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PS 3 – Best Practices in Transformers and Reactors Procurement

Impulse Testing of Power Transformers - Impact of Internal Varistors built into On-load Tap Changers

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SUMMARY

Dielectric testing of Power Transformers includes Lightning Impulse, Switching Impulse, Separate Source withstand test and Induced voltage with partial discharge measurement. Impulse testing of large power transformers is not always without any surprises. It happens sometimes that a dielectric fault indicated by waveform mismatch during impulse test may not actually correspond to a fault. In such situations, test engineers have a challenging task of finding out the real cause of these mismatches based on the travelling wave theory and test circuit verifications. Two such unusual discrepancies noticed are discussed in this paper. The cause of these mismatches were the varistors built into the tap changers, initially assumed to be a dielectric failure.

The first case was 417 MVA, 345/115/13.8 kV autotransformer and the second one was 600 MVA, 345/141.5/13.8 kV autotransformer. Both designs used On Load Tap Changers that has built in varistors in diverter assembly .When varistors are used by designers to limit the voltage across tap winding, the waveform mismatch between the reduced and full wave impulse is caused by conduction of varistors. Hence, the special IEEE impulse test protocol for varistor designs will be applicable. This protocol, in contrast to those without varistors, will require comparing the reduced to reduced voltage waveforms instead of reduced to full voltage waveforms, to identify a fault. However when varistors are part of tap changers, it is more likely that they go unnoticed especially when not indicated by LTC vendor and assumed as non-varistor designs. This can result in using the standard test protocols for identifying failures, which can show up as a fault and can take significant effort before figuring out the root cause.

The aim of the paper is to save time and effort of transformer manufacturers by

1. Sharing our experiences when using LTC with internal varistors and how it can be misinterpreted for a fault

2. Recommendation to look for usage of LTC varistors and add appropriate checkpoints in test instructions so that appropriate IEEE test protocol is followed.

This study is particularly important because this can trigger partial varistor operation that shows up in transient voltage waveforms interpreting as a fault.

KEYWORDS

Power Transformers, On Load Tap Changers, Varistors, Impulse Test, IEEE C57.12.90, Nonlinear protective devices.

1. INTRODUCTION

Transformers are key links in any electric power systems, and their reliability should be ensured for the uninterrupted power delivery. The dielectric, mechanical, and thermal reliability of the transformer is ensured by various factory tests. Impulse testing of the transformer is a reliability test that checks the dielectric integrity of the transformer under lightning and switching impulse, which a transformer can see during its lifetime. Any failures during the lighting impulse test might indicate a design or manufacturing weakness that needs to be corrected.

The impulse test failures can be visible, audible, and measurable, or sometimes can result in voltage collapse. In few cases, the only way an impulse test failure can manifest will be the mismatch between the voltage and neutral current waveforms that are measured during 100% and reduced impulse test. A typical scenario where the waveform mismatch that did not indicate a failure, but was due to the operation of built-in varistors in tap changers, is discussed in the paper.

2. DETECTION OF FAILURE DURING IMPULSE TEST

As per IEEE C57.12.90, Sec10.3.4, different protocols are to be followed to detect a failure when employing nonlinear protective devices like varistors. In order to distinguish a transformer failure from the normal operation of the non-linear devices, it is necessary to demonstrate the repeatability and reversibility of any changes being caused by the non-linear devices. This can be achieved by the application of additional impulse tests as in the sequence suggested below.

- One reduced full wave at a level between 50% and 70% of the required full-wave impulse level
- One or more intermediate reduced full waves at a magnitude between 75% and 100% of the required full-wave impulse level
- One full wave at 100% of the required impulse level
- Two chopped waves at 100% of the required chopped-wave impulse level
- One full wave at 100% of the required impulse level
- One or more intermediate reduced full waves at the same voltage levels that were used before the first 100% full wave
- One reduced full wave at the same voltage level, between 50% and 70% that was used prior to the first intermediate reduced full-wave shots

Because of the operation of the non-linear devices, the comparison of the voltage and current oscillograms are made only between two tests performed at the same voltage level. All intermediate reduced full-wave tests performed after the full-wave tests are compared with the corresponding intermediate reduced full wave test performed prior to the 100% full-wave tests.

3. ON-LOAD TAP CHANGERS WITH BUILT IN VARISTORS

Nonlinear protective devices like varistors are not only used in transformers, but also by tap changer manufacturers to limit the voltage across the diverter. The vacuum tap changer series VRx and VM always have ZnO elements (varistor) as shown in Figure 1.

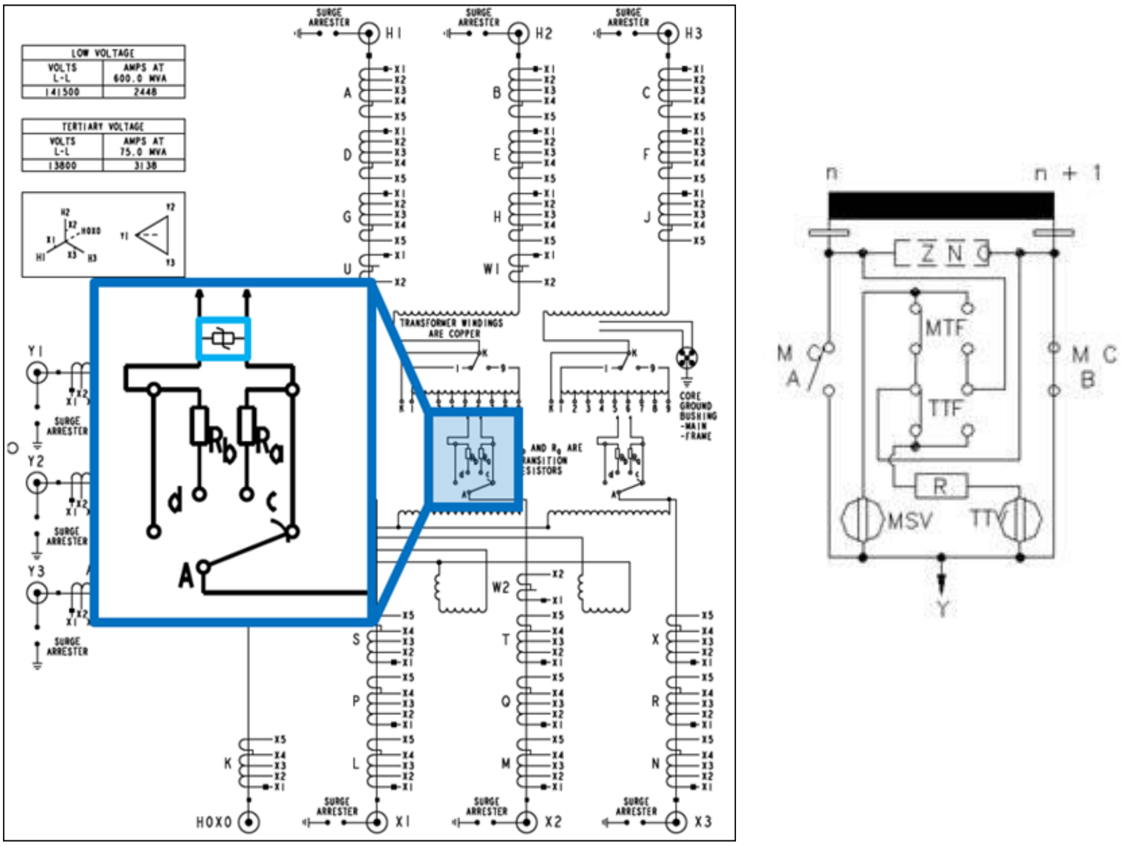

Figure 1 Tap changer with Varistor connection

The ZnO elements are made from a zinc oxide alloy. Their resistance is very high under normal operating voltage but reduces to a small value in overvoltage conditions. These voltage-dependent resistors engage constantly and instantaneously into the surge operation. The protection level is determined by the the current-voltage curve of the varistor which is shown in Figure 2.

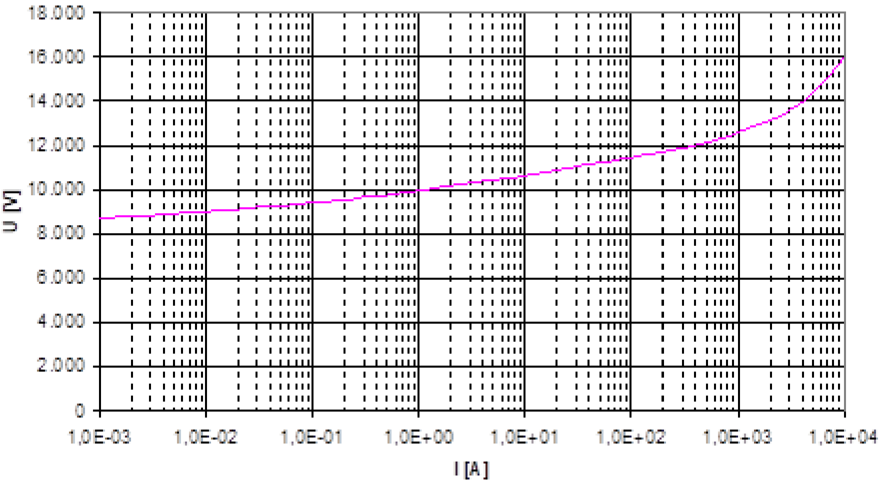

Figure 2 Current-Voltage curve of Tap changer Varistor

4. EXPLICIT VS INTERNAL LTC VARISTORS AND MISINTERPRETATION OF DIELECTRIC FAULT

Depending upon the transformer design, non-linear-protective devices such as ZnO disks may be used in transformers. These devices may be connected across the whole, or sections of the windings. Their purpose is mainly to limit transient over-voltages, which may be impressed or induced across the windings, to safe levels. These devices display nonlinear impedance vs. voltage characteristics. Their impedance up to a certain voltage level is very high. If voltage across these devices exceeds this level, their impedance decreases in a non-linear manner. The characteristics of these devices are so chosen that during normal transformer operation they present very high impedance, thus allowing whole windings or winding sections to perform in a normal manner. However, when voltage across them exceeds a certain level, their impedance decreases to limit the voltage and protect the winding sections.

By their very nature, non-linear protective devices connected across the windings may cause differences between the reduced full-wave and the full-wave impulse oscillograms. That these differences are indeed caused by operation of these devices are usually demonstrated by making several intermediate reduced full-wave impulse tests at different voltage levels to show that the trend of the changes seen on the impulse oscillograms are caused uniquely by operation of the protection device. Provided that the temperature of the protection devices remains relatively constant, impulse wave shapes recorded at the same voltage level should be identical.

The above discussion holds true for any type of nonlinear devices, like varistors, independent of where it is being used, such as windings or tap changers. When used in windings by transformer designers, the appropriate IEEE impulse test protocol for varistor designs is followed. However, when used as part of tap changer they may go unnoticed if not indicated by LTC vendor and will result in test time surprises. This can result in using the standard test protocols for identifying failures, which can show up as a fault and can take significant effort before figuring out the root cause. Two such unusual discrepancies noticed are discussed in this paper. The first case was 417 MVA, 345/115/13.8 kV autotransformer and the second one was 600 MVA, 345/141.5/13.8 kV autotransformer. Both designs used On Load Tap Changers that has built in varistors in diverter assembly.

5. CASE STUDY 1 - 417 MVA, 345/115/13.8 KV AUTOTRANSFORMER

5.1. Transformer Data

Table I Case Study 1 - Transformer Data

Transformer MVA:	HV 250 / 333 / 417 LV 250 / 333 / 417 TV 60 / 80 / 100	HV	345 kV GrdY	BIL 1050 KV
Transformer Cooling:	ONAN / ONAF / ONAF	LV	115 kV GrdY	BIL 450 KV
LTC	Yes – XV Line End	TV	13.8 kV	BIL 110 KV
DETC	Yes - HV	Neutral		BIL 150 KV

5.2. Problem Description

During the Full wave test, the voltage waveform at reduced voltage did not match the waveform at full voltage on X3 during impulse testing on 16L tap, but the voltage waveforms matched on N and 16R taps (see Figure 3). The X3 reduced-to-reduced and full-to-full voltage waveforms matched on all taps. X1 and X2 impulse voltage waveforms matched on any tap.

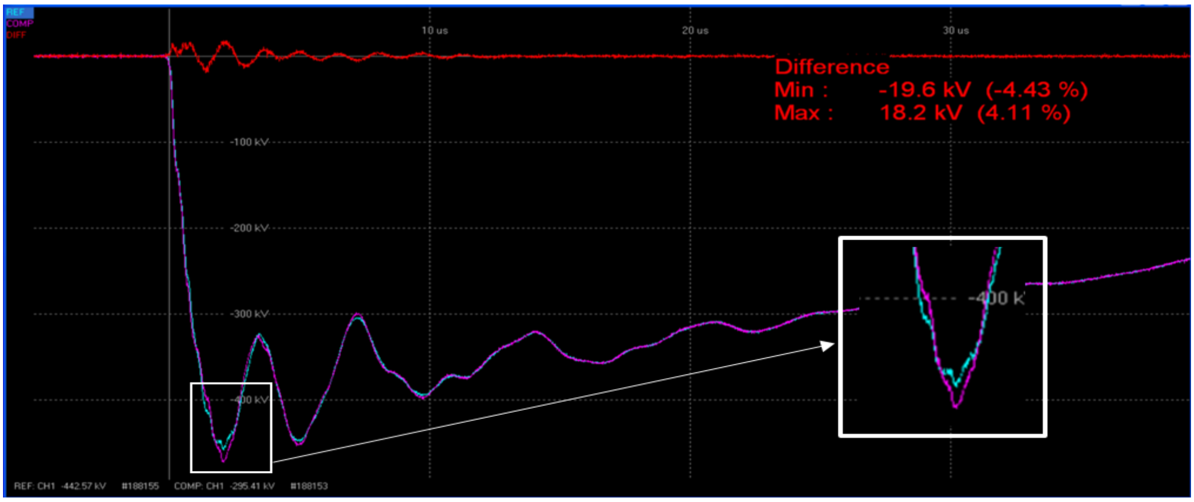

Figure 3 Voltage waveform for X3 (reduced to full)

The unit was drained and an internal inspection was performed. No issues were found during the inspection. After performing many diagnostic tests, it was found that varistors were used in the tap changers, which can cause waveform mismatches. Hence it was decided to bypass the varistors from the circuit on all three phases and re-test. The unit was processed and returned to test for diagnostic impulse tests.

Impulse testing was performed on X1, X2 and X3 (16R and 16L taps). The waveform mismatches previously seen when testing reduced-to-full on X3 (voltage) were no longer present, confirming the interaction of the varistors as shown in Figure 4.

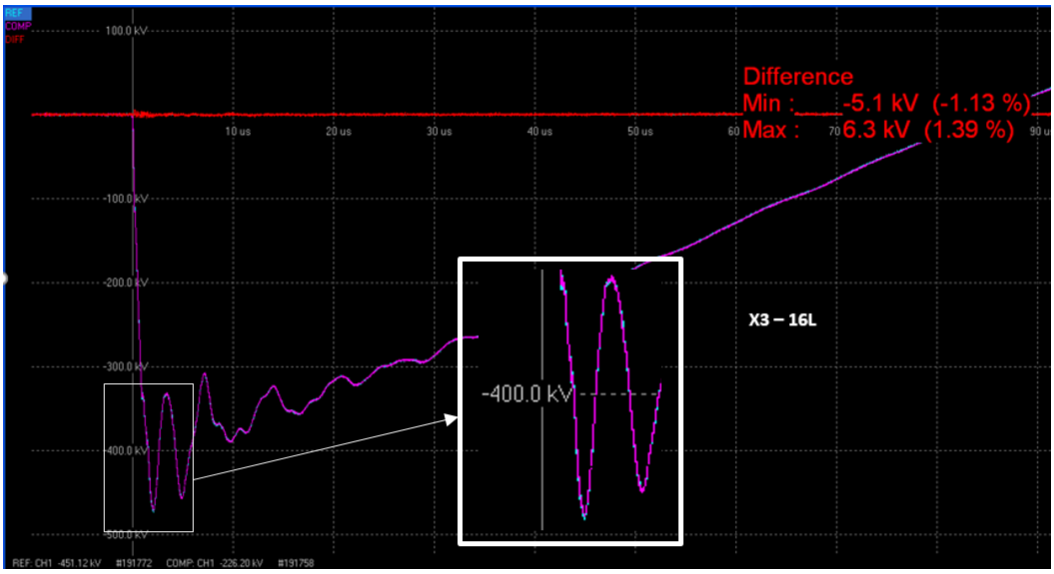

Figure 4 X3-16L voltage waveform with varistors bypassed

5.3. *Root Cause*

Variations observed in the voltage and current waveforms were due to varistors conducting in the tap changer during the impulse test. In the specified LTC, the manufacturer has installed varistors in the diverters of the LTC to optimize the size of tap changer. The difference in performance between phases could be attributed to LTC lead cable lengths slightly changing the RLC network for each phase, as well as tolerance in the conduction voltage of the varistors. This is probably the cause that the problem was noticed on one phase X3 and not all phases.

5.4. *Verification of Transformer Performance*

The unit underwent full dielectric testing with varistors connected and using the modified test protocol for varistor designs. This testing included additional impulse tests on X3 A-16L, X3 A-15L, X2 C-1R, X2 C-16L, X1 E16R and X2 E-16L. All tests were successful and impulse tests performed as expected.

6. CASE STUDY 2 - 600 MVA, 345/115/13.8 KV AUTOTRANSFORMER

6.1. *Transformer Data:*

Table II Case Study 2 - Transformer Data

Transformer MVA:	360 / 480 / 600	HV	345 kV GrdY	BIL 1175 KV
Transformer Cooling:	ONAN / ONAF / ONAF	LV	141.5 kV GrdY	BIL 650 KV
LTC	Yes – HV, Common end of series winding	TV	13.8 kV	BIL 150 KV
DETC	No	Neutral		BIL 150 KV

6.2. *Problem Description*

During impulse testing, the transformer showed voltage and current mismatches on X3 as shown in Figure 5. An audible noise was heard but the failure did not go to ground. X1 and X2 had minor mismatches at the time when X3 had its issue. All HV impulse testing had been completed and was acceptable.

The unit was drained and prepared for internal inspection. X3, RV and TV leads were traced and inspected and no failure points were found. The unit was processed, oil filled and returned to test. X3 impulse was good at 50%, but mismatches returned at 70 and 100%, with mismatch getting larger after chop wave testing. During this round of testing X2 also failed on full wave (after chop wave), with sound internal to the unit and mismatches on both voltage and current. X1 was tested, but did not exhibit significant mismatches.

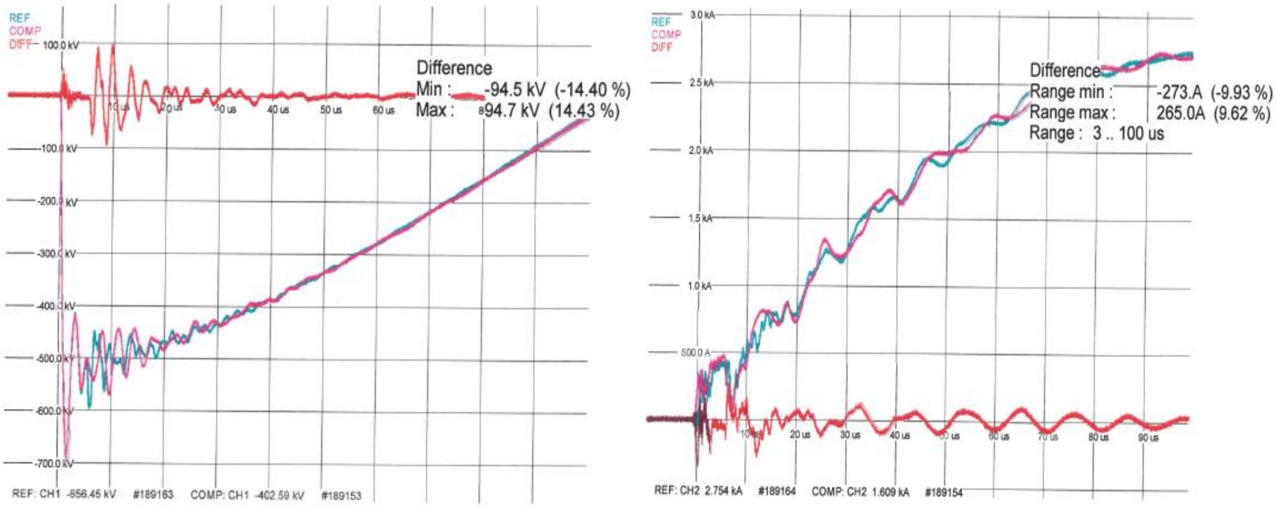

Figure 5 X3 Impulse voltage and current waveforms

The unit was drained and prepared for an additional internal inspection. A failure point was found between the B-phase #3 and #8 leads. An extensive inspection of LTC lead cables, including opening up all accessible clamps to look for tracking or damage along the inside of the cable clamps, was performed with no findings.

To locate the source of the X3 failure, the transformer was un-tanked for a more detailed inspection. The failure point at the B-phase #3 and #8 leads was confirmed, but an additional failure point was not discovered. The coil assemblies were removed from the core for all three phases and all coils were un-nested. All coils and the core were inspected for potential failure points. The failure point on the C-phase RV coil was easily identified between leads 8 & 6, followed by leads 6 & 4. No additional failure locations were identified.

Mismatch seen at 5-7 microseconds was due to conduction of varistors (operating Maximum Continuous Operating Voltage (MCOV) 45KV). After discussions with the vendor, the cause of varistor's operation (below the specified MCOV of 45kV at about 30KV design value) was believed to be the effect of gradual increase of conductivity before reaching MCOV, leading to misinterpretation of failure while comparing reduced to full waves.

This transformer was a typical example where both the tap changer varistor operation and a RV lead-to-lead failure were present. This resulted in both waveform mismatch and audible noise during the test. Since the built in varistor was not taken into account, the appropriate impulse failure protocols were not used. This delayed the process of troubleshooting and arriving at the root cause.

6.3. Corrective action

All three RV coils and all RV lead cables were replaced during repair of the unit.
The RV coils were redesigned changing lead numbering to achieve interleaving of cables. This helped to reduce the voltage between tap changer selector and pre-selector such that the varistor internal to the tap changer may not activate and cause mismatch between reduced full wave and full wave impulse shots.

To confirm if interleaving of parallel RV winding cables reduced the voltage across RV and thereby avoided triggering of varistors, an RLC based circuit simulation was performed. The simulation results for the voltage across tap circuit 8, with and without varistors, for interleaved and non-interleaved designs are shown in Figure 6 & Figure 7.

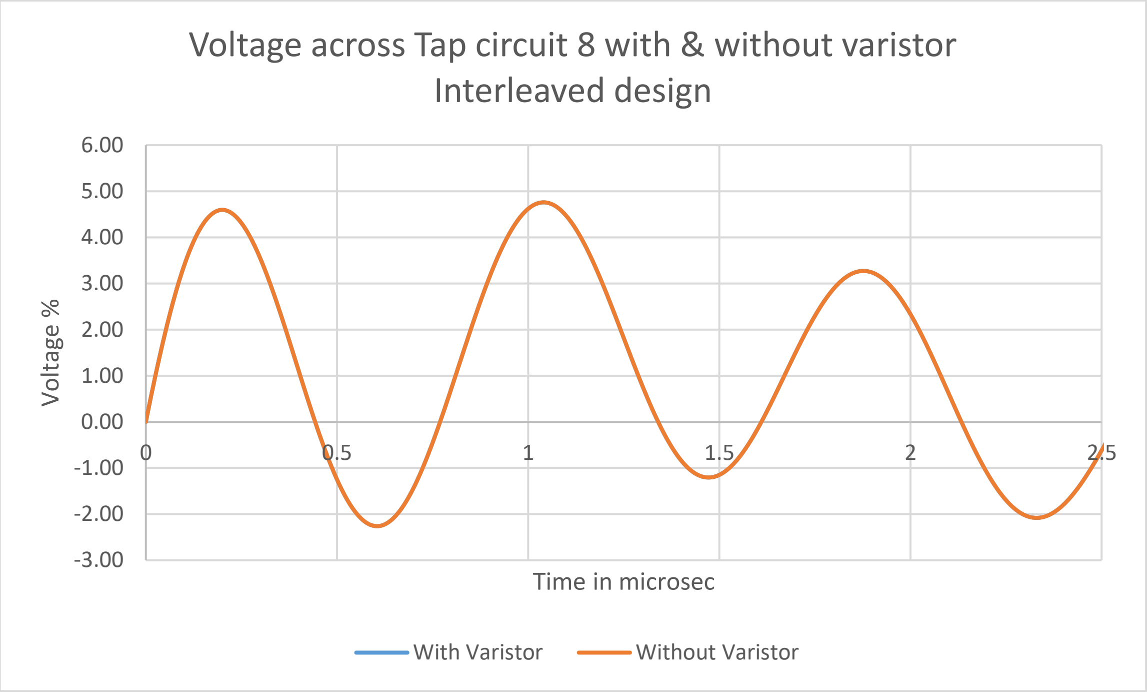

Figure 6 Varistor operation for interleaved design

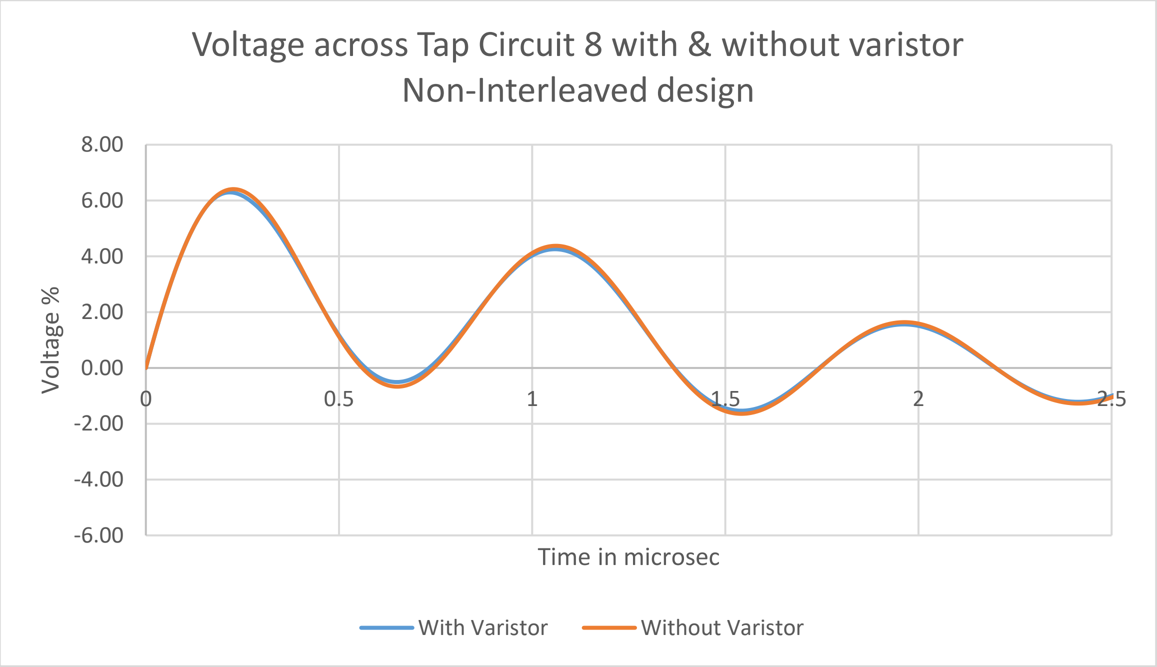

Figure 7 Varistor operation for non-interleaved design

As seen from Figure 7, there is a small voltage mismatch with and without varistor indicating that the varistors are triggered for non-interleaved designs. However from Figure 6, there is no voltage mismatch with and without varistors indicating that the varistors are not triggered for interleaved designs.

Full testing of the transformer was performed after the corrective action and it passed all tests. To avoid this issue in future, it was decided to use the appropriate IEEE impulse test protocol for varistor designs in the test plan whenever internal varistors are used in tap changers.

7. RECOMMENDATIONS

When selecting tap changers it is important to ensure if they have built-in varistors. If such tap changers are used, the test plans should reflect the appropriate test protocols. The other choice is to eliminate the operation of varistor during test by appropriate tap winding design. When the varistors are taken into account, troubleshooting becomes easy in case of a real impulse failure. Accounting for the presence of built-in varistors in tap changers during design can also avoid secondary failures that can happen when trying to find the root cause of mismatches.

8. CONCLUSION

Although it is well established that different impulse test protocols should be used when using varistors, these were usually assumed only for cases with explicit varistors used by designers to limit the voltage across tap changer. For cases like those discussed in the paper where the varistors are part of tap changer, varistors can go unnoticed and may result in test time surprises and delay troubleshooting. By bringing this to attention, this paper helps alleviate such problems in future.

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