Investigation of Distribution Transformer Overvoltage Protection by Computer Simulation

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ABSTRACT

Experiences based on field statistics show that in certain distribution system configurations the failure rate of distribution transformers is relatively high. In order to realise an effective overvoltage protection for the distribution network the voltage stresses inside the transformer windings have to be investigated. Authors have elaborated a complete, three phase transformer model, suitable for the calculation of lightning transients. The model is based on ATP. Laboratory tests verify the calculated results. The application of this transformer model is demonstrated by the analysis of a special transient [1], at which high stresses in the transformer insulation occur due to the operation of the arresters connected to the primary terminals. For the physical explanation of this process a simplified reference circuit has been created. According to the sensitivity analyses carried out by the authors, the transformer connection, the type of the overvoltage protection device, the transformer ground resistance and the value of the load are the most significant parameters affecting the voltage stresses in the transformer winding.

INTRODUCTION

Distribution transformers are important elements of the power systems. Significant percentage of failures of such equipment is caused by lightning overvoltages. The failure rate can be considerably reduced by means of overvoltage protection devices connected to the primary side of the transformers. However, the statistics of the utilities in Hungary [2] show that faults due to lightning overvoltages may occur even in presence of the above mentioned protection. Similar experiences gained in Norway [1] and in Australia [3] have been reported about. J. Huse created a theory for explaining the possible cause of this relatively high failure rate. His theory is supported by laboratory tests and field recordings. According to his assumption the failures of the transformers are indirect consequences of the HV arrester operation caused by lightning surges. The process is described in detail below.
The paper presents a transformer model adequate for the calculation of the lightning stresses in the transformer windings. An application of the transformer model is shown in connection with the afore mentioned phenomenon.

TRANSFORMER MODEL

In Hungary, generally used distribution transformers are D-y or Y-zigzag connected three phase units. The neutral of the HV winding is insulated (no possibility for a connection outside) and the LV neutral has a bushing. Both the HV and LV windings are of layered construction. The iron core has three legs.
For the analysis of the distribution transformer overvoltage protection, the lightning stresses in the windings have to be calculated. In the examined frequency domain, it is necessary to study the effect of the individual capacitances and to divide the windings as described below. The transformer model has to be suitable for insertion in all kinds of network configuration.

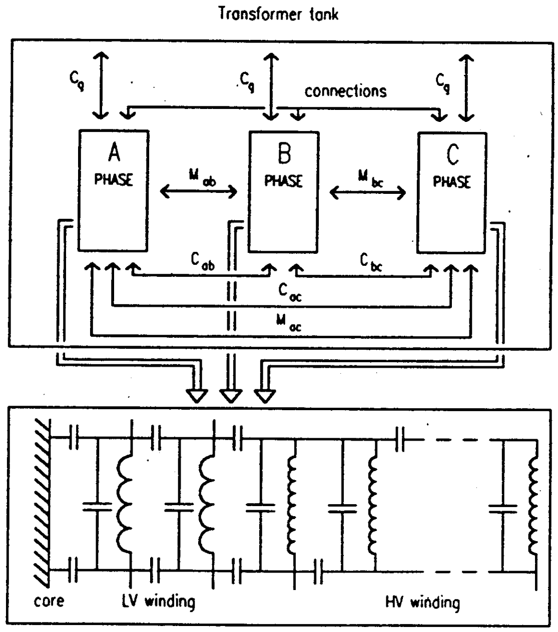


Figure 1. The transformer model

The complete model of a three phase transformer is shown schematically in Figure 1. The model is composed of three independent winding models and of the inductive, capacitive and conductive coupling

between them. The capacitances of the windings to the transformer tank and to the iron core are taken into consideration as well. Windings placed on the core legs constitute of the LV and HV winding models divided into individual sections. Measure of division depends on the dominant frequency components determining the voltage stresses and the location of the winding points where the stresses are to be calculated.
The self and mutual inductances of the individual winding sections have been represented. Interturn capacitances of the sections, capacitances between the different sections and capacitances between the sections and the ground are included in the winding models as well.
The above mentioned parameters have been established by calculation and measurements. The parameter calculation has been carried out on the basis of geometrical data and constants depending on the materials. Measurements have been performed in order to determine the inductive coupling between the different windings of the transformer. Further measurements have been accomplished to establish the capacitances between the windings, the interturn and interlayer capacitances of the windings and the capacitances between the windings and the grounded parts of the transformer.

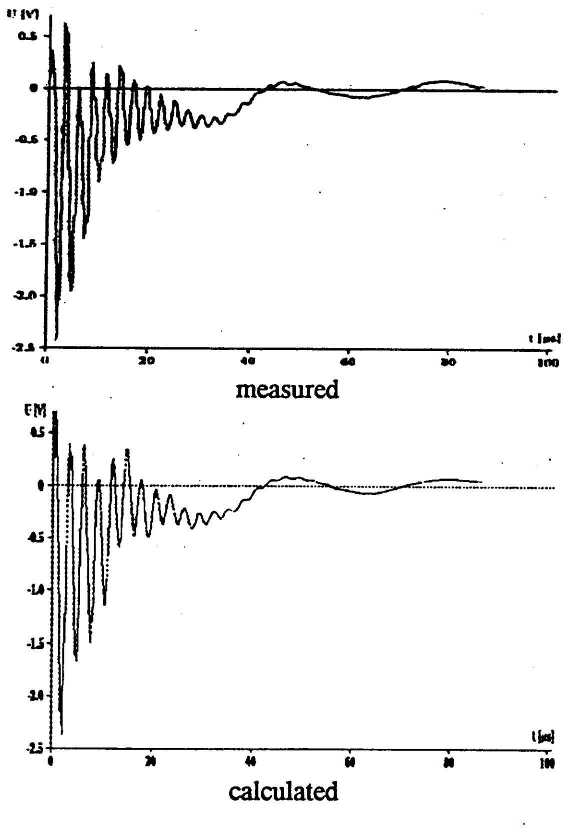


Figure 2. Comparison of the measured and calculated results

The transformer model has been verified by sending steep front wave to different connections of the transformer. Figure 2. shows the measured and calculated voltage curves of a LV winding terminal for the same configuration. The character of the curves the frequencies and the peak values show satisfactory agreement.

APPLICATION OF THE MODEL

The application of the transformer model is shown in connection with the phenomenon described below. The voltage stresses in the transformer during the examined process and the parameters affecting these stresses most significantly have been investigated.

DESCRIPTION OF THE PHENOMENON

Pole mounted distribution transformers used in Hungary are D-y or Y-zigzag connected three phase units. The neutral point of the HV winding is insulated while that of the LV winding is directly grounded. The nominal voltage of the overhead lines connected to the primary terminals of these transformers is 20kV. The 20kV distribution network is three phase and resonant grounded. The LV loads are supplied at 0.38/0.22kV voltage level by three phase directly earthed neutral system. The LV line has a neutral conductor grounded at the loads and at the transformer. The loads, which are generally single phase, are connected in between the phase and neutral conductor and are distributed almost symmetrically among the three phases. Arresters are used at the HV terminals of the distribution transformers only.

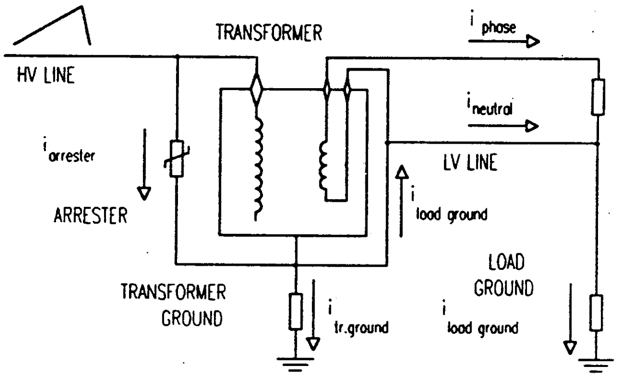
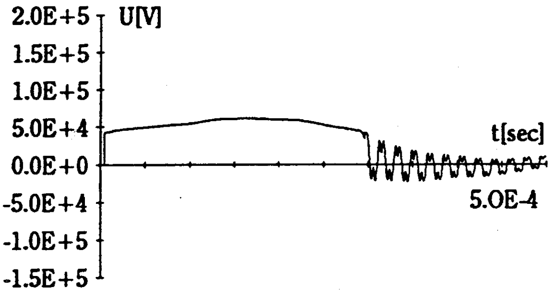
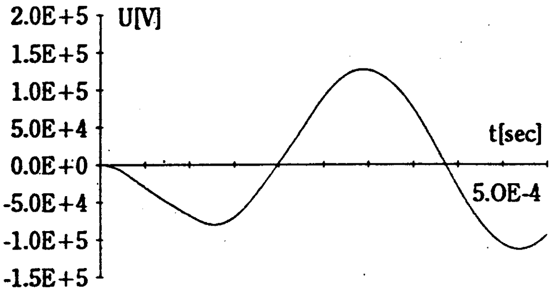


Figure 3. Single phase circuit

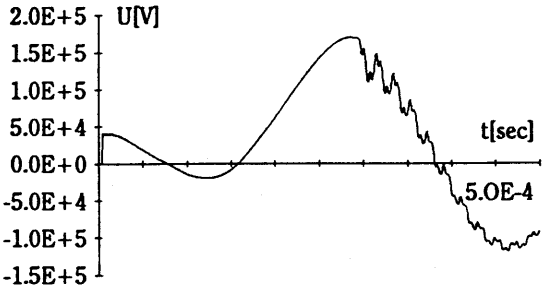
The process to be investigated can be explained by Figure 3. showing the simplified single phase circuit of the above described network. Lightning surge incoming on the HV line operates the arresters connected to the primary side of the transformer. The potential of the transformer HV terminal increases to the protecting level of the arrester. This sudden potential growth raises the voltage of the HV neutral point and produces low amplitude oscillation there (Figure 4.a). The arrester impulse current ($i_{arrester}$) will flow in two ways: the transformer ground ($i_{tr.ground}$) and the load ground ($i_{load\ ground}$). The latter component ($i_{load\ ground}$) flows through the conductors of the LV line. This component is divided between the LV phase (i_{phase}) and neutral ($i_{neutral}$) wires according to the impedances of the LV circuit. The LV phase current (i_{phase}) is forced through the load and the LV winding of the transformer as well. The component of the arrester current flowing through the LV winding induces an oscillation in the neutral of the HV winding (Figure 4.b). This oscillation superimposes on the afore mentioned potential rise caused by the arrester discharge voltage (Figure 4.c). The resultant voltage occurring in the neutral point results in high stress on the main insulation, exceeding not just the protection level of the arrester but the transformer BIL as well. Increase of both the arrester voltage and current component flowing through the LV winding will cause the rise of the stresses, which can not be limited by the HV arresters.



a.



b.



c.

Figure 4. Voltage components in the HV neutral

The described process may appear even if the LV side is unloaded. In this case all the current component flowing toward the load ground ($i_{load\ ground}$) will be conducted through the LV neutral wire. Consequently substantial voltage difference will appear along the LV line between the phase and neutral conductor. The value of this voltage difference depends on the inductive coupling between the LV wires. The smaller is the coupling the higher will be the voltage difference. If its peak value exceeds the strength of the LV devices then flashover or breakdown occurs in the LV network. Since these kinds of faults can be considered as a sudden rise of the LV load thus the process will be similar to one described above. A flashover or breakdown between the phase and neutral wires generally means smaller impedance than a normal load. Accordingly, the arrester current component flowing through the LV winding (i_{phase}) and the voltage oscillation arising in the HV neutral point will increase.

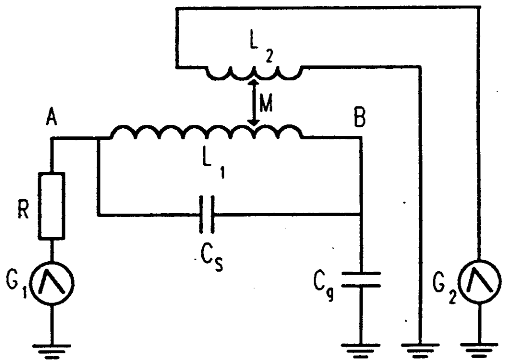


Figure 5. Simplified reference circuit

Figure 5. gives an equivalent reference circuit for the explanation of the physics of the above described process. This is a coupled resonance circuit that can produce the fundamental voltage components appearing during the investigated process. L1 is the inductance of the HV winding and L2 is the inductance of the LV winding. M is the mutual inductance between them. The value of C_g is the ground capacitance of the HV winding and C_s is its interturn capacitance. The junction of L1 and C_g (B point) corresponds to the neutral point of the HV winding. R is the resistance of the arrester and the HV line surge impedance connected in parallel. G1 generates the voltage at the HV terminals of the transformer. G2 produces the arrester current component flowing through the LV winding of the transformer.

At the front of the lightning surge, the inductance of the HV winding means high impedance, thus the voltage limited by the arrester is divided between the C_s and C_g. Since C_s is much higher than C_g, therefore the voltage of the junction of C_s and C_g (B point) will be almost equal to the voltage of the HV terminal (A point) at this time. The voltage difference between the mentioned points (between A and B) results in a small amplitude oscillation around the arrester residual voltage across C_g

(see Fig.4.a). After discharging of the arrester, the voltage of the HV terminal (A point) decreases almost to zero. This voltage change produces oscillation in the HV neutral (B point) as well. It should be noted that the increase of the arrester resistance results in changing the sign of the reflection coefficient at the transformer end of the transmission line. Accordingly, a higher frequency voltage component occurs. The frequency of this component is fundamentally determined by the travelling time of the transmission line.

The other main component of the HV neutral voltage (see Fig 4.b) is accomplished by the current of the surge generator G2. This current flowing through the inductance L2 induces a voltage oscillation at the junction of L1 and C_g (B point).

EFFECT OF THE SYSTEM PARAMETERS

A sensitivity analysis has been carried out to evaluate the influence of the system parameters on the investigated process. The arrester current component flowing through the LV winding and the discharge voltage of the HV arrester are the main factors determining the voltage stresses in the HV winding. Therefore every network parameter affecting these factors influences the mentioned stresses. The main parameters determining the process and the voltage stresses in the HV winding are: the connection of the transformer, the type of the overvoltage protection device, the ground resistances of the system and the LV loads.

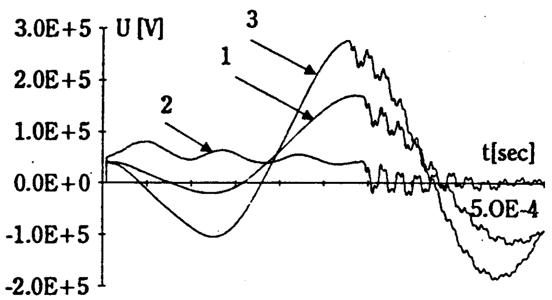


Figure 6. Calculated voltage curves for different transformers:
1.Y-zigzag, 2.D-y, 3.Y-y

Distribution transformers are generally Y-y, D-y or Y-zigzag connected three phase units. A sensitivity analysis has been undertaken for these types of transformers. Figure 6. presents the change of the HV neutral voltage as a function of time. The comparison of the curves shows that the highest voltage stresses appear in Y-y connected transformers. In this case the voltage in the HV neutral is determined by the previously described process only. The amplitude of the voltage oscillation in the Y-zigzag transformer is smaller than in the Y-y one. In Y-zigzag transformer currents flowing in the LV winding layers located on the same core leg are of opposite sign. Consequently, the resultant induced voltage along the HV winding decreases.

The voltage stresses in the main insulation in D-y connected transformers are less dangerous than in Y-y and Y-zigzag ones. The peak value of the voltage oscillation in the HV winding is almost equal to the arrester residual voltage. In case of D-y transformers the bulk of the current forced by the induced voltage can flow through the inductances of the delta winding. Accordingly, no high amplitude oscillation will arise.

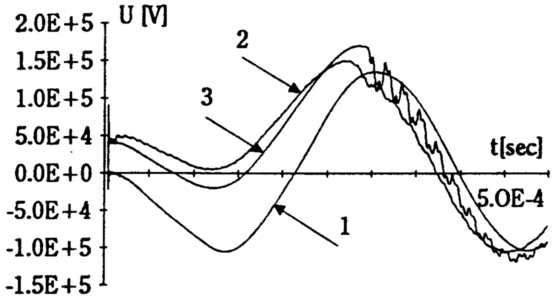


Figure 7. Effect of the HV overvoltage protection devices: 1.spark gap, 2.gapped arrester, 3.MOA

Overvoltage protection devices at the HV terminals of distribution transformers can be spark gaps, gapped or metal oxide arresters. These devices have different discharge voltage and discharge current. Consequently, they have significant influence on the voltage components determining the voltage stresses. Changing the type of the overvoltage protection device, the results shown in Figure 7. can be gained.

Using spark gaps the voltage component induced by the current flowing through the LV winding exists only, because the voltage across the gap is almost zero. Accordingly, the axis of the oscillation in the HV neutral is equal to zero voltage. If gapped arresters or MOA-s are used then the voltage in the HV neutral oscillates around the discharge voltage of these devices. Therefore the voltage stresses in the HV winding increases. Since the discharge current of MOA is higher than that of the gapped arrester thus the LV winding current and so the voltage stresses in the HV winding will be higher.

The transformer ground resistance has a significant effect on the magnitude of the current flowing through the LV winding. According to Figure 3., increasing this ground resistance a greater part of the arrester current ($i_{arrester}$) is forced through the load ground ($i_{load\ ground}$). Therefore the current flowing through the LV winding, the LV phase conductor and the LV load (i_{phase}) increases as well. Since this current determines the induced component of the HV neutral voltage, the voltage stresses in the HV winding become higher. The peak value of the resultant voltage in the HV neutral can be seen as a function of the transformer ground resistance in Figure 8.

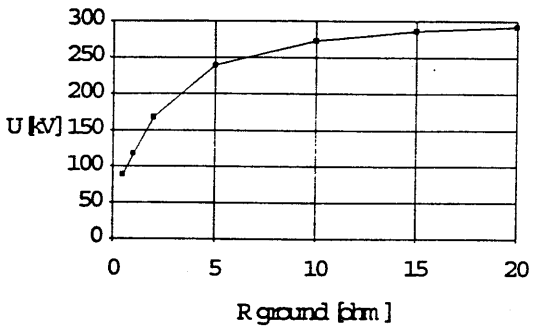


Figure 8. Effect of the transformer ground resistance

Figure 9. shows the influence of the load and its asymmetry on the voltage stresses in the HV winding. The stresses are significantly increased by growing the LV load. Increase of the load, that is the reduction of the load impedance results in the rise of the arrester current component flowing into the load ground ($i_{load\ ground}$). On the other hand it is seen from Figure 3. that the current division between the LV phase and neutral conductor is changed by varying of the LV load. If the load rises then the current flowing through the LV winding (i_{phase}) and consequently the amplitude of the voltage oscillation in the HV neutral increases. In case of unsymmetrical load the magnitude of the voltage oscillation decreases in comparison with the symmetrical one.

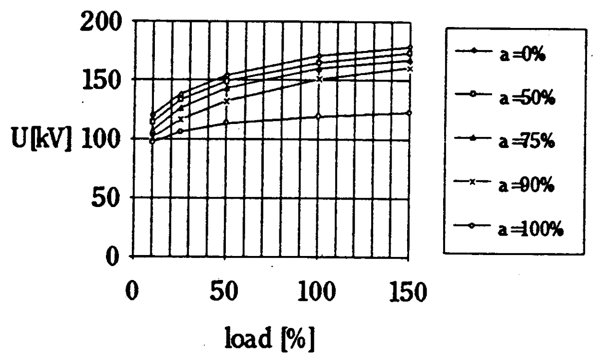


Figure 9. Effect of the load
(a:degree of asymmetry)

Finally the effect of the overvoltage protection devices (MOA, spark gap) connected to the low voltage terminals of the transformers has been investigated. The discharge voltage of a MOA with a protection level of 1 kV forces sufficient current through the LV winding resulting in high voltage oscillation in the HV neutral. A spark gap provides a near to zero impedance path for the surge current to bypass the LV winding and therefore significantly reduces the voltage stresses in the HV winding.

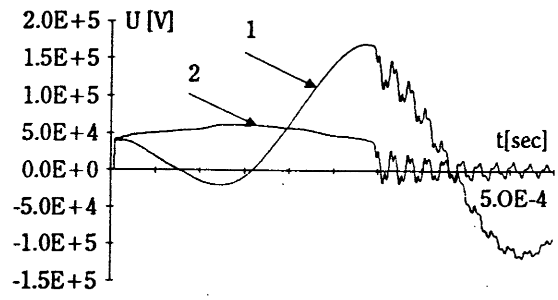


Figure 10. Effect of the LV spark gaps
1.without spark gap 2.with spark gap

CONCLUSIONS

A computer simulation model for the investigation of voltage stresses in distribution transformers is proposed. The suggested model is suitable to calculate the voltage distribution due to lightning surges along the transformer winding.
By this model the authors have investigated a phenomenon that may cause failures in pole mounted distribution transformers, even if they are protected on their HV side.
Furthermore a simplified reference circuit has been created to explain physically this phenomenon.
The overvoltage arising in the HV neutral during the process can be divided into two main components. One of them is determined by the discharge voltage of the HV overvoltage protection device, the other one is induced by the arrester current component flowing through the LV winding.
In Y-y and Y-zigzag connected transformers stresses arising in the HV winding may exceed not just the protection level of the HV arrester but the transformer BIL as well. In D-y transformers the overvoltages are less dangerous.
The stresses in the winding insulation can be significantly decreased by reducing the transformer ground resistance and by means of spark gaps at the LV terminals of the transformer.

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[2] DÉDÁSZ Pécs, ÜVOF-ÜTO Statistical Analysis of the Operational Characteristics of the Distribution Network, 1989
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