CONTROL OF INDUCTIVE LOAD SWITCHING TRANSIENTS

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ABSTRACT

Voltage transients are inevitable when switching in MV and HV networks. Overvoltages up to a level of 3 p.u. are quite normal and acceptable in relation to insulation coordination. Only in very specific cases, extra precautions are needed in order to limit the probability and/or level of unacceptable overvoltages, irrespective of the arc-quenching medium.
The new edition 3 of the IEC 62271-110 standard on inductive load switching demands both stalled motor switching and shunt reactor tests for MV breakers.

Apart from overvoltages beyond the withstand capability, also voltage surges with high steepness and even internal resonances are considered to be a possible cause of failed dry-type transformers. This implies that transformer modeling plays a crucial role when studying these phenomena. The question is raised whether the transformer standards should be revised on the insulation versus overvoltage / resonance issue.

INTRODUCTION

In the early years of the vacuum switching technology (before 1980), current chopping has been identified as a major contributor to high overvoltages at inductive load switching. Since then a lot has been said and written about voltage transients when switching specifically inductive loads with vacuum switchgear (e.g. ref 1,2).
This paper reviews the present understanding of and testing for the generation of overvoltages at inductive load switching, e.g. the switching of transformers, high-voltage motors and shunt reactors. In addition, mitigation measures are highlighted. Switching of dry type transformers is treated to some more extent.

SWITCHING TRANSIENTS

Insulation co-ordination for cable-networks is in principle defined by the potential occurrence of switching overvoltages, where for overhead line-networks also lightning impulses must be taken into account. Both the amplitude and rise time of voltage transients should be considered for their possible negative impact on network components. Especially the switching of low (up to a few hundred A) inductive currents needs special attention. The basic phenomena for transients at inductive-load switching are: normal current chopping, virtual current chopping, multiple re-ignitions and pre-ignitions.(ref 2,3)

pre-ignitions

When closing the contacts of a MV breaker, pre-ignition is unavoidable. Depending on the dielectric strength of the medium and the momentary voltage, the gap will break down before contacts touch and a steep voltage surge will travel to the load. The corresponding high frequency current might be interrupted by vacuum breakers, but because of the closing contacts no voltage escalation is possible.
In a three-phase circuit, the voltage jump of the first igniting pole is at the most 1 p.u. (= $U\sqrt{2}/\sqrt{3}$). As a result of a load-side oscillation, the overvoltage on the terminals of an inductive load can easily reach 3 p.u.

normal current chopping

When opening a switch, the current can be interrupted before it reaches its natural current zero. This applies for all interruption media and chopping currents of 5A are not unusual, especially in oil or air breakers having (parasitic) capacitance across the contactgap.
With low inductive currents, the energy ½ Li^2 present at the moment of chopping in the inductive load will oscillate via the ever present (parasitic) capacitance, so that the overvoltage amounts to approximately $i^* \sqrt{(L/C)}$.

The first generation vacuum switchgear had pure copper contacts. They could have chopping currents of appr. 20 A, which resulted in (too) high overvoltages when switching low inductive currents. Vacuum never got rid of this overvoltage reputation, although since the early 1980's already CuCr contacts were applied, with corresponding chopping currents of 3 to 5 A. With this level of chopping currents, the overvoltages are limited in practice to appr. 3 p.u. and generally cause no damage to the network components.
The frequency range of the Transient Recovery Voltage (TRV) is up to 20 kHz, too slow for travelling waves.

multiple re-ignitions

Multiple re-ignitions might occur during both closing and opening operations. Breakers with a very fast recovering dielectric such as vacuum or SF6 can interrupt the instantaneous high frequency current after a pre-ignition when closing the switch, as explained before.
When opening the contacts, the TRV might exceed the dielectric strength of the (still increasing) gap, so that re-ignition occurs. This will be mainly the case when the contact separation takes place very shortly before the current zero in an inductive circuit, where the TRV has a high steepness and a high peak value. The resulting

current can be interrupted again when it reaches its high frequency current zero, by breakers with a fast recovering dielectric. Due to the larger distance between the contacts that has arisen in the meantime, continued re-ignition could occur when a higher voltage appears across the gap, after which a new interruption might take place. This phenomenon can be repeated several times. As a result of the multiple re-ignitions, the power frequency current through the load might also increase again after current zero. This instantaneous load current may be "chopped" up to a relatively high value when high frequency interruption takes place (the momentary current through the breaker "sees" a natural current zero on which the clearing is possible). The resulting overvoltages due to this voltage escalation can be higher than possible with normal current chopping.
The frequency at which the re-ignition repeats itself lies roughly between 25-250 kHz. The frequency range of the TRV, in which the overvoltage occurs, is up to 20 kHz. Every re-ignition itself causes a surge wave as described under pre-ignitions.

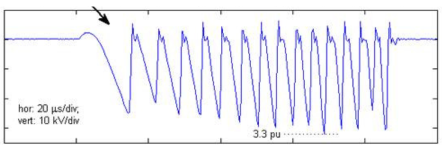

Fig.1: multiple re-ignitions in vacuum

The high-frequency re-ignitions themselves are not specific for vacuum or SF6, but on the contrary, will be much more prominent with e.g. oil breakers, see fig.2. Thereupon oil breakers may need several half periods of power frequency currents to build up the pressure needed to get to a final interruption. After each current zero in between restrikes may be present.

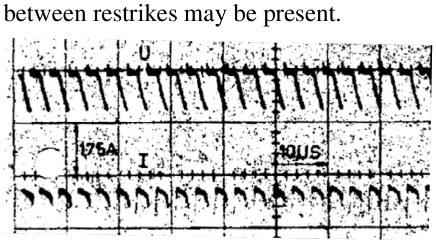

Fig.2: multiple re-ignitions when clearing 3.6A with an oil-breaker (ref 4)

Where multiple re-ignitions are possible with all kind of interrupting media, voltage escalation is more specific to arcing media with a high frequency interrupting capability and fast dielectric recovery. Examples of the latter are vacuum and SF6. A difference between vacuum and SF6 is the number of re-ignitions, being higher in vacuum due its excellent recovery (fig. 1).

virtual current chopping

When in a 3-phase circuit a re-ignition occurs in the first pole to clear, the instantaneous value of the current
in the other poles may be forced down to zero, due to the high frequency equalizing currents through the other phases. If these other poles have already opened contacts, interruption may take place at a high-frequency current zero. This phenomenon is called virtual current chopping because the instantaneous value of the power frequency current ($\sqrt{2}$ I sin60º, with the first pole to clear around current zero) is abruptly interrupted in the phases concerned. It is observed that this is the only overvoltage generation mechanism specific to vacuum because of its capability to clear extreme values of di/dt.
High overvoltages are possible, with TRV frequency up to 20 kHz.

resonance

The resonance frequency of especially transformers with small ratios such as 10/2 and 10/6 kV is within the same area as the repetition frequencies of occurring multiple re-ignitions (25-250 kHz). With these transformers, overvoltages can occur on the secondary side of 3 to 5 times the primary overvoltage, as a result of the resonance.

IEC 62271-110 INDUCTIVE LOAD SWITCHING

Inductive load switching duties are standardized by IEC in IEC 62271-110 (ref 5). The latest edition (September 2012) defines two type-test requirements for MV-switchgear: High-voltage motor switching and Shunt reactor switching.
Switching unloaded transformers, i.e. breaking transformer magnetizing currents, is not considered in this standard as a generally applicable model of transformers is not possible in this respect.

High-voltage motor switching.

This covers the switching of stalled motors in the range 100 A to 300 A and up to 10% of the rated short-circuit breaking current. Stalled motors are highly inductive loads. Test requirements are applicable to breakers in the range 1 kV to 17.5 kV. Motor switching tests are characterized by a test-circuit described in great detail, in order to represent the high-frequency phenomena that may lead to virtual current chopping and potentially destructive overvoltages. Tests using linear components to simulate the motors can be considered to be more conservative than switching actual motors.
A practical three-phase case of such a standardized test-series with a 12 kV vacuum circuit-breaker is described below. The 81 tests were performed in 4 test-duties (TD's): 20 tests in TD1, with 100 A load current and 30-50 nF to ground at load side, 20 in TD2 with 300 A load current and 1.5-2 µF at load side, 21 in TD3 with 100 A and small capacitance and 20 tests in TD4 with 300 A and large source capacitance. In 45 of the 81 tests, re-ignitions were observed, in 14 out of 45 these re-ignitions led to virtual current chopping with overvoltages up to 10 p.u. across the breaker.
The cumulative distribution of the peak voltages across the breaker, as observed during these tests, is plotted in fig. 3 for each test-duty. The grey region indicates the current chopping overvoltages, it reaches from 2.7 p.u.

(lowest possible value without chopping) to 3.5 p.u.. This confirms that current chopping is of no concern regarding overvoltage generation.

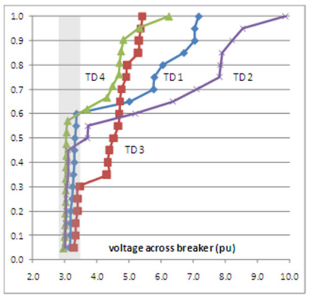

Fig.3: cumulative distribution of peak voltages across the CB during IEC 62271-110 tests

From the results, it is clear that TD2 is the most severe test-duty. This is because the higher current (300 A) makes the highest levels of virtual current chopping possible whereas the small load side capacitance enables higher frequency re-ignition currents.

Fig. 4 shows the test with the highest voltage across the breaker (10 p.u.) due to virtual current chopping in the middle phase, induced from the first-clearing (lower) phase. In this case, power frequency current was forced to zero from a momentary value of 237 A. Note that due to voltage escalation in the lower phase after an arcing time of 1.4 ms the multiple re-ignition process reaches values, comparable to that after virtual chopping.

An important observation is that because the switchgear was equipped with a three-phase surge arrester, the voltages at load side remain limited to 3.1 p.u., even at the worst case as demonstrated above.

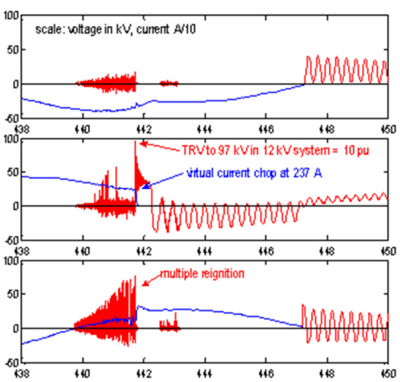

Fig.4: Test with highest voltage across the breaker (10 p.u.) due to virtual current chopping in the middle phase, induced from a first-clearing attempt in the lower phase.

Shunt reactor switching

In the former editions of IEC 62271-110 (2004, 2008) there was no reactor switching type-test defined for breakers below 52 kV. In the actual 2012 edition, shunt reactor tests below 52 kV are required, unless short-circuit test-duties T10 and T30 (as defined in IEC 62271-100) have equal or higher TRV values than those defined in the inductive load switching standard. In practice, when comparing TRV values of both standards, this implies that only for applications of switching shunt reactors with isolated neutral, these shunt reactor switching type-test are required.

Shunt reactor tests are defined with two different values of current: 500 A to represent the condition with maximum magnetic energy stored in the load and short minimum arcing time and 1600 A representing the condition of highest rate-of-rise of TRV and thus highest probability of re-ignition.

PROTECTION CONSIDERATIONS

Three possibly hazards of switching surges can be distinguished:

Amplitude: a high voltage will stress the load as a whole. Metal oxide (ZnO) surge arrestors can limit the overvoltage to the acceptable level of appr. 3 p.u. (see previous section).

Steepness: The rise time of the surge wave at the front, which can be below 1 µs, is the determining factor for the severity for the (inductive) load on the first turns of a winding. When, for instance, the rise time is 1µs, 60 to 80% of the resulting voltage appears across the first winding. Series inductances, like a current transformer in the circuit, reduce the steepness of a voltage surge; e.g. 26 µH reduces a 0.2 µs rise time already to 1.1µs, leading to a 60% lower interturn stress on the first turns (ref 6, point 4.5). Another measure for reducing the steepness is adding extra capacitance parallel to the load.

In general, the first windings of modern motors can withstand 3.2 p.u.

Resonance: When the repetition frequency of multiple re-ignitions is in the same range as the natural frequencies of the load, resonance inside the windings may take place. Detuning of the circuit, e.g. by R-C snubbers might be a solution, although the natural frequency shifts to another value.

Situations requesting protective measures:

When switching highly inductive currents up to appr 300A, protective measures could be necessary, depending on the capacitance (e.g. cable length) involved. The following situations can be distinguished:

Transformers in no-load: no need for protection as the magnetizing current is too low. Only when switching off transformers during inrush, surge arresters are advised.

In 1998, the at that time actual IEC 61233 (in later editions renumbered into IEC 62271-110, see ref 5) recognized also magnetizing currents of transformers. Tests were performed on a 630 kVA transformer with a vacuum circuit-breaker: 10*O with 3.8 m cable (screen earthed) and 10*O with only 1 m conductor (no screen) resulted in 3 re-ignitions in total. Max overvoltage was < 2.3 p.u. Because tests with 100 m cable gave such 'soft' voltages, this sequence was stopped after 4*O; no overvoltages occurred.

Transformers with highly Inductive load: Interrupting HV currents up to appr 300 A, especially with short cables: HV-arresters or RC-snubbers may be needed.

Blocked motor / generator, or motor during start up: depending on cable length between breaker and load, arresters may be needed (ref 2, 7)

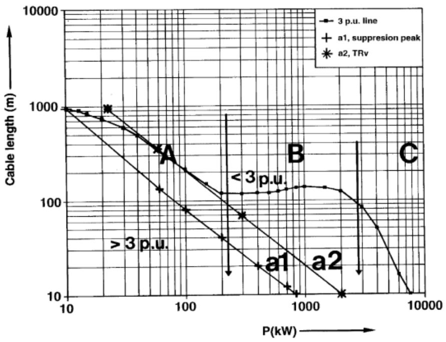

Fig.5: Example of minimum cable length calculation versus rated motor power at 6 kV. (ref 7)

SWITCHING DRY-TYPE TRANSFORMERS

Specific motor and generator applications are sufficiently recognized today, but it appears that switching of especially dry type transformers sometimes needs attention (ref 8, 9). Vacuum switchgear, being by far the most applied switchgear for this type of transformers, is sometimes automatically blamed for insulation failures of the dry type transformer. Faults where the first few turns of a HV-winding suffered a break-down suggest a high steepness of a surge.

Faults were also reported deeper into the winding instead of across the first few turns, which suggests that internal resonances took place. This could be the result of the frequency of multiple re-ignitions in combination with the amplitude of the surges; however, more long term effects with lower amplitudes could have had a degrading effect already. As the dry–type transformer can also have a natural frequency between 1 and 10 kHz, the possible influences of related power electronics on load side should also be taken into consideration.

The above considerations imply that transformer modelling plays a crucial role in theoretical studies. Essential design data regarding their high-frequency behaviour are difficult to obtain though.

From practical point of view:

Although transformer failures contribute only for a minor part to the total MV outage minutes in the Netherlands, experience shows an increase of these failures over the past years. Especially relatively young (0 to 5 years) dry-type transformers seem to be vulnerable. A clear increase of transformer faults is observed especially because of resonance and overheating. It is not clear to the authors if possible design changes, other additives etc. play a role. Maybe an increasing use in specific applications, like switched-power-supplies and smart grids, introduce accelerated aging as a result of harmonics.

It is generally known that dry type transformers often have a lower surge withstand strength than liquid-immersed equipment of the same voltage rating (ref 10, cl.5.10). Application of snubbers (RC filters) are generally not needed or even unwanted, as they imply a lower total MTBF for the system.

From standardization point of view

Dielectric tests on transformers are restricted to an induced voltage test to the double value of the rated voltage and an impulse voltage test (ref 11). Also in IEEE (ref 12) no extra tests, e.g. regarding oscillations / resonance effects are prescribed. In general a voltage jump at pre-ignition of 3 p.u. with a rise time of 0.2 us is quite possible. This means for a 11 kV HV winding that the impulse strength should be higher than dU/dt of $3*(11\sqrt{2}/\sqrt{3})\ /\ 0.2 = 135$ kV/µs, which is far beyond the IEC type tested impulse voltage for 12 kV: 75/1.2 = 63 kV/us. So the question is whether the test demands for transformers should be increased.

CONCLUSIONS

Irrespective of the arc quenching medium, voltage transients up to 3 p.u. are inevitable when switching.

Steep fronted surges always occur when closing a breaker

Only in specific cases, like interrupting small inductive loads with short connections, precautions like surge arrestors or RC filters are needed.

Dielectric tests for transformers should be reconsidered.

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