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OVERVOLTAGE PROTECTION OF POLE MOUNTED DISTRIBUTION TRANSFORMERS

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Abstract

The failure rate of pole mounted distribution transformers due to lightning is relatively high even if arresters are installed on their primary side. Dangerous voltage stresses resulted from the operation of the arrester connected to the primary terminals may appear in the transformer insulation. To clarify this phenomenon, a computer simulation has been undertaken. The authors have performed a sensitivity analysis in order to determine the main parameters influencing the stresses. It has been found that the most significant parameters affecting the voltage stresses in the transformer are the arrester current, the transformer connection and the transformer grounding resistance. The voltage stresses in the HV winding can be sufficiently reduced by means of spark gaps on the LV terminals besides the HV arresters.

Keywords: distribution transformer, overvoltage protection, computer simulation, sensitivity analysis.

Introduction

The statistics gained on the Hungarian distribution network show high failure rate (2–3%) of pole mounted distribution transformers due to lightning. Arresters or spark gaps are installed on the primary side of these transformers only. J. HUSE reported about similar experiences gained in Norway and Australia [1,2] and created a hypothesis for explaining the trend of statistical data. According to J. Huse's hypothesis, the failures in the HV winding are caused indirectly by the operation of HV arresters. Namely the arrester impulse current flowing through the grounding impedance initiates a sudden rise in the potential of the transformer tank causing an impulse current in the LV winding and high voltage oscillation in the HV one. HV arresters are unable to limit these stresses.

Results of laboratory tests and field recording are published in [1], supporting J. Huse's hypothesis. Authors complete and generalise the theory of Huse, analysing the effect of individual factors influencing the process, by means of a computer simulation based on ATP (Alternative Transients Program) and intend to give a wider physical explanation.

The authors make a proposal for a method suitable to reduce the voltage stresses in the HV winding arising in the way described above.

1. The Description of the Phenomenon

Fig. 1 helps to understand the origin of the current component causing high voltage oscillation in the HV neutral. It shows the simplified single phase circuit derived from the Hungarian distribution network. One terminal of the transformer HV winding is connected to the HV line and the other one is insulated from the tank corresponding to the HV neutral. The LV winding terminals are connected to the LV phase and neutral conductors. Arrester is mounted at the HV terminal of the transformer only. The LV load is concentrated in one point. The LV neutral conductor is grounded at the transformer and at the load.

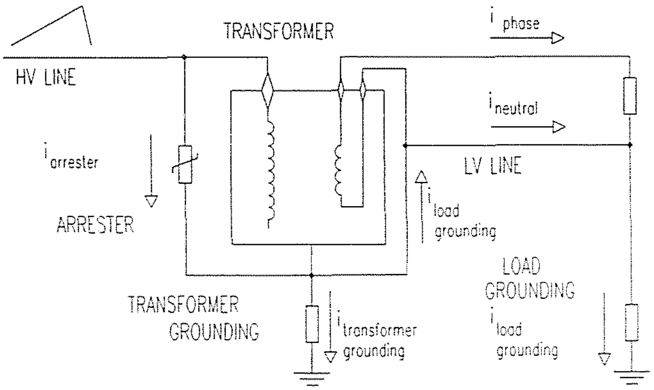

Fig. 1. Simplified single phase circuit

Lightning surge incoming on the HV line to the transformer operates the arrester and increases the voltage of the HV terminals to the arrester discharge voltage. Consequently, the potential of the HV neutral point will be increased too. The arrester current caused by the lightning surge is divided between the transformer grounding and the load grounding. $i_{loadgrounding}$ has two components. One of them is the LV neutral conductor current the other one is the LV phase conductor current. The latter one flows through the LV winding producing voltage oscillation in the HV neutral superimposed on the potential rise caused by the arrester discharge voltage (*Fig. 2*). The oscillation frequency is equal to the transformer first natural frequency. The voltage arising 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 discharge voltage and the current component flowing through the LV winding will cause the rise of the voltage stresses.

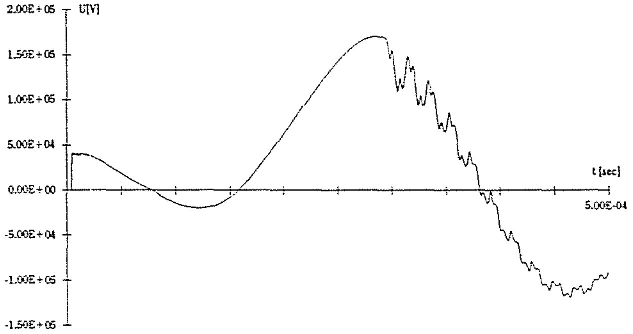

Fig. 2. Voltage oscillation in the HV neutral

The described phenomenon may appear even if the LV line is unloaded. In this case all of the $i_{loadgrounding}$ flows through the LV neutral conductor resulting in voltage difference between the phase and neutral wire (*Fig. 3*). Its peak value may exceed the strength of LV devices. Therefore, fault may occur in the LV circuit. A flashover can be considered as a sudden increase of the LV load, thus the process will be similar to one referred above. Since the flashover means a smaller impedance than the load, the current component conducted through the LV winding will increase. Consequently, the amplitude of the voltage oscillation in the HV neutral will be higher too.

A further simplification of the process is given in *Fig. 4*. *L1* is the inductance of the HV winding and the *L2* corresponds to the inductance of the LV winding. M is the mutual inductance existing between them. The value of C is determined by the ground capacitances of the HV winding. R is equal to the parallel resultant of the HV line surge impedance and the resistance of the arrester. The surge generator produces the i_{phase} current component (see *Fig. 1*) flowing through the LV winding.

The current surge forced through the *L2* inductance induces voltage oscillation in the series resonant circuit involving R, *L1* and C. The highest voltage to the ground arises at the junction of *L1* and C, which corresponds to the neutral point of the HV winding. It is clear, that using arrester at the HV terminals accordingly decreasing the values of R can not reduce the amplitude of the voltage oscillation.

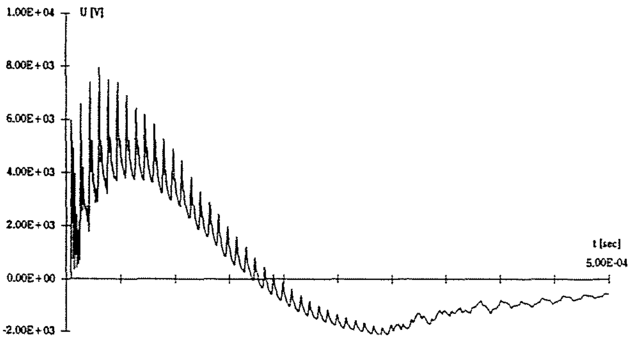

Fig. 3. Voltage difference between the LV phase and neutral wire

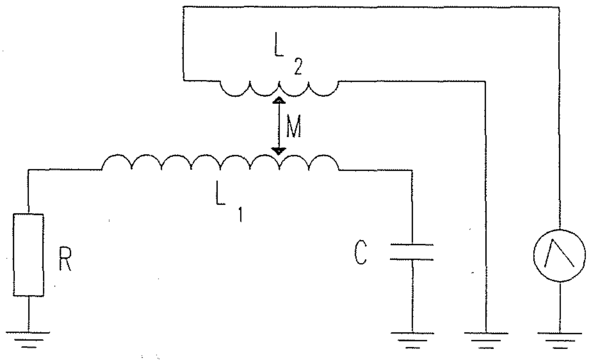

Fig. 4. Reference circuit

2. System and Model Description

Pole mounted distribution transformers are $D - y$ or Y-*zigzag* connected three phase units with 20/0.4 kV nominal voltage in Hungary. The neutral point of the HV winding is insulated while the LV neutral has a bushing and is grounded. The HV terminals are connected to a three phase resonant grounded network. The LV loads are supplied by a three phase directly earthed neutral system having a neutral conductor, which is grounded at the transformer and at the loads. The distribution transformers are protected only on their primary side by gapped or metal oxide arresters (MOA). A typical scheme of the described network can be seen in *Fig. 5.* The computer simulation has been established on the basis of the circuit shown in the figure. The main components of the model are the distribu-

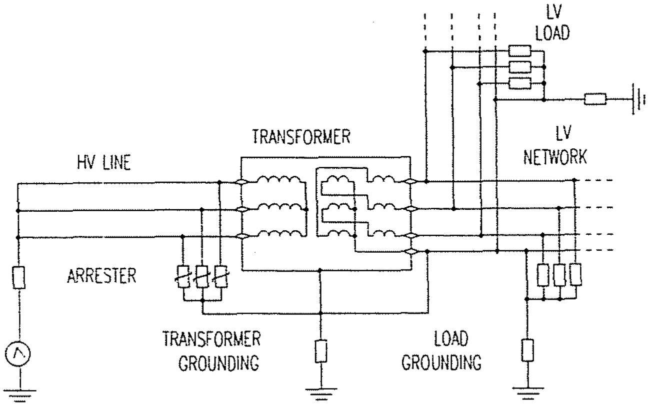

Fig. 5. Typical scheme of the distribution network

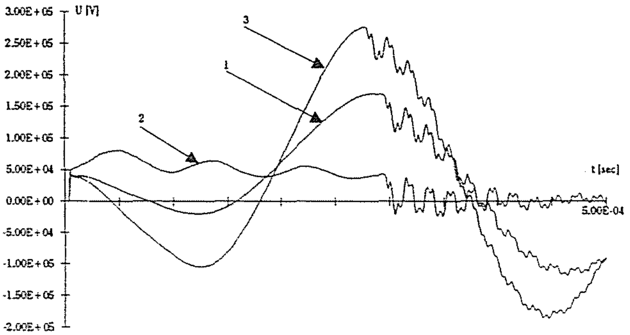

Fig. 6. Calculated voltage curves for different transformers
1. Y-zigzag, 2. $D-y$, 3. $Y-y$

tion transformer, the HV and LV line, the loads, the groundings and the overvoltage protection devices.

The transformer model is adequate for determining the transients caused by lightning surges. In such a case the winding capacitances have a significant influence. The calculation of the dominant frequencies determining the voltage stresses requires the division of the windings.

The HV and LV transmission lines are represented, by a distributed parameter model characterised by their travel time and surge impedance. These parameters are computed on the basis of geometrical data. Considering distribution networks, it may be supposed that all lightning strokes result in three phase to ground faults shunting the feeder side of the transmissult in three phase to ground faults shunting the feeder side of the transmission line. Consequently, only that part of the HV line has to be considered which lies between the transformer and the location of the closest flashover.

The lightning surge is represented by a Thevenin generator. Its parameters are calculated by the characteristics of the lightning and the network.

The program used for the simulation contains the model of the overvoltage protection devices (spark gap, gapped arrester, MOA) applied in the investigated network. These are considered by their operating principle and protection characteristic.

The LV load is modelled by a resistance and an inductance connected in parallel suitable for changing the value of the load and the power factor. The model is adequate for representing unsymmetrical load as well.

Groundings are simulated by an impedance considering the frequency dependent behaviour of the ground.

3. Results of the Computer Simulation

Sensitivity analysis has been carried out in order to clarify the effect of the network parameters influencing the described phenomenon. The network configuration to be simulated is shown in *Fig. 5.* The fundamental parameters affecting the voltage oscillation arising in the HV neutral point and their reference value or type are the following:

- connection of the transformer (*Y-zigzag*)
- the overvoltage protection device (MOA)
- magnitude of the arrester current (2.5 kA)
- value of the load (100% of the transformer nominal power)
- power factor of the load ($\cos \Phi = 1$)
- degree of the load asymmetry (0%)
- value of the transformer grounding resistance (2Ω)
- value of the load grounding resistance (1Ω)
- the type of the LV line (air insulated overhead line)
- bonding resistance in the circuit of the LV neutral conductor (0Ω)
- configuration of the LV network (single 960 m long line, loads are uniformly distributed)
- presence of LV overvoltage protection device (no protection)

The value or type of one circuit component only was changed during the sensitivity analysis in each case.

3.1 Impact of the Distribution Transformer Connection

The transformer connection is a main factor determining the voltage stresses in the HV winding resulted from the current surge in the LV winding. The analysis has been undertaken for three difference types of transformers ($Y - y$, $D - y$, Y-*zigzag*). The results are shown in *Fig. 6.*

The comparison of the curves shows that the highest voltage stresses appear in the HV neutral point of the $Y - y$ connected transformer. In $Y - y$ transformers the current forced by the induced voltage along the HV winding flows through the ground capacitances and raises the potential of the HV neutral.

The amplitude of voltage oscillation in the Y-*zigzag* transformer is slightly smaller than in the $Y - y$ one. In Y-*zigzag* transformers currents flowing in the LV winding layers located on the same core leg are of opposite sign. Accordingly, the resultant induced voltage along the HV winding will be smaller than in the $Y - y$ connected transformers. If the load is symmetrical an unsymmetrical arrangement of the winding can cause dangerous voltage stresses in Y-*zigzag* transformers.

The overvoltage stresses appearing in $D - y$ connected transformers are less significant than in $Y - y$ or Y-*zigzag* ones. In such a case the bulk of the current forced by the induced voltage can flow through the inductances of the delta winding. Therefore, high amplitude oscillation will not arise in the circuit shown in *Fig. 4.*

3.2 Effect of the Overvoltage Protection Device

At the analysed phenomenon the voltage in the HV neutral has two main components. One of them is resulted from the potential rise caused by the arrester discharge voltage and the other one is the voltage oscillation induced by the LV winding current. Different overvoltage protection devices can have different discharge voltage and discharge current. Consequently, the voltage stresses occurring in the HV neutral can be different too. The effect of spark gaps, gapped arresters and MOA-s as overvoltage protection devices installed at the HV terminals has been investigated by computer simulation. Results are shown in *Fig. 7.*

Using spark gap the amplitude of the voltage oscillation in the HV neutral is the least because the axis of the oscillation is equal to zero voltage.

Application of gapped arrester or MOA increases the voltage stresses in the HV winding since the voltage oscillation occurs around the arrester discharge voltage.

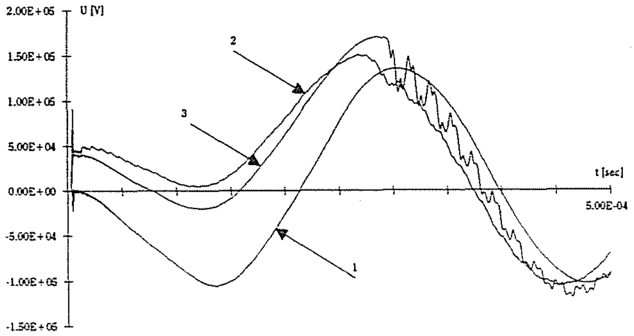

Fig. 7. Impact of the HV overvoltage protection devices
1. spark gap, 2. gapped arrester, 3. MOA

Because of the higher discharge current MOA-s produce higher voltage stresses than the gapped arresters.

3.3 Effect of the Arrester Current Magnitude

The amplitude of the voltage surge is determined by the potential rise on the HV pole grounding resistances caused by the lightning current. The discharge current of the overvoltage protection device depends on the amplitude and the shape of the incoming lightning surge. However, the parameters of the lightning surge are determined by the lightning current, the flashover voltage of the transmission line insulators and the distance between the transformer and the stroke. Consequently, the effect of the amplitude of the lightning and its distance from the transformer can be examined by changing the arrester discharge current. Network statistics show, that the probability of arrester discharge current higher than 0.5 kA is about 50%. The discharge current exceeds 5 kA only in 0.5% of the arrester operations [2]. Therefore, the value of the arrester current has been changed between 0.5 and 5 kA at the examination. The peak value of the voltage oscillation induced by the LV current can be seen in *Fig. 8* as a function of the arrester current. The voltage shows significant dependence on the amplitude of the current.

The rise of the arrester current amplitude increases the potential of the transformer grounding. Accordingly, a higher current will be forced to the load grounding at a higher arrester current. In such a case the current component flowing through the LV winding will increase too resulting in higher stresses in the HV winding.

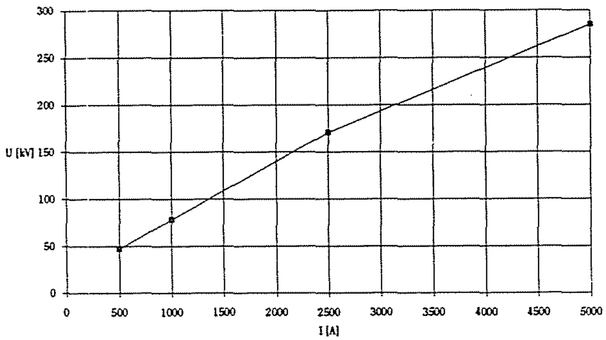

Fig. 8. Effect of the arrester current

3.4 The Impact of the Load

The load of the distribution transformers can vary in a wide range in Hungary. The load of some transformers may reach even 150% of their nominal power. The load was changed from 10% to 150% in the analysis. The effect of the load asymmetry has been investigated, too. The results (see *Fig. 9*) show that the rise of the load increases the voltage stresses in the HV winding.

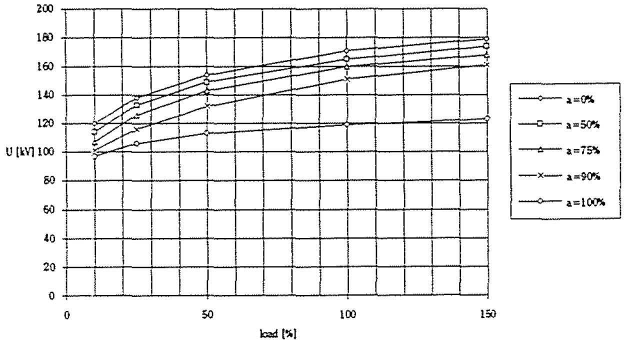

Fig. 9. Effect of the load (a: degree of asymmetry)

Increasing the load, that is reducing the load impedance a greater part of the arrester current will be conducted to the load grounding. The change of the load varies the current division between the LV phase and neutral conductor, too. Raising the load, the current component flowing through the circuit involving the LV winding, the phase conductor and the load impedance increases. Thus, the voltage stresses arising in the HV winding increase, too.

In case of unsymmetrical load one of the LV phase currents will be less than under symmetrical conditions. Therefore the induced voltage in the corresponding HV phase winding will be reduced. The ground capacitances of the HV neutral are charged by the resultant current of the three HV winding. Thus, this current, and the voltage oscillation will decrease in unsymmetrical case in comparison with the symmetrical one.

3.5 Impact of the Load Power Factor

Fig. 10 shows the amplitude of voltage oscillation appearing in the HV neutral as a function of the power factor. The curve does not show a significant dependence in the usual range of the cosΦ. At smaller power factors the voltage stress decreases. This can be explained considering the load model, which contains a resistance and an inductance connected in parallel. The inductive component has high reactance in the examined frequency range, therefore the resistance will determine the impedance of the load. Consequently, the decrease of the power factor corresponds to the reduction of a pure resistive load.

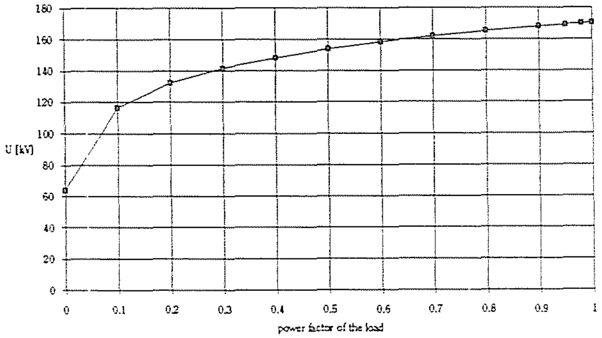

Fig. 10. Effect of the load power factor

3.6 Effect of the Transformer Grounding Resistance and the Bonding Resistance of the Neutral Wire

The effect of the transformer grounding resistance and the bonding resistance of the neutral conductor circuit on the voltage stresses occurring in the HV winding can be seen in *Fig. 11*.

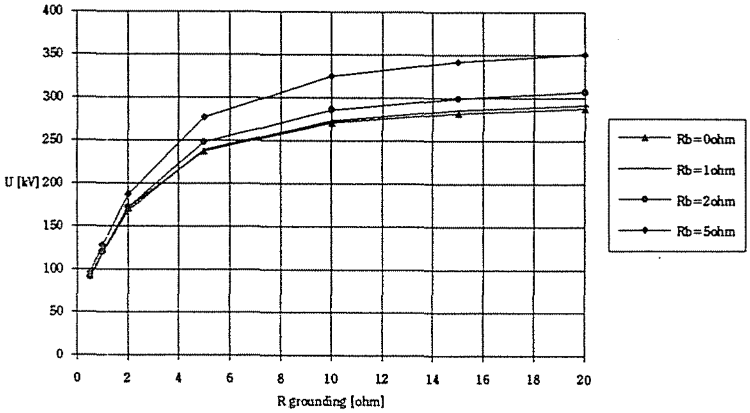

Fig. 11. Effect of the transformer grounding and bonding resistance (Rb: bonding resistance)

Increasing the grounding resistance a greater part of the arrester current is forced through the load groundings. Therefore the current flowing through the LV winding increases. Since this current component determines the amplitude of the voltage oscillation in the HV neutral, the voltage stresses become higher.

The bonding resistance of the neutral conductor circuit influences the current division between the phase and neutral conductor. The rise of this resistance increases the current component conducted through the phase conductor and results in higher voltage stresses in the HV winding.

3.7 The Impact of the LV Line Type

Two types of LV line are applied in Hungary. One of them is the open wire system, in which the conductors are horizontally spaced. The other is the twisted wire system with reduced distances between the plastic insulated conductors. Both line types have been examined in the investigation. The results can be seen in *Fig. 12.*

The decrease of the overvoltage stresses at twisted wire results from the reduced distances between the conductors. The reduction of the distances raises the mutual inductances between the LV conductors. Accordingly, the impedance of the LV circuit increases and the current through the LV winding becomes smaller.

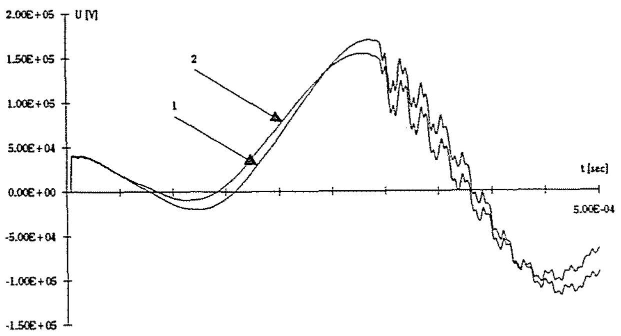

Fig. 12. Effect of the LV line type 1. open wire system, 2. twisted wire system

3.8. Impact of the LV Network Configuration

The real configuration of the LV network connected with the distribution transformer may vary in a wide range. The main parameters characterising the LV network are the length of the line and the number of the parallel branches.

The maximum line length is determined by the permissible voltage drop along the line. It is about 1000 m. The simultaneous change of the line length and the load centre results in the curve shown in *Fig. 13.* It can be established from the figure that the reduction of the line length and of the load centre distance from the transformer increases the voltage stresses occurring in the HV winding. Namely both of these parameters reduce the impedance of the LV circuit that is increase the current component flowing through the LV winding.

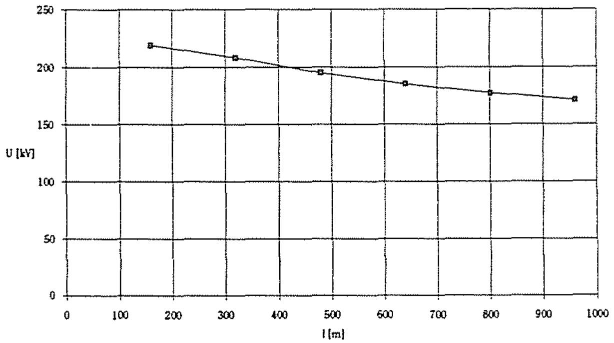

Fig. 13. Effect of the LV line length

At the same resultant load, but changing the number of the parallel branches, the peak value of the voltage oscillation induced in the HV neutral varies as presented in *Fig. 14*. Increasing the number of the parallel branches the voltage stresses rise slightly in the HV winding. This results from the reduction of the LV circuit impedance and the increase of the LV winding current.

3.9 Impact of the LV Overvoltage Protection Devices

The effect of spark gap and MOA connected to the transformer LV terminals has been analysed.

MOA with a protection level of 1 kV does not decrease significantly the voltage stresses in the HV winding. The reason is that the discharge voltage of the LV arrester 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 (*Fig. 15*).

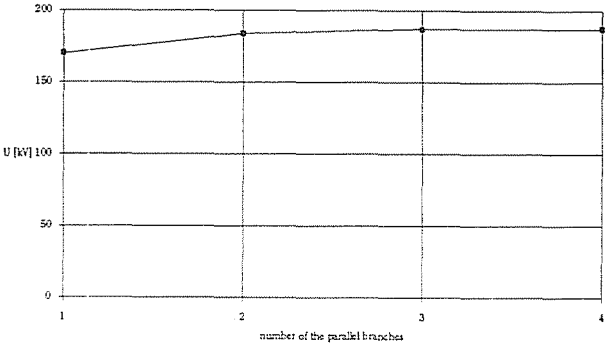

Fig. 14. Effect of the number of parallel branches

4. Conclusions

Lightning surges may cause dangerous voltage stresses in the winding tank insulation of the pole mounted distribution transformers, even if they are protected by arresters on their primary side. These stresses may exceed not just the protection level of the arrester but the transformer BIL as well.

Essentially, arising of the mentioned stresses is explained by J. HUSE [1]. The theory is based on the LV network potential rise resulted from the

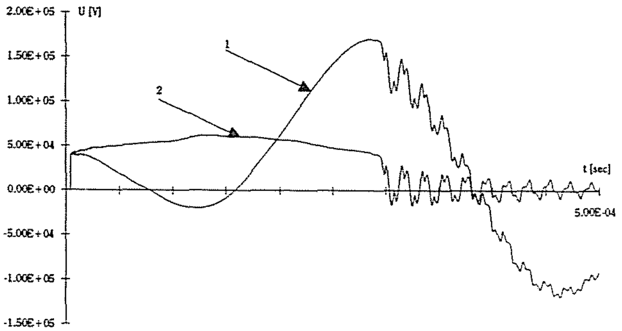

Fig. 15. Effect of the LV spark gaps 1. without spark gap, 2. with spark gap

arrester current component conducted to the transformer grounding. Due to this potential rise a flashover will take place somewhere in the LV circuit forcing an impulse current through the LV winding.

Authors showed that a high voltage oscillation may develop without any flashover in the LV circuit as well if the LV line is loaded. The amplitude of the voltage oscillation depends on the value of the loads.

The overvoltage in the HV neutral can be divided into two components. One of them is a potential rise caused by the arrester discharge voltage, the other one is a voltage oscillation resulted from the current surge through the LV winding. The second one is the dominant component in a great range of the lightning impulse parameters. This circumstance underlines the importance of taking the phenomenon into consideration at projecting the overvoltage protection.

The transformer connection has a significant influence on the overstresses. If $D-y$ transformer is used the voltage stresses on the HV winding are of less importance.

In principle, the phenomenon cannot arise in case of *Y-zigzag* connected transformers if their winding arrangement and the LV loads are symmetrical. Under real conditions usually there is unsymmetrical arrangement, so the above mentioned process will arise.

The overvoltage stresses are significantly increased by growing the value of the transformer grounding resistance.

The voltage stresses in the HV winding can be substantially reduced by means of spark gaps on the LV terminals of the transformer.

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