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ELECTROMAGNETIC SWITCHING TRANSIENTS IN TRANSMISSION LINE COOPERATING WITH THE LOCAL SUBSYSTEM

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ABSTRACT: The article investigates the overvoltage occurring during switching states in the line cooperating with the local subsystem. It discusses the possibilities of determining extreme values of overvoltage of all kinds by means of simulation tests. In particular, special attention was paid to the need to faithfully representation of components in power system i.e. transmission line, voltage transformer and surge arrester for correct reproduce electromagnetic waveforms on the primary as well as secondary side of voltage transformers. Overvoltages appearing in the line connected to the local subsystem during switching operations are forced by the change of network operating conditions. Electromagnetic transients in the unloaded line were tested after its sudden disconnection from the power supply. In the research, particular attention was paid to the conditions of switching off the line (moment and disconnection unity), the influence of surge protection devices, the type of the voltage transformer and the short-circuit power of the power subsystems. Simulation tests have shown that under certain conditions overvoltages with dangerously high values (e.g. 2.25x400 kV) may occur.

Keywords: Overvoltages, Switching Surges, Electromagnetic Transients, Equivalent Network

1. INTRODUCTION

The subject matter discussed in the article is directly related to the activities recently undertaken in the energy sector for environmental protection and climate policy.

It is known worldwide, "Energy Transition" is progressing which is the transformation of the energy system towards the age of renewables and energy efficiency.

In this situation, the conventional power supply system (in Poland 400 kV) will work more and more often with local subsystems with renewable energy sources (as so-called Clusters), and will be underloaded. This situation creates a danger of overvoltages.

In the 400 kV transmission network the overvoltages can occur which are mainly caused by the following factors:

- maintaining normal voltages in relation to the rated voltage of the network,
- expansion of the 400 kV transmission network (lines, especially in low-load states, are a source of reactive power, and as a result, increase the voltage level),
- insufficient equipment of the 400 kV transmission network in devices for capacitive reactive power compensation (parallel reactors),
- development of local production sources that relieve the transmission network.

The waveforms of electrical quantities in the highest voltage lines depend on many factors of which for the steady-state the most important are: shunt parameters, short-circuit power and line symmetry. This influence is emphasized in the case of a weak line load or if the line is opened at one end. However, one-side opened transmission line is a source of reactive power (the value of generated reactive power is proportional to the length of the line - 1 km of the 400 kV line generates approx. 0.5 MVAr). If the attached end of the line is connected to a weak system, it can cause a large voltage boost.

During transient states there are many important factors affecting the maximum values of electromagnetic transient components. For a full assessment of critical value, a comprehensive analysis was carried out, including the moment of switching off the line, the nonsimultaneously disconnection, the influence of surge protection devices, the type of the voltage transformer and the short-circuit power of the subsystems of the power supply.

Figure 1 presents a schematic diagram of the studied system and a graphic model introducing the input data to the MicroTran [1] program (UBC version of the Electromagnetic Transients Program -EMTP) used by the simulation. The program provides tabular display, printer plots and high-resolution graphics plots as output. The method used in the program is based on Bergeron's method for transmission lines and trapezoidal rule of integration for lumped parameters.

Using MicroTran program it is shown that all transients in high voltage systems can be determined and the most severe conditions can be modeled without risk and with very flexible possibility to determine the performance of electrical equipment in the high voltage line under all possible fault conditions in transmission system.

The analysis was made for the signals with soaring level of high-frequency component. Methods were tested with the help of MicroTran program and NETOMAC – program [2].

The test results are of great importance from the point of view of the reliability of the power system operation. This applies above all to the identification of input signals for power protection automation. Due to the occurrence of high frequency components in voltage transients and, as a consequence, the occurrence of overvoltage, the voltage signals are distorted and there is very important the faithful representation of transient voltages appearing on the both side of voltage transformers. In addition, high voltages on the primary side are harmful to both the safe operation of the system (insulation damage) but also to the possibility of erroneous protection automation causing cascading line shutdowns and, as a result, blackout.

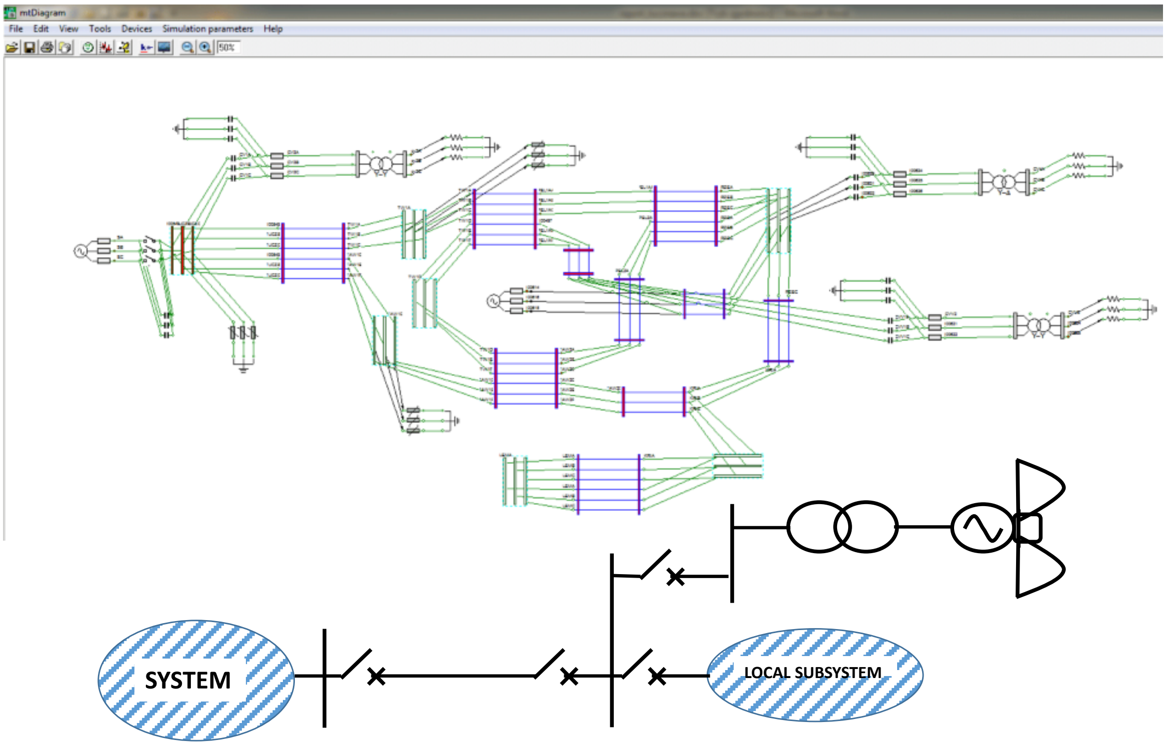


Fig.1 Diagram of tested system

2. SELECTION OF SIMULATION METHOD

2.1 Transmission Line Model

The transmission line in real is the only one element of the power system with distributed parameters, and therefore for the simulation the adequate numerical models and methods must be used. Figure 2 shows the elementary dx section of the transmission line.

Line modeling by means of a series of substitute elements connected in series – three-phase PI-gliders taking into account inductive and capacitive couplings - can lead to erroneous results manifested by the presence of artificial components that do not exist in real systems.

For the model of lines with distributed parameters, the dependence of parameters on the frequency is taken into account by the use of the so-called Marti model [3], which is the optimal solution from the point of view of accuracy and speed of calculation.

The obvious error can also be - as the results of calculations showed - the lack of skin effect in the line model, especially for interfacial interfacial disturbances.

2.2 Primary Equipment Models

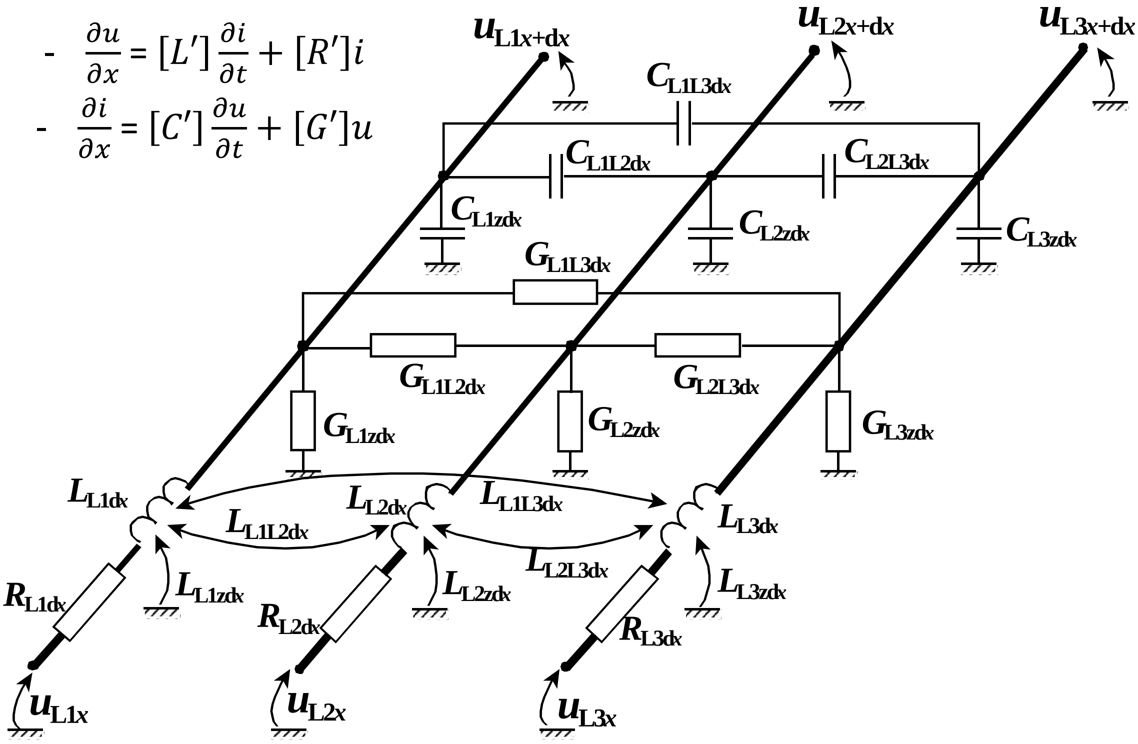
In order to obtain reliable results of electromagnetic studies of transient phenomena, apart from the overhead line model, it is very important to get the correctly representation of primary equipment such as voltage transformers and surge arresters.

There are two constructions of voltage transformers:

- inductive, which are measuring transformers with a primary winding connected directly to the network;
- capacitive, in which the measuring transformer is powered by a capacitive voltage divider, thanks to which the insulation of the transformer itself can be designed for a much lower voltage than in the case of induction transformers;;

In many constructions of inductive voltage transformer, the effective counteracting of ferroresonance phenomena for both harmonics and subharmonics is protracted.

Figure 3 is a substitute diagram of an inductive voltage transformer.



$$- \frac{\partial u}{\partial x} = [L'] \frac{\partial i}{\partial t} + [R']i$$

$$- \frac{\partial i}{\partial x} = [C'] \frac{\partial u}{\partial t} + [G']u$$

Fig. 2 Representation of the transmission line section length dx

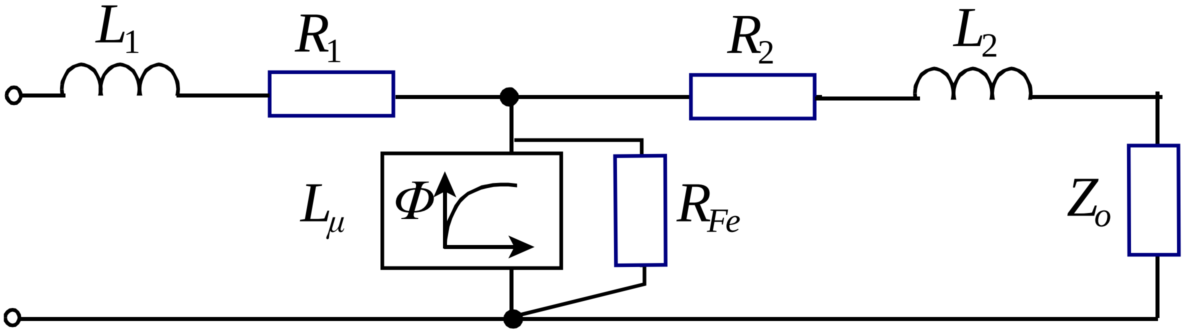


Fig. 3 Model of inductive voltage transformer

The errors in the transfer of the voltage signal transformer to the secondary side can be caused primarily by the impedance values of the load and the magnetization inductance L_{μ} and loss resistance in the R_{Fe} core.

The schematic diagram of the capacitive voltage transformer is shown in Fig. 4. During transient voltage transformers accurately transmit the voltage signal. The share of a non-periodic component in the voltage signal is small - there is no threat of saturation of the transformer. All significant harmonics are reproduced exactly on the secondary side and the impact of the magnetizing currents appearing during switching the transformers is damped very quickly. Signal transfer errors can only occur for very high frequency.

To protect the electrical apparatus against transient overvoltages, surge arresters (lightning arresters) are used to limit the duration and frequency of the subsequent current.

In MicroTran program two models of the surge arrester are available to the user: using non-linear resistance (Fig. 5) and built of a non-linear element - usually ZnO (Fig. 6).

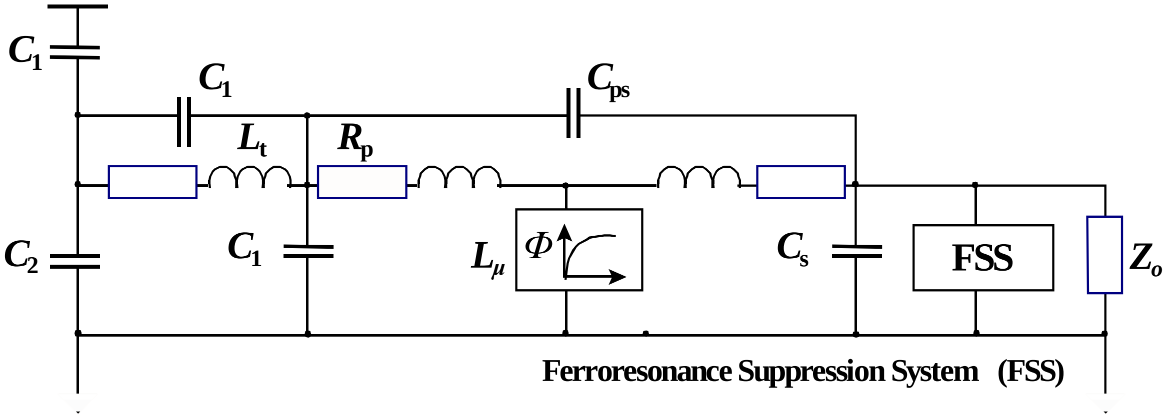
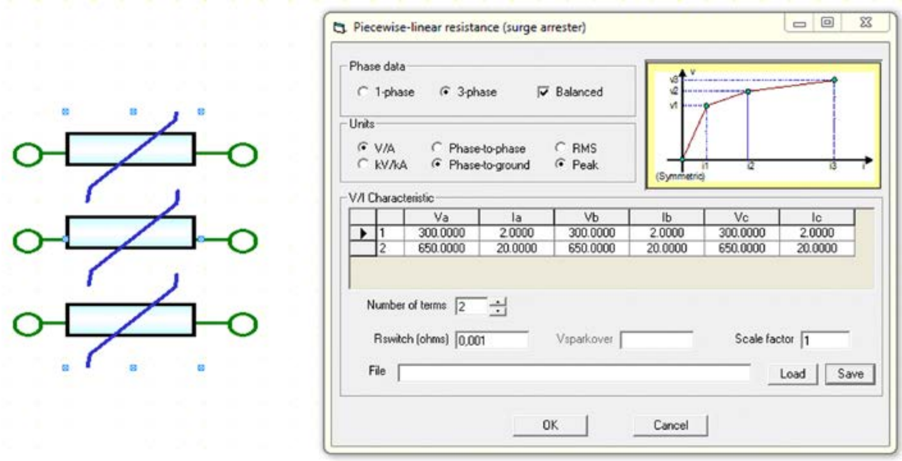


Fig. 4 Model of capacitive voltage transformer



Piecewise-linear resistance (surge arrester)

Phase data
○ 1-phase ● 3-phase ☑ Balanced

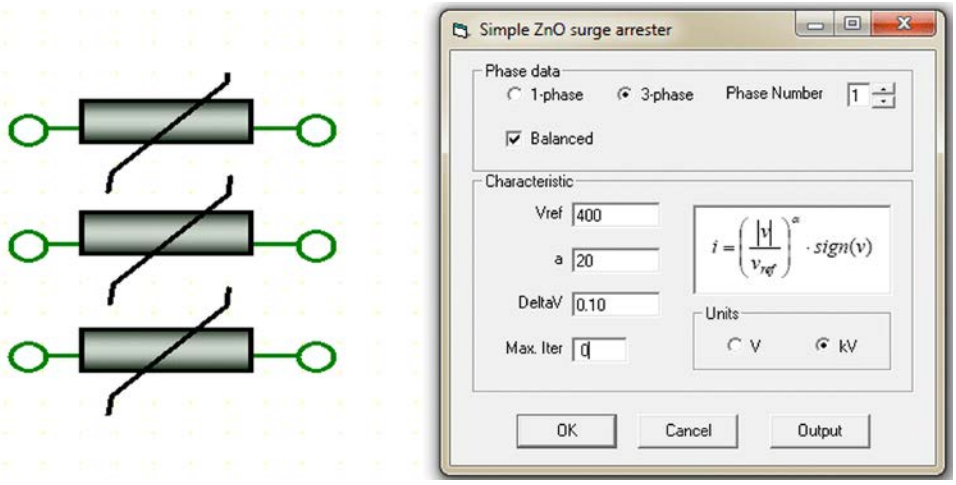
Units
● V/A ○ kV/kA
○ Phase-to-phase ● Phase-to-ground
○ RMS ● Peak

V/I Characteristic

		Va	Ia	Vb	Ib	Vc	Ic
▶	1	300.0000	2.0000	300.0000	2.0000	300.0000	2.0000
	2	650.0000	20.0000	650.0000	20.0000	650.0000	20.0000

Number of terms: 2
Rswitch (ohms): 0,001
Vsparkover:
Scale factor: 1
File:

Fig. 5 Representation of surge arrester with non-linear resistance



Simple ZnO surge arrester

Phase data
○ 1-phase ● 3-phase
Phase Number: 1
☑ Balanced

Characteristic
Vref: 400
a: 20
DeltaV: 0.10
Max. Iter: 0

$$i = \left(\frac{|v|}{v_{ref}}\right)^{\alpha} \cdot sign(v)$$

Units
○ V ● kV

Fig. 6 Model of surge arrester used ZnO element

The voltage in the line after disconnection from the power supply remains at a certain level - maintaining the instantaneous value as it had before the fault. This is due to the fact that the line voltage is not (or minimal) discharged. Connecting devices - voltage limiters on both sides of the line improves this situation. Both types of surge arresters were considered in the tests

2.3 Equivalent System

During analysis in complex system call in question both the necessity of detailed representation of each element and the range of reduction of network and its influence on credibility of results of investigation. Generally to get correct results of calculation in equivalent system is possible only when:

- element of system, for which transient (voltage or current) should be determined, must be modeled in detail without any simplification taking into consideration every factor having influence on result of investigation,
- remaining part of system which will be reduced must be represented by equivalent network but the parameters must by identified with the help of according optimization method.

By process of identification for given transient input signals there are searching the parameters of determined mathematical model representing part of system designed for reduction. For solution of such problem it is assumed at begin unchanged structure of investigated model and possibility of unlimited choice of parameter for equivalent.

By lack of information of identified equivalent system the identification process is going in 4 steps after preparation of input and output data signals:

- determination of structure of equivalent system,
- choice of optimization criterion,
- choice of numerical method and determination of parameters according to chosen criterion,
- testing of structure of model taking into account that for each new structure new parameter identification will be performed.

The choice of structure depend on later application but critical verification must be only after determination of optimal parameters of equivalent system. Very important is optimization method used during identification of parameters of equivalent structures.

The modification of least-square method proposed in [4] was tested for signals with high level of high frequency free components with MicroTran program and for signals with low level of this components with NETOMAC program.

The new idea using artificial neural network (ANN) determine the new direction of search of equivalent solution for the range of electromagnetic transient [5]. The aim is to replace part of systems by suitable universal ANN-based dynamic equivalents.

3. SIMULATION TESTS FOR VARIOUS WORK AND DISTURBANCE VARIANTS

3.1 Verification of Computer Simulation with the Values Measured During the Fault Test

Comparison of computed transient waveforms with those measured on an actual system allow some assessment to be made of the methods of calculation. The measurement techniques must be free of error and comprehensive system data must be provided in order to achieve maximum computational accuracy.

In Figure 7 the comparison of two measured voltage transient are presented.

The results were recorded during two measurements at the beginning of 260 km line length, during disconnection at the end of line. To be able to use the test results the values measured during the tests have been transferred into a mathematical model for the MicroTran program. The computer simulation was used for very detailed transmission line model and simple equivalents of complex transmission networks.

Comparison of the measured and calculated values for the voltage and current transients indicates that the system modeling was precise enough for further transient analyses.

3.2 Determination of the Value and Nature of Overvoltages Appearing in the Opened Line

The research has shown a huge number of factors affecting the surge coefficients, whereby repeatedly changing individual parameters for a given system configuration does not cause a significant change in the values of these factors, but only a change in "circumstances", e.g. time of peak voltage during an ongoing transient process. numerical analysis to determine the phasing delay times during which maximum overvoltages can occur is very tedious and time-consuming.

The maximum amplitudes of free components occur in the phase whose voltage at the moment of switching off reaches the maximum value. From the extremely different conditions of maximum transient voltage values (maximum overvoltages for the initial moment of the disturbance, when the disconnection phase voltage reaches the maximum) it follows that virtually always during the interferences there are free components with different amplitudes and damping times. Taking into account the phenomenon of superimposition of these components during non-simultaneous disturbances, there is the problem of the increase of these amplitudes and damping times in relation to these values calculated for simultaneous disturbances. The inconsistency of the switching disturbances results in a significant increase of the overvoltage coefficients in relation to the maximum calculated during these disturbances treated as simultaneous.

Figures 8 and 9 show the example of transients on the secondary side of the capacitive and inductive transformers installed at the beginning of the line when the circuit breakers are off at each of the two transmission line systems.

Overvoltage coefficients obtained during non-simultaneous switching off significantly exceed these values (as can be seen in the presented drawings) and despite the fact that overvoltages are transient, but due to the repetition of this phenomenon may pose a threat to the primary apparatus.

Figure 10 shows the same example of transients but on the primary system.

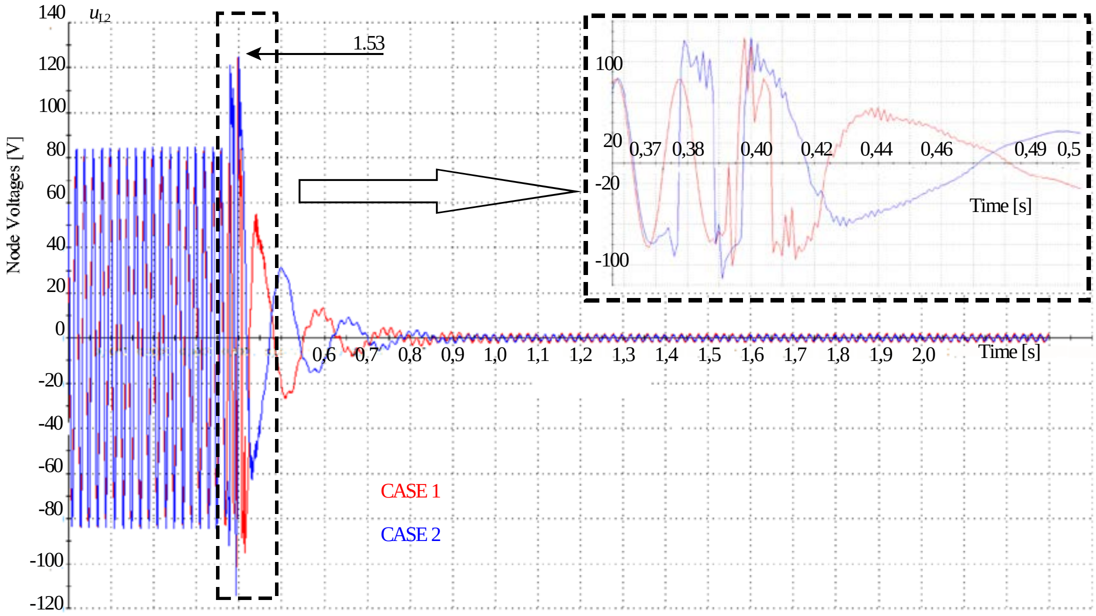


Fig. 7 Recorded voltage waveforms.

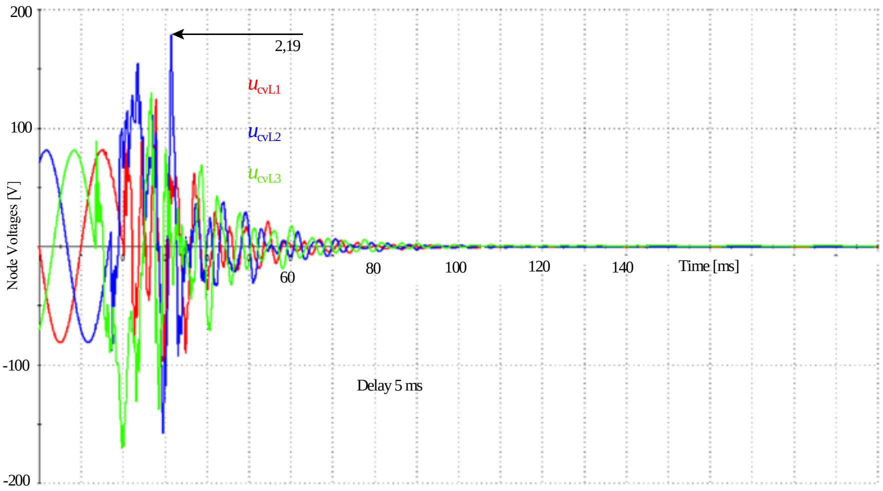


Fig. 8 Waveforms on the secondary side of the capacitive transformer after 5 millisecond delay of shutting down the second system

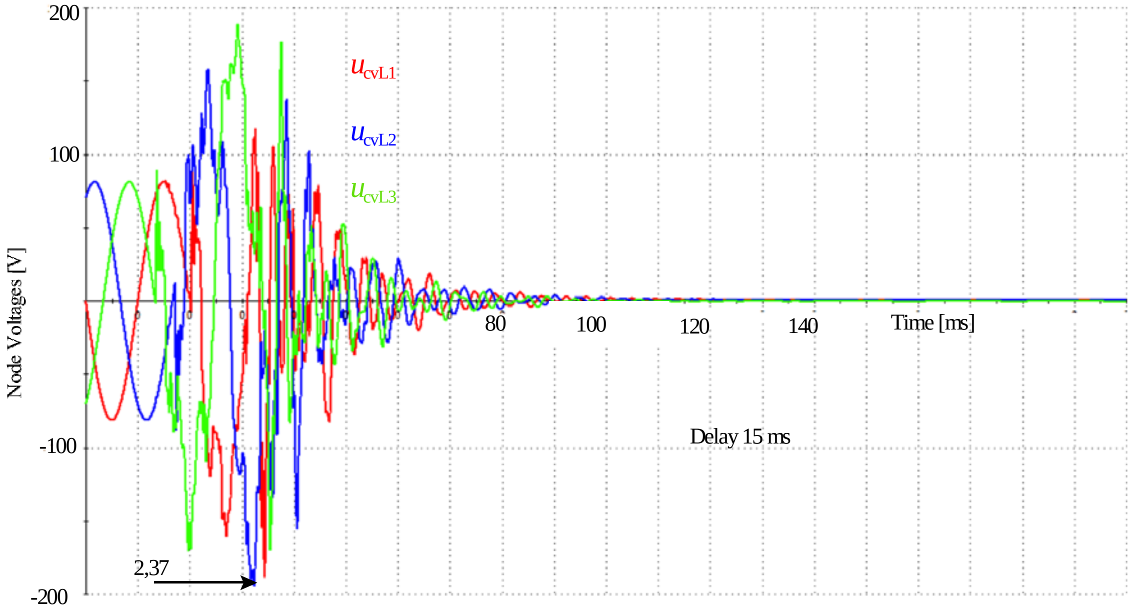


Fig. 9 Waveforms on the secondary side of the capacitive transformer after 15 millisecond delay of shutting down the second system

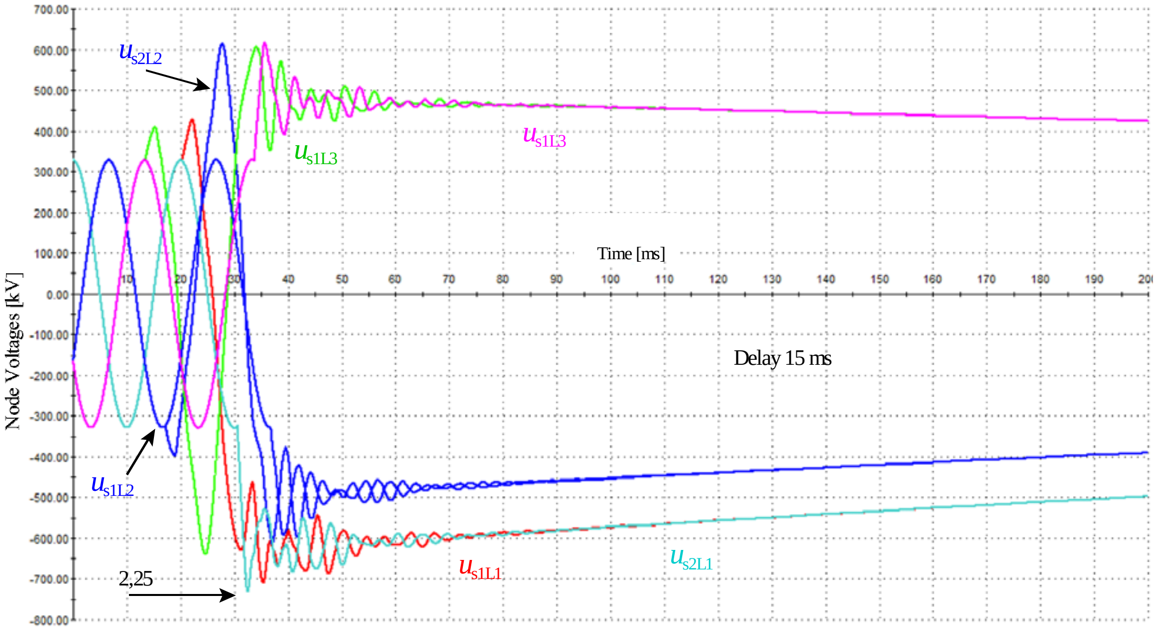


Fig. 10 Waveforms on the primary side of the capacitive transformer installed at the beginning of the line at the 15 millisecond delay of switching off the second system.

3.3 Discussion of the Impact of Data on Test Results

Situation in the line after disconnection from the power supply is stable. The voltage remains at a certain level - keeping the instantaneous value as it was before the disturbance. This is due to the fact that the voltage in the line is not possible (or they are minimal) for unloading. Connecting the equipment - voltage limiters on both sides of the line improves this situation.

Note that both types of representation of surge arresters do not contribute to large differences in the values of extreme surge coefficients. There is clearly faster damping in the case of modeling using a resistive model, but there is no major difference in the obtained surge coefficients, what is illustrated in the Fig. 11 and 12.

Transient waveforms occurring on the secondary side of capacitive voltage transformers do not change their character along with a change in the representation of surge arresters in the transmission system on the primary side. In both cases these waveforms are faster suppressed than the primary voltage, but there are oscillations resulting from the free components of the higher frequencies. Overlapping of these components causes a large number of voltages on the secondary side of capacitive voltage transformers. However, this does not pose a threat to the transformer due to the voltage value on the secondary side of the transformer.

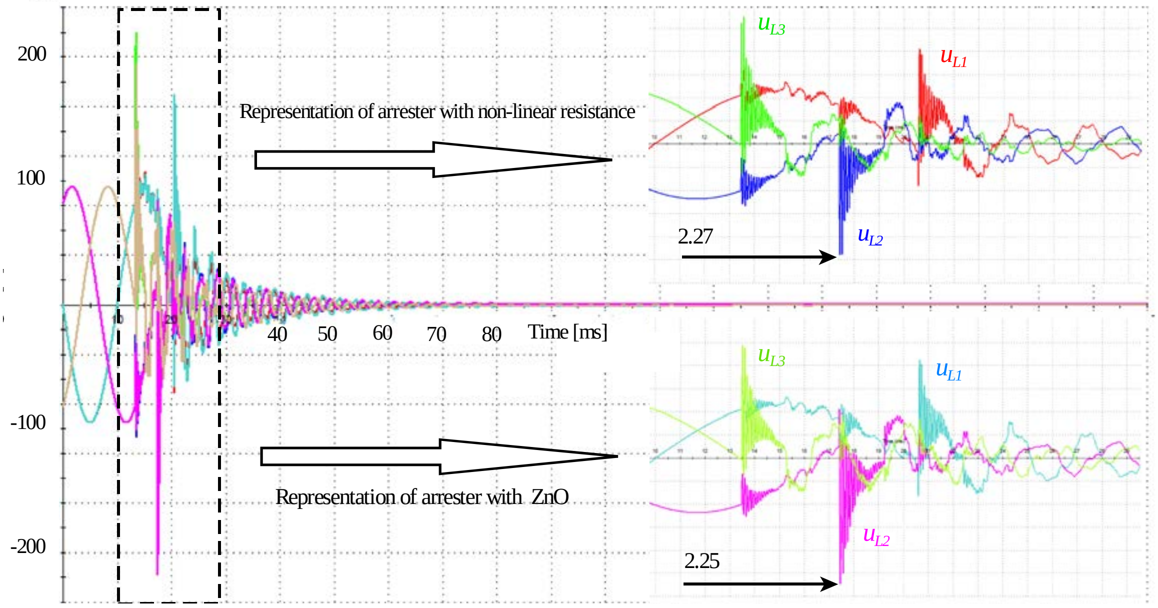


Fig. 11 Comparison of transients calculated on the secondary side of the capacitive transformer with two representation of surge arrester

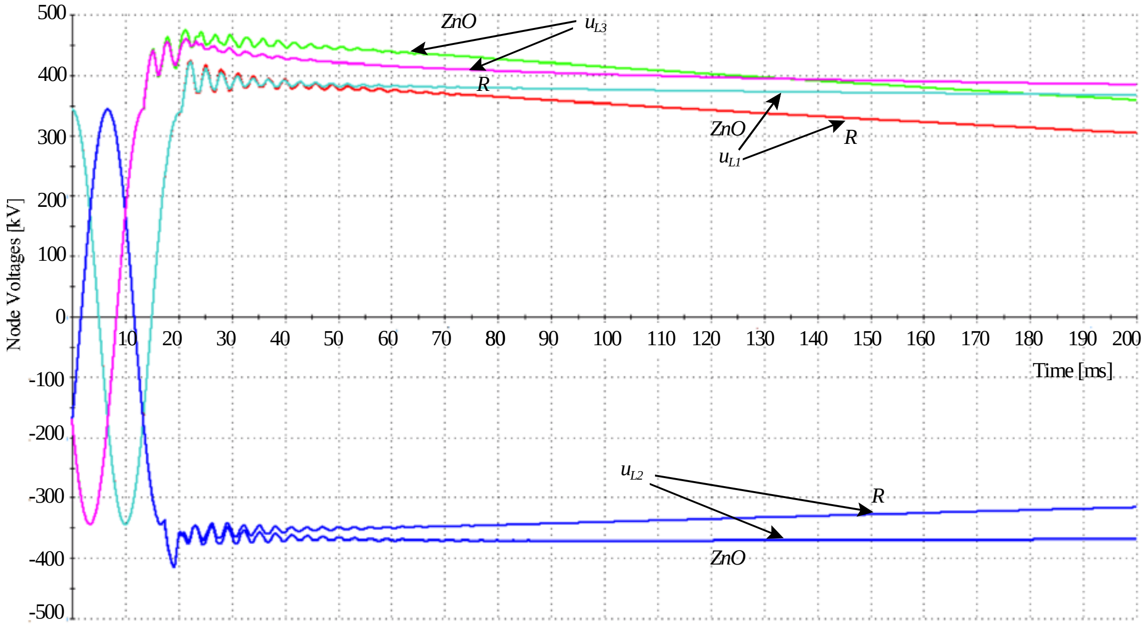


Fig. 12 Comparison of transients calculated on the primary side of the capacitive transformer with two

representation of surge arrester

4. CONCLUSIONS

As stated in the research, the high frequency components that disappear relatively quickly have a significant impact on the peak values of instantaneous voltages on both sides of capacitive voltage transformers. The extreme peak of the instantaneous voltage was noted at both ends of the switched off line with multiples significantly value (>2) in relation to the maximum phase voltage of the line.

The nonsimultaneous switching (e.g. non-simultaneous disconnection of lines on both sides and in each phase) causes a significant increase in overvoltage coefficients in relation to the maximum calculated during these disconnections treated as simultaneous.

During the disturbance state on the primary side of the capacitive transformer, the energy stored in the capacities and inductances results in transient oscillations on its secondary side. Transient waveforms are a combination of low frequency signal oscillation (2-15 Hz) and high frequency oscillation signal (900-4000 Hz).

The high frequency components disappear quickly - (unless ferroresonance occurs), but the free components of the lower frequency (dominant f = 2 Hz) attenuate very slowly and after 5 seconds keep the value below 30% of the rated voltage

The overlapping of free components created on the primary side of the transformer and its own oscillations may cause false signals from the secondary side. This mainly applies to free components of higher frequencies that determine the amplitude of induced overvoltages.

The cause of the disturbing phenomena investigated in the paper is the problem of switching overvoltages arising when switching off the unloaded line of considerable length, but still equipped with capacitor voltage transformers. The line with a fairly complex course is over 260 km long, so the power of charging it is about 150 MVar. It follows that the switch is designed to disable the capacitance of significant value.

Therefore, to determine the correct conditions for conducting mergers, one or several of the remedial measures resulting from the analysis should be applied:

- for the suppression of transient states, the simplest remedy could be to replace capacitive transducers with inductive voltage transformers. This is particularly important for the tested line of considerable length.
- it would be advisable to use high-voltage transverse chokes to reduce the overvoltages of the mains frequency (the so-called compensated line).
- discharge resistors, a short-term bypass switch, would be helpful.
- a good damping effect of oscillations after switching off the line could give short-term switching of resistors

Generally, for the elimination or reduction of the overvoltage in the line after disconnection of line - the best and the fastest solution would be to replace the capacitive voltage transformers with the use of inductive voltage transformers.

However, this causes the risk of occurrence of ferroresonance phenomena (in particular chaotic ones).

In future tests, the non-linearity of the transformer magnetization characteristics should be taken into account during simulation, because it can cause ferroresonance phenomena with line capacities and/or possible load

The use of controlled energoelectronic regulators system is not - from the point of view of development of network conditions conducive to the generation of ferrorezonance chaos - only the risks, but it can be an effective means of great potential to prevent or mitigate the effects of the phenomenon of ferroresonance or ferroresonance chaos in the power system.

Effective and efficient use of energoelectronic controllers, must be preceded by a series of simulation studies and not limited only to determine the presence and impact of regulatory options to change the substitute driver impedance parameters of the network and the resulting possibility of preventing ferrorezonance chaos but also taking into account, the impact of network parameters control using energoelectronic devices on systems stability - especially dynamic - power system or selected parts of system.

System requirements for Surge Protection mainly consist in the elimination of unnecessary operations.

Analyzing the transient waveforms presented in the paper, it can be generalized that the overvoltage protection measuring body should respond to the 50 Hz harmonic fundamental component. The system should be detached from both free components and higher harmonics.

The local subsystem cooperating with the transmission system can be replaced with an equivalent verified on on the basis of a constant update of the structure and parameters,

The specificity of the replacement system and the method of determining it does not require monitoring of the structure and parameters of the local subsystem.

Local power subsystems will be represented as equivalent in such a way that the identification of the parameters of the replacement schemes will be done in the time domain, and the result will be a simple system with selected parameters, so that the results of the calculations will accurately reflect the transitions of the real system.

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