MODELING AND SIMULATION OF VCB RELATED TRANSIENTS IN INDUSTRIAL INSTALLATION. CASE STUDY: ARC FURNACE TRANSFORMER.

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Abstract: Vacuum breakers are commonly used in the Medium Voltage (MV) industrial installations due to their perfect switching capabilities and durability. Fast and very fast transients which could be generated during the operation of VCBs are known and appropriate mitigating means should thus be applied in certain cases, especially when connecting and disconnecting inductive currents. In the present article an analysis of transients generated in a typical arc furnace installation, comprising a VCB and a typical supplying transformer is presented. Analysis of the state-of the-art protection by means of surge arresters and RC-snubbers is included pointing out its limitations regarding the mitigating of the high dU/dt transients. Therefore an improvement of the present state of the art protection system was proposed, comprising series-connected filtering elements (chokes).

1 INTRODUCTION

In industrial installations comprising large transformers, no-load inductive currents may significantly exceed the chopping current value of a typical Vacuum Circuit Breaker (VCB). Thus the VCBs operation connecting the transformer to the plant network can cause very fast transients having negative effects on the insulation systems of electrical equipment within the installation.

The problem of transients generated during the operation of the VCB and its influence on the adjacent equipment is well known in the field and broadly analyzed in the literature. The mechanisms of generating re-ignitions due to the fast oscillations of the Transient Recovery Voltage (TRV) competing with the dielectric strength of the contacts gap are also well described in literature (e.g. [1-3]).

The statistical aspects of the switching events result in the fact that the impact of the VCB on the equipment switched strongly depends on the frequency of the switching operations. Therefore the industrial installations in which the production cycles determine the frequent connecting and disconnecting the equipment such as motors or transformers, for example, are particularly exposed to the risk of failure due to accelerated aging of the insulation system exposed to high amplitude and high du/dt transients.

An example of the above is an arc furnace installation, typically comprising a several tens MVAs transformer, connected and disconnected several times a day at its MV side. Multiple failures of the arc furnace transformers in the past focused an attention of many research groups on investigating this phenomenon in order to elaborate appropriate protective means.

Various protective elements which can be found in the field installations clearly demonstrate that there has been a continuous improvement in the protective systems.

As shown in [4] the typical strategy developed initially had been to apply lightning arresters as a primary overvoltage protection and supplement them with surge capacitors to further limit switching overvoltages. The authors indicated, that despite the use of such a protection, failures of transformers in the high voltage windings were still reported. Those failures have been attributed to the transient overvoltages during switching operations. The authors analyzed various alternatives of improving the protection by surge capacitors, including pre-insertion resistors , line-to-line connected arresters, and resistors connected in series with capacitors, forming the RC snubbers. It has been clearly demonstrated that the resistive damping in the circuit is necessary and the use of RC snubbers was recommended as the best and cost-efficient solution. The use of RC snubbers has thus been demonstrated to be an adequate mitigating strategy to address potential hazards to the transformer both during the unloaded transformer disconnection and during the loaded transformer primary current breaking.

Further work in this field confirmed those findings (e.g. Maksic in [5]) and the generally recognized recommendations regarding the protection of the arc furnace transformers has been established. It is thus now a common practice to install protection against switching transients, typically in the form of RC snubbers located close to the transformer.

The importance of the reliability of the arc furnace transformer and the fact that field failures are still reported, stimulated further investigation in this field which led to the conclusion, that despite the fact that the RC snubber provides the best state-of-the-art protection method, in some situations however, this type of protection may be not sufficient.

It has been demonstrated by the authors with the transient simulations performed for a typical arrangement of the arc furnace installation that high du/dt transients can be generated during opening as well as during closing operation. The simulation results show that both types of switching operations can pose a risk to the electrical equipment e.g. arc furnace transformer. The efficiency of the RC protection however, in the two cases analyzed is different. It has been demonstrated that the RC protection may practically eliminate the re-ignitions during the VCB opening, but the pre-strikes during the VCB closing may potentially still pose a hazard to the equipment. These conclusions were supported by field tests which revealed high dU/dt transients at the transformer terminals during the closing operation of the breaker, despite the use of RC snubbers as well as the surge arresters. These findings lead to a conclusion that further improvement of the protection scheme should in certain cases be developed and implemented.

2 SYSTEM STUDIES

A typical arc furnace installation, presented in Fig.1, has been assumed. The factory network is backed-up by a star-connected capacitors upstream the VCB. The capacitors are 1.5uF/phase and the star point is grounded through a 2 Ohm resistor. The network voltage is 30kV. The VCB connects the transformer HV windings to the network with several tens of meters long busbars. In the simulations the length of the connections was assumed 10m. The disconnector, typically located in series with the VCB, has not been included in the diagram as it operates when the VCB contacts are open. A 110 MVA 30/1.1 kV delta-delta transformer unit was assumed in the studies. The RC snubbers considered comprised 50 Ohm resistors in series with 0.15uF capacitors.

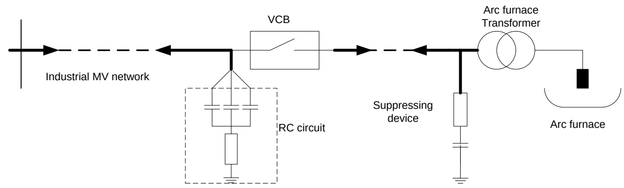

Figure 1: Typical industrial installation supplying arc-furnace.

3 MODELS EMPLOYED

3.1 VCB

The model of the circuit breaker is based on well established approach described in [1]. In the present article the VCB is modelled as an ideal controlled switch with added parallel (to the switch) resistance, reactance and inductance. The 3-phase model works as the tree non-coupled, single phase models. The decision whether the switch should be opened or closed is made in every sampling time. The algorithm is taking an action based on the following data:

- the value of the phase current
- the value of the voltage between contacts
- the time from the starting point of the closing or opening operation;
- the state of the switch in the former sampling time;
- the calculated value of the voltage of the arc

It is important to mention that the model is applicable to investigate both the contact making and the contact breaking process. In the case of the contact making analysis, the contacts are initially open (the dielectric withstand of the fully open contacts is typically 5xUr for the given breaker type) and the dielectric withstand decreases in time. In the case of the contact breaking process analysis, the contacts are initially closed and the dielectric withstands increases from an initial value linearly, until it reaches the maximum value. It is assumed that the process of contacts movement duration is 5ms. The assumed chopping current of the VCB is 3A at 50Hz and 1A at high frequency.

The model was implemented in the ATP/EMTP program using the typical parameters known from the literature (e.g. [5]).

The concept of the VCB model is presented in the Fig.2.

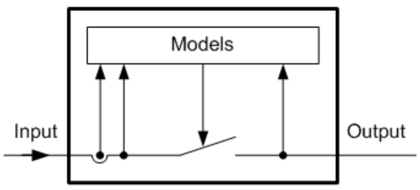

Figure 2: VCB model concept applied.

3.2 Connections between the VCB, snubbers and transformer

The busbars connecting the VCB and the snubbers are modelled as transmission lines (Line-Z elements) of 200Ohm surge impedance and length 10m. The remaining section between the snubbers and the transformer is also modelled as Line-Z elements, but in this case the length is 3m.

3.3 Transformer

The transformer model must combine the ability to represent the relatively low frequency phenomena related with oscillations of the TRV during the disconnecting of the transformer, which is taking several milliseconds, as well as very fast transients characterized by times of tens to hundreds of nanoseconds. For the sake of the TRV oscillations modelling, the inductances and losses in the transformer must be appropriately represented. Also, the capacitances of the windings must be included, so that the TRV oscillations are taking place at appropriate frequency. These capacitances play a key role in the analysis of the VFT phenomena occurring around the prestrike or the re-ignition event (sub-us time range).

In order to perform the analysis reflecting both the relatively slow phenomena related with the TRV oscillations as well the VFT phenomena related with pre and restikes, the following approach was applied:

1. The standard BCTRAN ATP transformer model was used, so that typical transformer parameters at 50Hz could be represented (power rating, voltages, losses, windings arrangement)

2. The BCTRAN model was supplemented by a matrix of capacitances, representing realistic values of phase-to-ground, phase-to-phase, and primary-to-secondary capacitances of this type and size of a transformer.

4 RESULTS

4.1 Reference case: unprotected transformer

The simulations of the transients during the switching operations for the unprotected transformer were performed in order to visualize the importance of the protective elements application. Typical simulation results are shown in Fig.3. In the case of a large arc furnace transformer the no-load (inductive) current significantly exceeds the chopping current of a VCB. It can thus clearly be seen that the known effects associated with inductive load switching are present. During the contact making process multiple pre-strikes can be seen and during the contacts breaking the TRV oscillations resulting in arc re-ignitions are present, as expected.

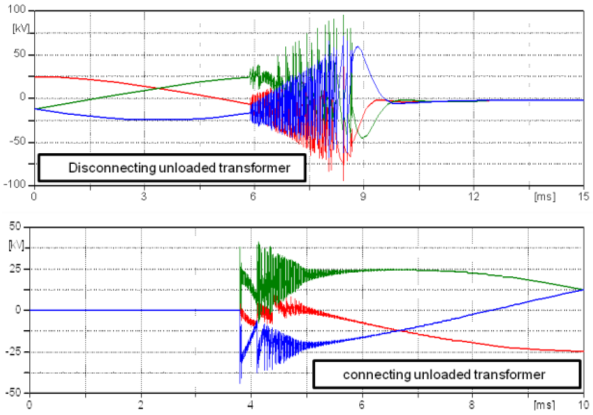

Figure 3: Reference case: switching off and on unprotected, unloaded transformer

4.2 RC snubber protection – impact on transformer disconnecting

Including the RC snubber circuit significantly affect the simulated waveforms as shown in Fig. 4.

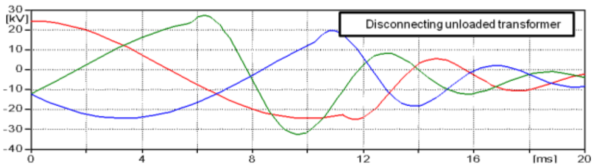

Figure 4: Switching off an unloaded transformer. RC snubber protection included.

The influence of the snubber capacitance value on the simulated waveforms is shown in Fig.5. In the simulations the value of the capacitance was varying from 30 up to 200nF, while the resistance value 50Ohm was maintained constant. It could be seen that already at C=50nF the re-ignitions are eliminated and that the 150nF value assumed provides significant safety margin.

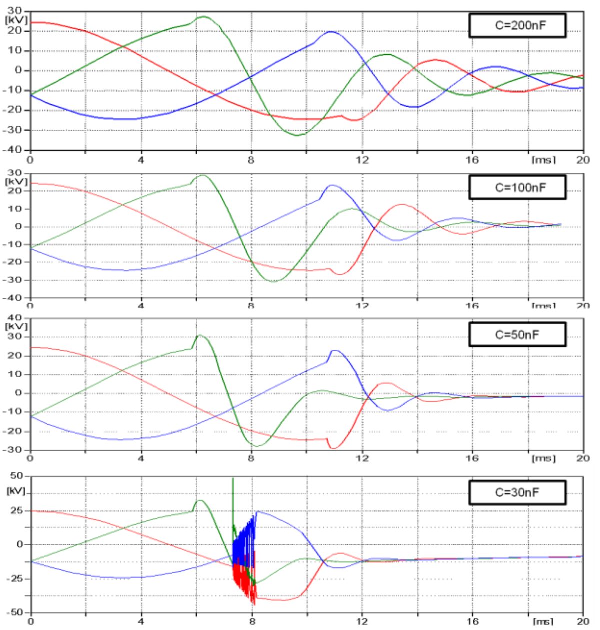

Figure 5: Switching off an unloaded transformer: dependence of the phase voltage on the C value. The resistance maintained constant (50 Ohm)

The case of a loaded transformer disconnecting was also verified. Fully loaded transformer (load cos (φ) =0.94) was assumed. The results obtained for the RC protected transformer (150nF and 50Ohm, see Fig. 6) demonstrate that the transients resulting from the switching off operation are appropriately addressed with the snubber as well.

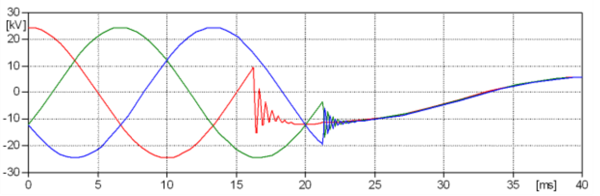

Figure 6: Switching off a fully loaded transformer protected with 150 nF and 50 Ohm snubber circuit.

4.3 RC snubber protection – impact on transformer connecting

As demonstrated by simulations performed for connecting the arc furnace transformer to the network, the high du/dt transient overvoltages can in particular situations be generated in this case. Despite the fact that transformer failure risk can be mainly attributed to the phenomena occurring during the disconnecting of the transformers, the phenomena associated with the connecting the transformer should also be addressed.

Fig. 7. Illustrates the phase voltages at the transformer during the switching on of the VCB. In this case the transformer is protected with RC snubbers (50 Ohm + 150nF). It can be clearly seen that the impact of the snubbers on the transients suppression is significant (for reference see Fig. 3) however, high dU/dt overvoltages resulting from pre-strikes in the VCB are still present. Magnified view of the first pre-strike indicates an overvoltage peak value of 38kV (1.55 put.) characterized by du/dt of 110kV/us.

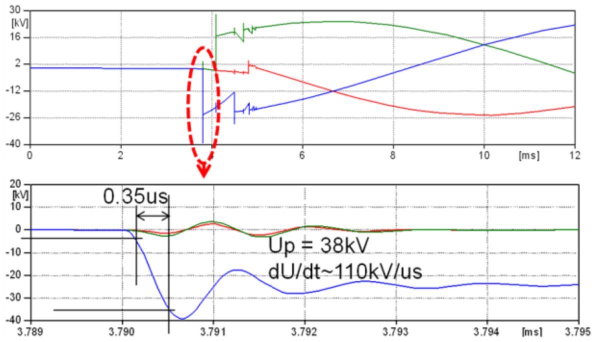

Figure 7: Switching on unloaded transformer protected with RC snubbers.

The first pre-strike in the VCB, occurring when the dielectric strength of the gap in one of the phases is smaller than the voltage across the breaker results in that the voltage step appears at the VCB terminal. Since the large capacitance exists upstream the breaker the surge source impedance is very low. The input capacitance of the transformer is thus very rapidly charged and dU/dt is limited by this capacitance value (typically single nanofarrads) and the impedance of the connections between the VCB and the transformer. The capacitor of the snubber is connected in series with a 50Ohm resistor and thus in the case of relatively short connections of low impedance the resulting du/dt can reach high values. The explanation of this situation is shown in Fig. 8. For the practical system analyzed in this article, the results are as shown in Fig. 7.

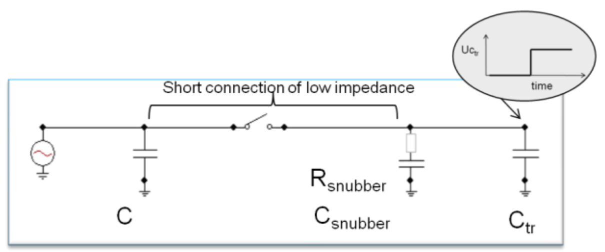

Figure 8: Explanation of switching on unloaded transformer protected with RC snubber case

5 PROPOSAL OF THE PROTECTION SYSTEM IMPROVEMENT

As demonstrated by the simulations performed, high du/dt transients at the arc furnace transformer input can be present during the connecting of the transformer, despite the use of the state of the art protection by RC snubbers. These transients are particularly severe in the case of short connections of low impedance between the breaker and the transformer. In such cases the du/dt problem can be addressed by introducing series connected filtering chokes between the surge source (VCB) and the transformer. Similar concept was previously successfully developed by the authors to protect smaller transformers against VCB induced transients [6]. Later, similar idea was implemented to protect small distribution transformers against high du/dt transients resulting from lightings chopped at the front by a spark gap [7]. The concept is based on introducing a series R-L component, which combined with the capacitance of the transformer or with an additional capacitor connected in shunt, forms a low-pass filter, reducing the du/dt, overvoltage peak value, and filtering potential HF oscillations in the circuit. The concept is schematically presented in Fig. 9.

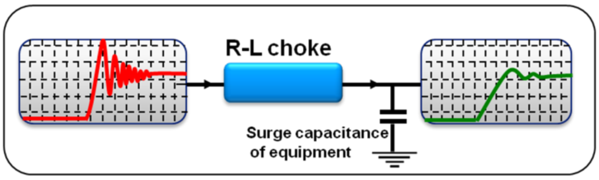

Figure 9: The concept of high du/dt transient mitigation using the series chokes

Exemplary simulations of the switching operations for the choke introduced to the system under the present study are shown in Fig. 10. In the present simulations the realistic parameters of the choke, similar to those used in the previous applications were considered.

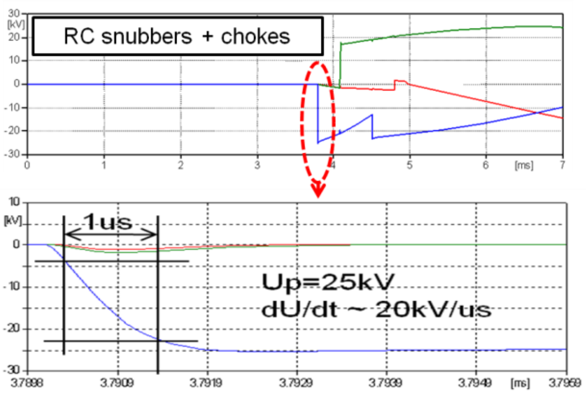

Figure 10: Switching on unloaded transformer protected with RC snubbers and series RL chokes

Comparison between the results obtained previously for the system protected with snubbers only (see Fig. 7) and that obtained for the protection complemented with the series chokes shows that the use of chokes can significantly improve the transformer protection by reducing the du/dt of the transients associated with the pre-strike in the VCB. However, it has to be pointed out that the practical implementation of the series choke concept for protecting an arc furnace transformer is much more technically challenging task than the protection of small distribution-size transformers. In the present case the nominal values of primary current are very high (typically several kAs) and thus the technical issues such as the heat dissipation or electrodynamics forces must be addressed when constructing a physical device.

6 CONCLUSION

Multiple failures of the arc furnace transformers have resulted in continuous improvement in the protective systems. As confirmed by the simulations performed for a typical case study example of an industrial arc furnace installation, high du/dt transient overvoltages which could potentially pose a hazard to the insulation system of the transformer exist both during the connecting and disconnecting the transformer. While the re-ignitions during the transformer disconnecting can be addressed by using appropriately sized RC snubbers, high du/dt overvoltages resulting from the pre-strikes in the VCB may still be present, especially when the connections between the switchgear and the transformer are relatively short and characterized by a low impedance value. In such a case frequent switching operations may pose an additional risk to the insulation system of the transformer.

Therefore an improved protection of the arc furnace has been proposed on the basis of the former experience with applications of the series-connected filtering RL choke for mitigating high du/dt transients impact on smaller transformers. A combination of RC-snubbers, eliminating the re-ignitions during the transformer disconnecting and appropriately designed chokes can significantly improve the operating conditions of frequently connected arc furnace transformer.

7 REFERENCES

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