VACUUM CIRCUIT BREAKER AND TRANSFORMER INTERACTION IN A CABLE SYSTEM

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ABSTRACT.

Vacuum circuit breakers can cause repetitive transient overvoltages with steep fronts in some cases, depending on the combination of the system configurations and type of circuit breaker operations.

Laboratory testing has been performed to improve the understanding of the high frequency system interaction between vacuum circuit breaker, transformer, and cables. A dry type medium voltage transformer has been energized and disconnected in a 20 kV medium voltage laboratory cable system using a vacuum circuit breaker. The transformer is a standard transformer, equipped with additional voltage measuring taps along the disks of one of the high-voltage windings, enabling the measurement of the voltages in the winding when exposed to transient overvoltages.

The results show that normal no-load energizing and disconnection of the transformer do not cause any high overvoltages. Disconnection of the transformer with an inductive load or a trip on inrush current during energizing can cause transient overvoltages. Surge arresters, both phases to ground and phase to phase, are recommended for a transformer exposed to these types of circuit breaker operations.

TESTS ON A DRY TYPE TRANSFORMER.

A dry type cast coil transformer was used for the cable system testing (Figure 1). The transformer was manufactured with extra measuring taps along one of the Δ-connected high-voltage windings to enable recording of the internal voltage distribution along the disks of the winding. The taps were positioned at every disk at both ends of the winding, and at every second disk in the middle of the winding.

The voltages at the terminals of the high-voltage winding as well as the voltages between the measuring taps and ground have been recorded.

The transformer was also exposed to the lightning impulse test for comparison and reference.

Figure 1. Test transformer with measuring taps along one of the high-voltage windings.

Cable system laboratory testing.

Extensive testing has been performed in a laboratory cable system at ABB Corporate Research high power laboratory (Figure 2) when energizing and disconnecting the transformer. The aim was to find out if a transformer installed in a cable system and operated by a vacuum circuit breaker is exposed to higher or other types of stresses not covered by the standard lightning test.

The worst cases with respect to both the system configuration and to the type of circuit breaker operation were identified and selected for the testing. The highest stress is expected when combining the worst system configuration with the worst circuit breaker operation.

Cable system.

The cable system test circuit was designed to enable testing with the circuit breaker either close (4 m) to the transformer or with a 72 m long cable between the transformer and the circuit breaker (Figure 2). A ring main unit (RMU) with a vacuum circuit breaker was used for the testing.

One example of a worst system configuration is with a long cable upstream the circuit breaker and a short cable between the circuit breaker and the transformer, which is fulfilled when installing the RMU 4 m from the transformer.

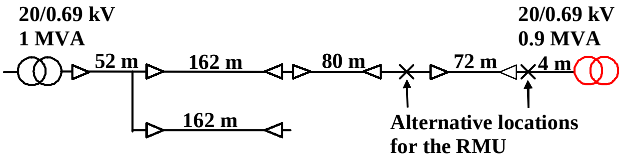

Figure 2. Laboratory cable system and the two selected locations of the vacuum circuit breaker.

Vacuum circuit breaker operations.
The following circuit breaker operations were selected and performed in order to cover both the normal transformer circuit breaker operations and the worst cases:

1. Energizing the transformer during no-load.
2. Disconnecting the transformer during no-load.
3. Interruption of the transformer inrush currents.
4. Disconnecting the transformer with inductive load.

The normal transformer circuit breaker operations are energizing and disconnection during no-load conditions corresponding to cases 1 and 2. A worst case for the circuit breaker operation is disconnection of an inductive load, corresponding to cases 3 and 4.

RESULTS.

Energizing during no-load.

Energizing the transformer causes always at least one prestrike per phase. The transformer terminal voltages (Figure 3) show a few step voltages with 1.5 times the amplitude of the nominal phase to ground voltage.
The distortions seen in the 50 Hz voltages during energizing of the test transformer is a consequence of the low rated power of the feeding transformer. The transformer inrush current is several times higher than the nominal current, and the result is that the inrush current of the test transformer exceeds the nominal current for the feeding transformer.

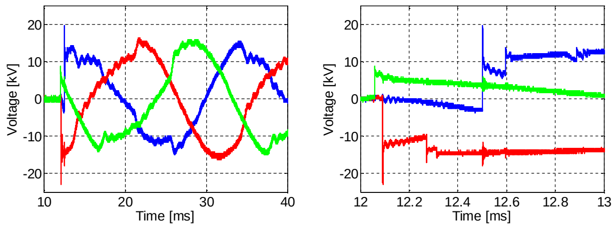

Figure 3. Transformer terminal voltages.

The left diagram in Figure 4 shows the two terminal voltages and the midpoint voltage for one of the high-voltage windings. The step voltages excite the internal resonances of the high-voltage winding. The time expansion of the front of one of the pre-strikes in the right diagram in Figure 4 shows the terminal voltages and the midpoint voltage and the voltages for the 4 disks at the end of the winding. The disk voltages are not uniformly distributed, stressing disks close to the winding ends more than others.
The fronts of the step voltages are steeper than for the lightning impulse test. However, the voltage distribution between the disks still follows the expected capacitive voltage distribution in the same way as for the lightning impulse test. The voltage is however well below the lightning impulse test.

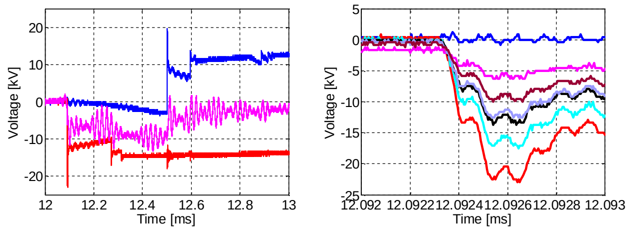

Figure 4. Left: Terminal voltages and voltage at the midpoint (200 µs/div). Right: Voltages at the terminals and the midpoint and at the 4 end disks (0.2 µs/div).

Disconnection during no-load.

The rated power of the transformer used for the tests is 0.9 MVA. The transformer no-load current is significantly lower than the current chopping level of the vacuum circuit breaker. Therefore, the currents in the three phases are immediately interrupted (chopped) when the circuit breaker contacts start to open. The highest chopped current occurs when the current is close to the peak value at the instant when the contacts separate, see an example in Figure 5. No severe overvoltage is built up due to the combination of the low chopped current and the low voltage withstand of the circuit breaker contacts immediately after contact separation. In this case, the chopping current is below 100 mA and only two re-ignitions occur.
Another important reason for the low transient voltages is that the voltages at the transformer terminals are very well damped and without oscillations when disconnecting the no load transformer.

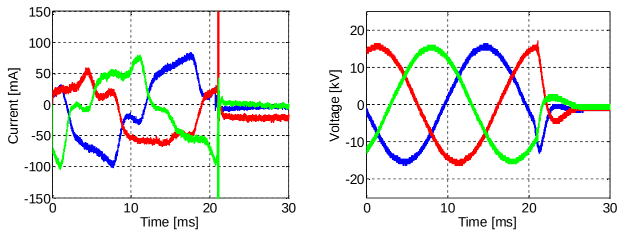

Figure 5. Left: Circuit breaker currents. Right: Transformer terminal voltages.

Interruption of transformer inrush current.

Disconnecting the transformer before the steady-state no-load current is reached can imply interruption of much larger currents. This is the case when the inrush current causes the circuit breaker to trip on over-current. The current that is chopped is now larger and determined by the vacuum circuit breaker and not by the transformer no-load current. The current chopping overvoltage causes the vacuum circuit breaker to re-ignite (Figure 6). The first re-ignition is followed by a large number of interruptions and re-ignitions causing higher and higher peak voltages.

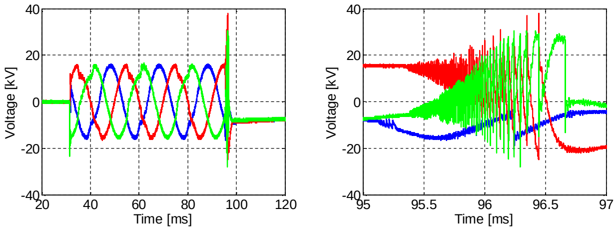

Figure 6. Transformer terminal voltages.

Disconnecting the transformer with inductive load.

This is regarded as the worst-case circuit breaker operation; in order to reduce the stress on the transformer, the vacuum circuit breaker was connected by a longer cable to the transformer for this test, making the system configuration "less bad" (Figure 7). In addition, surge arresters were installed phase to ground at the transformer terminals.

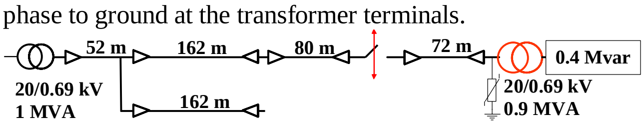

Figure 7. Inductive load and surge arresters at the transformer and 72 m cable between the transformer and the vacuum circuit breaker.

Figure 8 shows the transformer terminal voltages for an operation when multiple re-ignitions occurred. The voltages were limited to 30 kV by the surge arresters. The limitation of the voltages also helped to end the re-ignitions

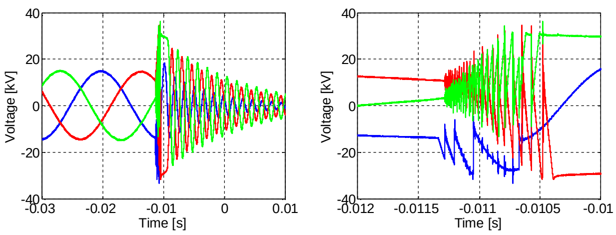

Figure 8. Transformer terminal voltages.

ANALYSIS.

The worst case with respect to transient overvoltages occurs when interrupting a current of several amperes with an inductive load. This case has been analyzed and compared with the standard lightning impulse test.

The following properties characterize the transient overvoltages:

1. Amplitude, U
2. Rate of rise, dU/dt
3. Repetition frequency, $f = 1/\Delta t$

Amplitude *U*.

Both the voltages from the transformer terminals to ground and the voltages across the windings have to be taken into account The terminal voltages stress the insulation to ground, whereas the voltage across the windings stress the inter turn insulation. The terminal voltages were limited to 30 kV by the surge arresters, in order to protect the high-voltage probes. A protective level selected according to the nominal system voltage would have given higher voltages. The voltages across the windings (Figure 9) reach 60 kV, which is twice the surge arrester protective level but still only half the lightning impulse test voltage level of 125 kV.

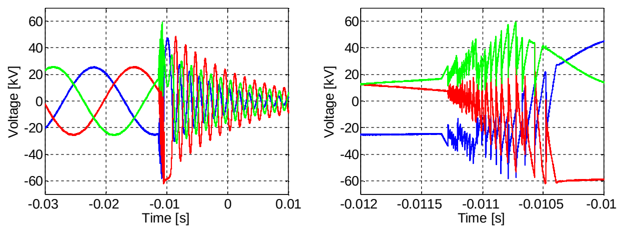

Figure 9. Voltages across the high-voltage windings.

Rate of rise d*U*/d*t*

The rate of rise has an impact on how the voltage across the winding is distributed between the turns, and also on the excitation of internal resonances in the winding. One example of the voltage across one of the high-voltage windings is shown in Figure 10. The time expansion of one of the re-ignitions is shown in the right diagram. The amplitude of the voltage step (ΔU) is about 60 kV. The rise time (Δt) is less than 0.1 µs, giving a rate of rise of about 600kV/µs which is higher than for the lightning impulse test but not as high as originally expected, for reasons discussed further below. The step voltages did excite the same transformer winding resonance frequencies as the standard lightning impulse test and the voltage distribution along the winding was the same as for the standard lightning impulse.

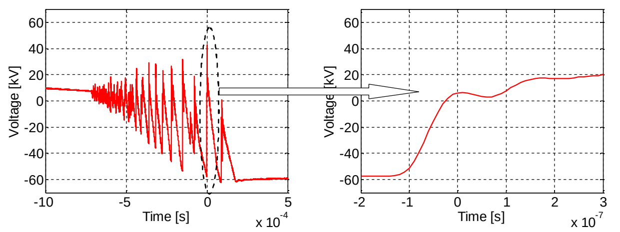

Figure 10. Voltage across one of the high-voltage windings. Right: Time expansion (0.1 µs/div).

The expected rise time of the voltage steps at the transformer terminals caused by pre-strikes or re-ignitions of the circuit-breaker is usually estimated by the surge impedance of the cables (~ 25 Ω) and the transformer surge capacitance (~ 0.2 nF) terminating the cable. Assuming an ideal step voltage the rise time of the voltage at the transformer would result in 11 ns ($t_{10\%}^{90\%} = 2.2RC$), which is much shorter than measured.

The difference can be explained by taking into account the stray inductances in the switch gear connecting the cables on both sides of the circuit breaker (Figure 11). Modeling this phenomenon with inductances connected in series to the circuit breaker reduces the rise time of the step voltage considerably. This has a similar effect as a shunt capacitor at the transformer. The rise time of the voltage step entering the cable downstream the circuit breaker is then given by the resistance calculated from the surge impedance of the cable ($R = 2\,Z_{surge}$) and the stray inductance L. For instance, $R = 50\ \Omega$ and $L = 2\ \mu\text{H}$ lead to $t_{10\%}^{90\%} \approx 2.2L/R \approx$ 88 ns, which is similar to the recorded rise times.

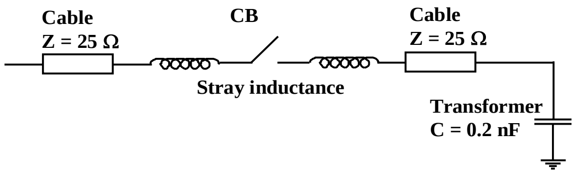

Figure 11. Single phase electrical model of cables, circuit breaker and transformer.

The conclusion is that the rise times of the step voltages caused by the pre-strikes or re-ignitions of the vacuum circuit breaker are limited by the stray inductances of the switchgear. This was verified by closing the circuit breaker with and without the transformer and measuring the phase to ground voltages at the end of the cable. The same rise time was obtained in both cases.

Repetition frequency $f = 1/\Delta t$.

One major difference between the lightning impulse test and the system transient overvoltages is the multiplicity of the step voltages. The concern is whether repetitive step voltages could cause higher stress to the transformer winding than a single high-voltage impulse. The voltages at the transformer terminals as well as at the midpoint of each high-voltage winding were recorded when disconnecting the transformer with inductive load.

The voltages at the terminals (Figure 8) were limited to 30 kV by the surge arresters, but the voltages to ground at the winding midpoints reached 50 kV, see Figure 12.

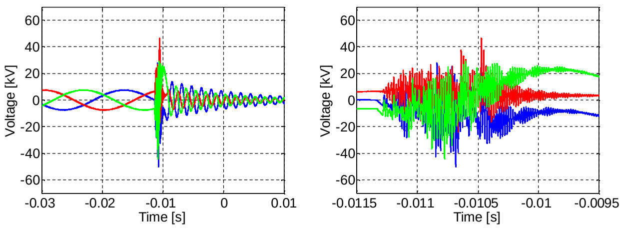

Figure 12. Transformer winding midpoint voltages.

The voltages at the terminals and at the midpoint of one winding are shown expanded in Figure 13. Each re-ignition causes a step voltage at the transformer terminal exciting the internal resonances of the transformer winding. The repetition rate of the re-ignitions varies, starting with a high rate above the resonance frequency of the transformer winding and ending with a rate below the winding resonance frequency for the last re-ignitions. The winding midpoint voltage oscillates with the resonance frequency of the winding and the amplitude varies. The amplitude increases when the transformer resonance frequency is close to a multiple of the repetition rate of the re-ignitions and decreases in between.

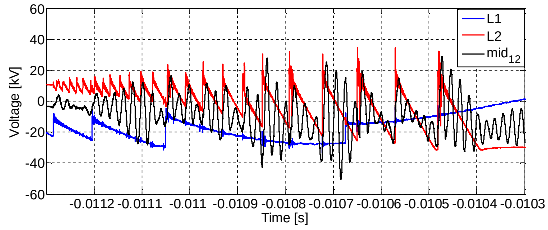

Figure 13. Time expansion of terminal voltages phases "L1" and "L2" and winding midpoint (100 µs/div).

Strong amplification of the resonance occurs only if the source frequency (or a multiple of it) is equal to the resonance frequency and if it is applied for many periods. This is not fulfilled in this case since the re-ignition rate quickly varies with time and only very few re-ignitions have suitable repetition rates.

CONCLUSIONS.

Circuit breaker operations.

Normal energizing and disconnection of the transformer during no-load conditions did not cause high overvoltages. Interrupting the transformer inrush current or disconnecting the transformer with inductive load can cause multiple re-ignitions and high transient overvoltages.

Transformer properties.

The tested transformer shows the same voltage response to transient overvoltages produced by the vacuum circuit breaker as to the lightning impulse test. The voltage distribution along the high-voltage winding follows the expected capacitive voltage distribution in both cases and the steep fronts of the pre-strikes or re-ignitions did not excite any higher winding resonances than found in the lightning impulse test.

Recommendations.

Surge arresters are recommended for protection of the high-voltage winding if there is a risk that the transformer is disconnected shortly after energizing, thus interrupting the inrush current, or if it is disconnected during load conditions. The surge arresters should be connected both phase-to-ground and phase-to-phase, left diagram in Figure 14. An alternative is the Neptune configuration utilizing 4 arresters, right diagram in Figure 14.

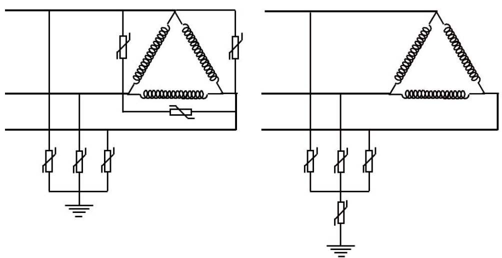

Figure 14. Recommended surge arrester alternatives.