Detailed Study of Fast Transient Phenomena in Transformers and Substations Leading to an Improved System Design

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SUMMARY

In recent years several unusual failures were reported in medium voltage distribution systems. Some conventional dry-type and oil-filled transformers had clearly been exposed to a specific type of overvoltage. During thorough lab and factory investigations, no design or manufacturing faults could be found. Internal winding resonances were generally accepted to be the cause of the failure.

This paper describes typical symptoms, critical factors and some ideas for appropriate protection and total system design, based upon experimental results from laboratory and on-site measurements.

Laboratory tests are performed to investigate the high frequency behaviour of layer windings in distribution transformers. It is shown that multiple reignitions in vacuum circuit breakers can initiate internal winding resonances. Impulse tests confirm the resonance patterns at the natural frequencies.

Long term high frequency measurements are performed in a medium voltage substation where problems have been detected before.

The main purpose of the paper is to make system designers more aware of fast transient phenomena and to show that they represent a larger problem than generally accepted.

1. INTRODUCTION

1.1. Typical problem description

During the past 7 years, some remarkable faults occurred in dry-type and oil-filled distribution transformers, especially in medium voltage networks between 11 and 33 kV. All these faults had similar characteristics and occurred in similar circumstances.

The first investigations on the transformer showed that insulation breakdown had occurred at locations where no overvoltages were to be expected. The transformers were generally operated at low load levels and breakdown always took place at a moment when the load level was very low, and when no switching manoeuvres nor thunderstorms occurred. The breakdown typically occurred after 1 to 3 years of operation. In one particular case a large number of identical oil-filled distribution transformers suffered from a similar internal insulation breakdown phenomenon on two symmetrical positions inside the windings.

When the transformers were replaced by identical transformers, they soon failed again. However, thorough investigations in the production facilities never showed any reason to suspect unreliable material or production quality, or bad product design. On the contrary: identical transformers, manufactured in the same period, even installed in the same systems but at other locations, never showed any problem.

Further laboratory investigations showed that no unusual voltage distributions were generated during standard tests. Impulse tests at full impulse level and higher, with full or chopped wave, proved that the impulse withstand strength of the transformers was more than sufficient to comply with the present standards. On the other hand, additional measurements showed that there was an increased voltage response for certain frequencies and unconventional wave shapes, i.e. short front waves or high frequency sine waves.

All investigations reinforced the trust in the applied production and design methods, and required a more thorough investigation of the electrical power system, or at least of other network elements in the transformer neighbourhood.

1.2. First conclusions

It was quite obvious from the investigations on the returned units, that the transformer failures were caused by an overvoltage phenomenon. Other causes, such as excessive overheating, could be ruled out easily.

A number of indications pointed in the direction of fast transients. In several cases frequent switching operations had been reported by the system operator. The dry-type transformers, installed in commercial or industrial systems, were all equipped with vacuum circuit breakers. All transformers operated at a low load level and there was no overvoltage protection on or near the transformer terminals. Some systems were equipped with capacitor banks or with power electronic devices (PWM, IGBT, etc.).

The results of the first investigations and laboratory experiments lead us to believe that the failures were all caused by a similar combination of electrical transients, e.g. switching transients with multiple restrikes, internal resonance inside the transformer windings and material deterioration by partial discharges. The insulation deterioration by partial discharges explains why many of the failures were not directly related to a switching manoeuvre or a lightning strike. The symmetrical occurrence of failures inside the winding is due to an internal resonance pattern. Finally, the existence of electrical fast transients can explain why the transformers failed while they all complied with the present standards.

2. LITERATURE SURVEY

2.1. Phenomena

An extensive literature survey shows that several similar cases have been reported by different manufacturers and users. Theoretical and practical investigations often lead to the conclusion that the most probable cause of failure is a repetitive high frequency disturbance initiating internal resonances in the transformer windings.

Identical problems with circuit breakers are reported in a number of papers [1-7]. Since the nature of the phenomena is valid for any other inductive element, similar problems occur in EHV power transformers [8-13] and motors [14-17].

A special case is the interruption of inrush currents by circuit breakers [3, 5, 9, 18-24]. Usually this problem is caused by the inappropriate tripping of the protection relays [18-19].

On the other hand, there are numerous papers by circuit breaker specialists analysing the behaviour of vacuum and SF_6 circuit breakers when interrupting low inductive currents [1, 7, 16, 20-23, 25-30]. While some of these references are very revealing and extremely valuable (e.g. [21, 23, 28]), most are far too optimistic and sometimes contradictory, probably causing more confusion than clarification to the designers of electrical power systems.

Most papers represent current chopping as a rare problem and try to prove that the produced transient recovery voltages are generally very low. This is probably true, but the fact remains that : (a) overvoltages are produced ; (b) they have an unusual wave shape that is clearly not covered by conventional switching or lightning surges.

Essential factors, such as the pulse repetition frequency and the internal winding resonance risk, are generally neglected, while they are the key elements of the transformer failure process. The chopping of inductive currents by powerful circuit breakers causes a voltage rise due to the release of the magnetic energy stored in the inductive elements. Multiple reignitions produced in the circuit breaker generate repetitive pulses with a wide frequency spectrum, exciting one of the transformer's natural frequencies. Under unfavourable circumstances the multiple reignitions can even cause voltage escalation.

Modern power electronics are also mentioned as sources of high frequency voltage and current disturbances [31-32]. Thyristors and IGBT's in rectifiers, inverters, PWM motor drives, modern lighting equipment, etc., can cause pulse trains with a repetition frequency up to 20-36 kHz or more. In some cases system resonances are reported too. Most papers on this subject only discuss motor failures. Motors are indeed more vulnerable to high frequency pulses, because of their frequent use in an industrial environment, and because of lacking lightning impulse withstand requirements. Resonances however are as dangerous to transformers as to motors.

Besides vacuum circuit breakers and power electronics other transients are discussed [33-35] and often found to be the cause of resonances too.

2.2. Analysis

In the past, resonances in electrical systems and specifically inside transformer windings have been studied by different authors and working groups [9, 36-42]. Generally, these studies were focused on high voltage transformers, because of specific problems with EHV transformers at that time. However, most of the observations and conclusions remain valid for distribution transformers:

- resonance frequencies of transformer windings are generally situated between 5 and 200 kHz, thus are typically initiated by fast transients;
- overvoltages can not be measured at the terminals, but occur inside the windings;
- the required measurements at different points inside the winding can only be made on special prototype transformers; as a result of this, little detailed measurements are available;
- arresters at the transformer terminals can not protect the transformer against resonance;
- empirical formulas for natural frequencies are practically useless.

The importance of internal winding resonances is very often underestimated: resonance will not necessarily result in immediate breakdown, but will very often only develop partial discharges, causing accelerated ageing of the winding insulation [31-32, 43-44]. For a long period of time the influence of the resonance will not be visible, and in the case of a failure, the resonance phenomenon will most probably not be recognised.

2.3. Protection devices

Several technical solutions are mentioned in the literature, ranging from surge arresters [2-3, 8, 16, 22-23], surge capacitors [3, 7, 9, 15-17, 21-23, 26-27, 37] or additional cables [33], surge reactors [22-23, 29], or combinations of all these [15], up to improvements in the circuit breakers [15, 41, 43] and controlled switching [24].

2.4. Some general misunderstandings

Some persistent misunderstandings seem to survive, often in spite of clear and convincing evidence published in the past. Most of the following statements may sound very logical, but practice shows that they are not generally accepted.

The high frequency region is generally a forgotten dimension of the electrical system. People instinctively think of transformers as static black boxes, and high frequency components are merely regarded as unimportant fringes. However, resonance is an inevitable and potentially harmful phenomenon, and a resonance free transformer does not exist. Resonance can be avoided at a specific frequency by proper designing, but only within a very limited range.

Often people think that transformers are able to withstand any type of overvoltage, as long as the magnitude of the overvoltage is lower than the impulse withstand voltage or

BIL specification. According to the remarks above on resonance, this is definitely not true. However, this assumption is generally accepted as good practice.

Arresters never fully guarantee the protection of a complete system, they can only reduce risks. Arresters actually only limit voltage levels, and they only protect the voltage level in one particular point. They do not eliminate the high frequency components which give rise to resonances, thus they do not influence the steepness of the waves. They may well protect a terminal against incoming travelling waves, and they will reduce the risk of overvoltages building up in a small zone around their actual location, but they cannot protect a transformer against internal resonance or any other voltage increase inside the windings (such as overvoltages occurring at current chopping).

Circuit breaker standards are established to guarantee the well-being of circuit breakers. They are designed to interrupt high currents, without damaging the circuit breaker or its contacts, in order to guarantee a maintenance free circuit breaker. The actual effect of this interruption on the rest of the system is affected too much by the specific circumstances and properties of the other network elements like cables, transformers, capacitor banks, etc, ... It can be understood that the tendency to develop ever faster and more powerful circuit breakers, is potentially harmful, since it shifts the fundamental energy interruption problem towards the capacitive and inductive elements in the system. Circuit breaker standards certainly do not cover this problem.

2.5. Conclusions and confirmation

The literature survey shows that transient phenomena are often complex interactions between different system components. The study definitely convinces us that a combination of phenomena is responsible for many unexplained failures in distribution transformers. The phenomena themselves are each well-known and accepted, but the combined action of them, leading to a transformer breakdown, is only recognised by a limited number of people.

A lot of confusion has been caused by circuit breaker specialists who generally tend to minimise the problem, or even deny its existence. Lots of misunderstandings are still alive, and need to be removed. The large number of papers and reactions reporting similar problems shows that this specific overvoltage problem is not just a rare exception, and that similar problems will occur more and more often in the future. The ever wider use of modern equipment, as powerful circuit breakers and fast switching power electronics increases the high frequency contents in the electrical power system and they are clearly entering the range of natural frequencies of the electrical systems and its components.

Even though typical symptoms, critical factors, and suggested protection devices can be collected from the available literature, practical diagnostic tools or decision criteria are not available yet.

Confirmation of our assumptions can be found in the discussions of the IEEE/PES Transformer Committee Working Group “Switching Transients Induced by Transformer / Breaker Interaction”. This working group started in 1997, and is preparing a guide to prevent, or mitigate, the switching transients caused by circuit breakers. The scope of this guide was intentionally limited to switching transients, but many of its guidelines will be extendable to other transient overvoltage types.

While most constructors of circuit breakers and/or transformers are still in the stage of denying the problem, one large European contractor informally admitted that they indeed take several measures to protect transformers or motors against fast transient overvoltages. They mention vacuum and SF6 circuit breakers as the most important risks.

3. LABORATORY EXPERIMENTS

The increasing number of transformer failures due to transients certainly demonstrates the need for an elaborate investigation on fast transient phenomena :

- first of all we need to prove that all above mentioned suspicions about transients initiating internal resonances are right;
- to enable an optimised system design, we need to determine some critical factors that cause transient overvoltages and insulation breakdown;
- to solve these specific critical situations, we still need to determine the most appropriate measures and protection devices;
- to optimise the transformer design, new design criteria for the transformer insulation have to be determined.

3.1. Vacuum circuit breaker tests

As a first step, extensive laboratory measurements were performed to investigate the switching transients produced by vacuum circuit breakers, and the influence of different factors such as the vacuum circuit breaker type and its contact material, the cable length between breaker and transformer, the applied protection devices and the different winding types.

The measurements were performed on a Nicolet Pro 40 wide band analyser, equipped with TEK P6015 voltage probes and Pearson current probes. A special synchronising device was used to guarantee current chopping at any chosen current phase angle. The measurement arrangements were optimised in co-operation with a well-known circuit breaker manufacturer.

The following elements were used in the test set-up :

- one cast resin transformer 1600 kVA 11 kV/400 V;
- 3 different disk winding types encapsulated in cast-resin. The winding types mainly had different conductor dimensions and different numbers of disks;
- 2 different circuit breakers from different manufacturers, one with Cu-Cr contacts, one with Cu-Bi contacts;
- 3 sets of different cables between circuit breaker and transformer: a 10 m long three phase cable, three single phase cables of 4 m, and 3 blank copper conductors of about 4 m;
- 3 types of surge arresters with different protection levels
- an RC surge protection (6.3 kV / 3x0.1 μF / 100 Ω).

Most of the components were specifically chosen to simulate a specific failure case that had occurred in the past. Some experiments were conducted on the full level of 11 kV, while most tests were conducted on a reduced voltage level of 6 kV in order to reduce the risk of partial discharges damaging the test transformer.

For different combinations of winding types, circuit breakers, cables and protection devices, a large number of switching operations were performed. The responses were measured on the transformer taps and digitally recorded. A typical multiple reignition response measured during disconnection of the unloaded transformer is shown on Fig.1. The specific contact material was Cu-Bi and the voltage level was reduced to 6 kV.

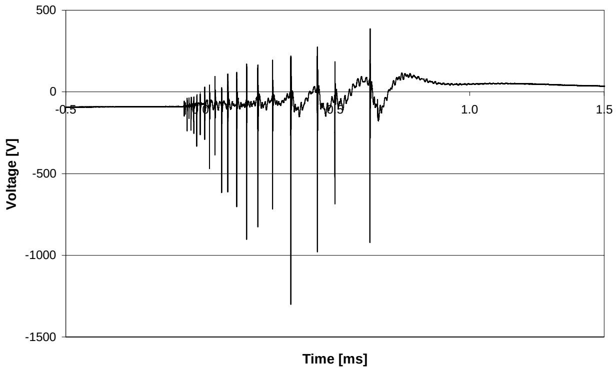

Fig.1 : Multiple reignition pattern between taps at disconnection

The main criterion used to evaluate the performance of a given set-up was the amplification factor (q-factor) being the ratio of the measured overvoltage peak and the peak voltage at 50 Hz. Some important conclusions could be drawn from the measurement results :

- all performed switching operations produced spectacular switching transients with multiple reignition pulse trains, sweeping through a complete frequency range between 6 and 160 kHz;
- the magnitude and the appearance of the occurring overvoltage transients varied stochastically, even with a synchronisation of the chopping angle;
- the contact material plays an important role in the current chopping process. Cu-Cr clearly produces lower overvoltage levels than Cu-Bi. Measured q-factors at the transformer terminals: up to 1.2 pu for Cu-Cr, up to 2.49 pu for Cu-Bi; between two taps : up to 12 pu for Cu-Cr, up to 29 pu for Cu-Bi;
- surge arresters were able to limit the overvoltage magnitude at the transformer terminals, thus reducing the internal overvoltages as well. However, the arresters could not guarantee a maximum overvoltage level inside the windings;
- the RC protection statistically performed better (lower overvoltages at terminals and inside the windings) than the arresters; using the Cu-Cr breaker, q-factors were measured inside the winding up to 4.95 for RC, up to 8.87 for ZnO;
- winding types with larger conductor sizes (larger eddy current losses) statistically performed better;
- the stochastic behaviour of the vacuum circuit breaker is so determining, that only statistical conclusions can be drawn; the use of, for example, a statistically better protection device will not guarantee a better performance for one specific switching operation.

3.2. Frequency response analysis

Further laboratory experiments were performed on three oil-filled distribution transformers (400 kVA/12 kV and 630 kVA/ 15kV) in order to determine the natural frequencies of layer windings and their internal winding resonance patterns.

Three special transformers were built, equipped with a large number of exit leads in order to measure a large number of internal voltages inside each layer. This enabled to determine the full frequency behaviour of three different HV layer windings. Radial voltage differences for one double layer of a transformer are shown on Fig.2. The voltage amplification at the resonance frequency around 60 kHz is clearly seen. From the measured patterns it was concluded that :

- all three transformers had similar natural frequencies;
- amplifications (q-factor) up to 21.7 were measured between turns, or up to 19.7 between layers;
- the radial insulation was stressed most; the most critical positions were located at 25% and 75% of the winding height; this was confirmed to some extent by the investigation of the failed transformer windings;
- one particular transformer performed better (lower amplifications) than the others; this enabled to determine some critical design parameters.

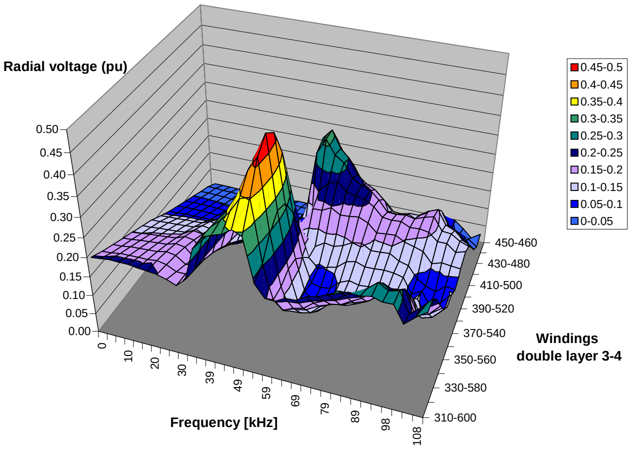

Fig.2 : Double layer voltage transfer characteristic

3.3. Conclusions of the laboratory measurements

The first study shows that vacuum circuit breakers certainly produce multiple reignitions when an unloaded transformer is switched off. The experiments confirm most of the other conclusions found in literature [4, 28]:

- overvoltage amplitudes are not extremely high at the terminals;
- the influence of the circuit breaker contact material is large;

- the presence of a cable and protection devices has a positive influence;
- due to the statistical behaviour of the circuit breaker and the resulting switching transients, surge arresters and untuned capacitors do not guarantee a full protection.

The second laboratory study shows that distribution transformers exhibit a wide range of natural frequencies, in our specific cases starting from 30 kHz. These natural frequencies will clearly be triggered by circuit breaker transients.

Although no winding design will ever eliminate the risk of internal resonances, one specific winding design has proved to be less sensitive to resonance than the others.

4. HIGH FREQUENCY ON-SITE MEASUREMENTS

Several on-site field studies have been reported by various authors. An interesting recent study is described in [45]. In most cases, however, only measurements on the low voltage side are performed, while high frequency/ high voltage measurements are very rare.

Indeed this kind of measurements appears to be very complicated, as they not only require special measurement instruments and techniques, but also special measurement precautions to prevent all kinds of interference by stray capacitances, circulating earth currents, etc. ... This is probably one of the many reasons why fast transient phenomena are still largely unknown, not enough understood and certainly underestimated.

Therefore long term high frequency measurements are performed in a 15 kV substation. Currents and voltages are monitored on the HV and LV side of the transformer, to identify the specific phenomena that could have caused a transformer insulation failure on this location. Transients are recorded by an event recorder. Results of this study will be published in the near future.

5. DESIGN, PROTECTION AND COMMERCIAL ASPECTS

5.1. Technical and economical aspects

Technical solutions to fast transient problems are already available. One may install external protection devices as surge arresters or surge capacitors to reduce terminal and internal overvoltages, or increase the insulation level of the transformer to a certain degree. Some questions however remain to be answered. How does one select the appropriate protection? How much does the insulation level have to be increased?

A closely related aspect will be the cost. The relatively low average risk of transformer failure due to fast transients and resonance will not urge utilities or contractors to install full protection on all vulnerable equipment. The cost of a transformer failure, however, is often very high, especially in industrial applications. One logical step to take would then be the development of criteria to determine the existence and height of fast transients risks.

5.2. Moral, legal and commercial aspects

In most cases of transformer failure due to transient overvoltages, the transformer manufacturers will find themselves in a difficult position. Even if they are convinced that their product is in full compliance with all applicable standards, their explanation is often disbelieved. Whatever effort they make to help the customer, e.g. a replacement by reinforced windings, it will always be regarded as a confession of guilt, and finally the customer will always end up asking the replacement of all identical units. Ref. [17] clearly confirms this typical reaction. In the end the transformer manufacturer will always be forced to accept some kind of commercial agreement.

6. CONCLUSIONS

The present standard tests do not cover the specific fast transients phenomena, nor will it be possible to define a new test that will fully cover them. Therefore, during the system design stage, more attention should be paid to the influence of the neighbouring equipment, such as circuit breakers and cables, on the transformers. This will require a more intensified interaction between the customer or contractor, and the transformer manufacturer.

As a first step contractors and utilities should be better informed of the existence of the problem. A second step should be the formulation of specific guidelines, in order to allow system designers and transformer manufacturers to select the appropriate specifications for the transformer and its protection. The efforts made by the IEEE working group on Switching Transients are in this respect very promising.

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