer resonant frequencies can be excited.

Load currents are normally interrupted by the circuit-breaker(s). However, disconnect switches are sometimes used to de-energize or energize light capacitance loads within the substation.

After the load current is interrupted, the substation bus often needs to be isolated by a disconnector. The current flowing in the disconnector to be operated is the capacitive current produced by the bus voltage applied to the capacitance of the open end bus. These currents are many times less than 1 A.

Disconnectors move very slowly when compared with other types of switching devices, such as breakers and load interrupting devices. For example, the opening operation of a 550kV or 800kV disconnect switch may take several seconds to move from the closed position to the fully opened position. For lower disconnector rated voltages, the operating speed is generally faster, due to the physical size of the switch and the length of the open position air gap required.

When a disconnector is operated with a small capacitive current flowing, an arc will be established between the contacts as soon as they have separated. This arc will be maintained until a sufficient isolating distance is reached. During the arcing process, the disconnector will temporarily interrupt the current but the current will be reinitiated as soon as the voltage across the disconnector contacts becomes higher than its voltage withstand capability for the disconnector gap spacing. This re-striking process is repeated for each half cycle of the power frequency. Tests made on an 800kV disconnector show that this re-striking process during an opening operation may last for several seconds, typically ranging from 1 to 5 seconds, thus leading to many consecutive restrikes per disconnector opening operation. The number of restrikes is typically larger for opening operations than for closing operations.

At each restrike, high frequency transient voltages and currents are produced. Current transients of a few 100 kHz can be generated in each single restrike. This transient is produced by the source side capacitance (energized bus) discharging into the load side capacitance (open bus) at the instant of the restrike. The source side capacitance includes the distributed bus capacitance, instrument transformer capacitance, and transformer capacitances (bushings capacitance + stray winding capacitances). A sample waveform from an 800kV bus de-energization is shown in Figure 4.

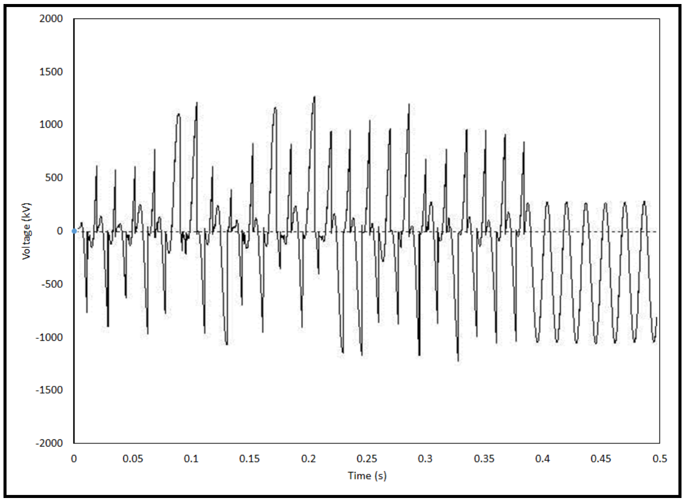

Figure 4
Disconnect Switch Bus De-Energization Transient

Equipment located close to the disconnector source side terminal normally supplies most of the high frequency re-striking current. This current is particularly harmful to instrument transformers and transformer bushings using capacitive graded insulation systems. Several failures have been observed in these particular systems. Special tests have been introduced, particularly for instrument transformers, in order to demonstrate that the instrument transformer is able to withstand such stresses produced during a disconnector operation. Power transformer bushings use insulation systems similar to those used in instrument transformers and can also be subjected to these same stresses.

The same re-striking phenomenon occurs when the disconnector is closing and making a small capacitive current. When the disconnect switch arm reaches a gap that can no longer withstand the applied voltage, the small currents will be initiated by a series of several restrikes and reignitions until switch contacts touch. The restrike phenomenon during a closing operation is generally much shorter than that observed during an opening operation.

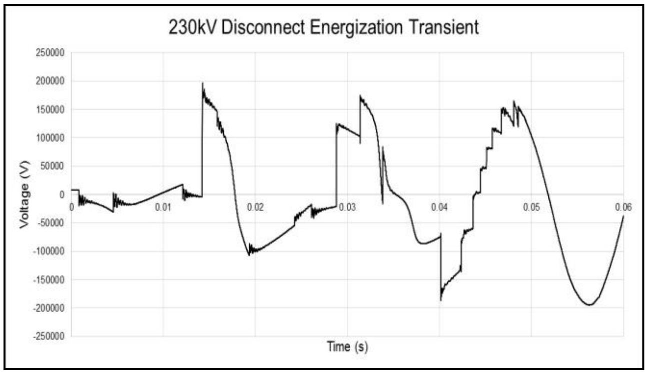

Figure 5
Disconnect Switch Energization Transient

A sample energization voltage event recording caused by energization of a 60MVA transformer using a 230kV circuit switcher closure is shown in Figure 5. The operation is the closing of an air insulated disconnect switch. In this case, several restrikes and reignitions can be seen on the voltage waveform before the switch blades engage and complete the energization of the transformer.

Several failures of HV and EHV devices have been attributed to these high frequency transients. These failures occurred on units with a voltage range from 500kV to 69 kV. Most of the failures were observed during disconnect switch operations.

Mitigation methods for these interactions could be achieved through various means, such as using alternate methods of switching, using surge arresters, and varying the procedures used to connect and disconnect these transformers.

III. HV AND EHV MITIGATION METHODS

In general, HV and EHV mitigation methods are different than those for lower voltage systems. Although, RC snubbers commonly used in medium voltage system, they are not typically applied for these HV systems. This is most likely due to the energy levels being produced, the physical size, and cost for snubbers at these voltage levels.

Typical HV and EHV mitigation methods are:

- Installing surge arresters at high stress locations
- Distributing grading capacitances in the windings
- Increasing the transformer insulation levels
- Applying synchronized switching devices
- Applying TRV capacitors

In addition to these methods, work is being done within the power industry to measure and to quantify the severity of system transients. The measurement of these transients allows for the improvement of system modeling and can help to pin point the sources of potentially damaging transients.

CIGRE working groups are currently working on improving high frequency models of the transformer and systems. The primary method to verify these models is to make quality high frequency measurements to validate the models.

This modeling has led to the development of methods to quantify the severity of system transients. This work has led to the definition of both frequency domain severity factors (FDSF)[2] and time domain severity factors (TDSF)[9]. These factors are defined to quantify the severity of a particular transient by defining its normalized magnitude compared to factory test levels. When used in conjunction with wide bandwidth transient measurements, this could lead to the identification of damaging system transients. Once these transients are identified, the development of additional mitigation methods may be possible.

IV. CONCLUSIONS

The current revision of C57.142-2010 does not include specific information on HV and EHV interactions and equipment failures. However, the concepts and scope of this standard apply to system interactions with all voltage classes. The absence of specific HV and EHV examples might lead those utilizing this standard to believe that system interactions do not occur in higher voltage systems. This would be an incorrect conclusion.

Failure of large power transformers can be very costly. In addition, the parties that are involved may not be as open to discussion of the root causes until a full investigation and a mitigation method has been finalized and proven. Many times these failures are studied extensively, but the data is often not widely shared. We may not be able to avoid this situation, but it should not lead users to believe that interactions do not occur at these voltage levels.

After reviewing work done by CIGRE, we observed that the recently published brochure includes many specific high voltage examples. In fact, this brochure includes more HV and EHV examples than lower voltage examples. This CIGRE work was included in the development of the three categories described in this paper.

In addition to the CIGRE work, this task force has reviewed presentations and received input from several industry experts that have confirmed that these interactions do occur at HV and EHV voltages.

V. RECOMMENDATIONS

In order to clarify the applicability of this standard and help the understanding of these interactions, this task force recommends that material on HV and EHV interactions be included in a proposed revision of the C57.142 standard. Specifically, the three failure categories identified in this paper could be used as an initial basis for additions to C57.142.

All of these sources indicated that the inclusion of this HV and EHV information would be beneficial to the future and current users of C57.142. The discussions of the task force support the inclusion of this information and the decision of this task force to recommend such inclusion of this information.

References:

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