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Switching overvoltages in low voltage system

Streszczenie. (Przepięcia łączeniowe w systemie niskiego napięcia). *Ochrona przepięciowa urządzeń elektrycznych jest nadal problemem aktualnym. Oprócz niekorzystnego wpływu przepięć na układy izolacyjne zawsze zakłócenie elektromagnetyczne ma negatywny wpływ na pracę urządzenia elektrycznego lub może być przyczyna jego uszkodzenia. Przepięcia w sieciach niskiego napięcia są generowane przez użytkowników energii elektrycznej lub są przenoszone ze strony pierwotnej na stronę wtórną transformatorów rozdzielczych. W artykule opisano system pomiaru przepięć łączeniowych, jego zastosowanie w sieci niskiego napięcia oraz ocenę mierzonych przepięć łączeniowych.*

Abstract*. Overvoltage protection of electrical equipments is still topical problem. Except negative influence of overvoltages on insulation of electric equipments often electromagnetic interference occur which can result in defective operation of electric equipment or its failure. In low voltage networks overvoltages are generated by consumers or are transformed from primary to secondary of distribution transformer. In this article we describe system for measurement of switching overvoltages its application in low voltage network and evaluation of measured switching overvoltages.*

Słowa kluczowe: przepięcia łączeniowe, system niskiego napięcia, EMC.
Keywords: switching overvoltage, low voltage system, EMC.

Introduction

At the beginning of development of electrical engineering arrangements dealt with limitation of overvoltage influence mainly on atmospheric overvoltages and switching overvoltages were oriented. With semiconductor production with high density integration the destructive effect of electrostatic discharge on semiconductive elements became topical problem.

In the distribution electric network e.g. 22/0.4 kV the distribution transformer is protected against influence of overvoltages on primary with surge arresters. The protection against influence of overvoltages on secondary (low voltage) is rare; protection of the loads carry out consumer and in many cases this step is realised until overvoltage event which cause defective operation e.g. failure of terminal equipment. Transient overvoltage in low voltage AC power system, caused e.g. by switching overvoltages, can cause either temporary malfunctions in electronic components and systems, or permanent deterioration. Impulse of voltage during transient state originated from reactions of arresters installed on primary is transformed to secondary and propagated on lines to customer. So even though the insulation of distribution transformer is protected against overvoltages on primary, loads connected on secondary are stressed by overvoltages transformed on secondary.

Another failure cause appears when overvoltage propagated from primary does not excite surge arrester because of low amplitude and it is transformed again on secondary. However the overvoltages can be generated on the secondary by loads e.g. technological processes.

Electromagnetic compatibility of electric and electronic equipments deals with overvoltage phenomenon, too. Negative influence of overvoltage on insulation of electric equipments eventually on insulation of electronic equipments in addition often originates in electromagnetic interference. Industrial localities are characteristic with disturbance mainly in the range of resonant frequencies from 80 kHz to 200 kHz, seldom in the range from 1.2 MHz to 2 MHz.

It is necessary to protect the insulation of electric equipments against damage by influence of overvoltages. Then ensure if by influence of overvoltages electric equipments does not generate disturbances into the control circuits and communication circuits.

Let us assume that the transformer station MV/LV supplies the office building and there was not evidence of failures of electric equipments due to overvoltages. The failure rate can increase when new loads with high density of integration e.g. computing machine, communication facilities, communications, adjusting equipments and control equipments were installed.

On the market there are sufficient electric devices and electric equipments for overvoltage events recording in low voltage AC power systems. Simple devices record the number of overvoltage events only and activation of counter is defined by amplitude of overvoltage, amplitude of current impulse or its combination. More complex devices record the amplitude of overvoltage, voltage pulse steepness e.g. current pulse steepness, pulse polarity, number of events.

Some devices record all overvoltage events which are defined by start conditions (trigger) and with all data in time domain. These data can be analysed and evaluated later.

Switching overvoltages

Switching overvoltages in low voltage system are well known. Occurrence of transition phenomenon depends on switch operation in AC power system.

System switching transients in low voltage AC power sytem can be divided into transients associated with:

- major power system switching disturbances, such as capacitor bank switching, distribution transformer switching,
- minor switching near the point of interest, such as an appliance turn-off in a household or the turn-off of other loads in an individual system,
- resonating circuits associated with switching devices, such as thyristors,
- various system faults, such as short circuits and arcing faults.

The highest overvoltage occurrence is in industrial centers and the smallest in households. The amplitude of transients covers the range from harmless values just above normal voltage to several kilovolts.

Frequency of occurrence of overvoltages with high amplitudes is smallest in household. Overvoltages with amplitude above 10 kV are rare because above these levels flashover in system installation appear.

The amplitude of temporary disturbance depends more on externally bounded energy and system impedance than on nominal voltage. Steepness of impulse is important behaviour which has influence on insulation and electronics. Measurements suggest that overvoltages with high amplitude have lower steepness, especially in industrial and business centre [1].

In the previous paragraphs the overvoltage event is described by four characteristics: amplitude of overvoltage, steepness of overvoltage impulse, spectrum of transition disturbance. The fourth considered parameter is the energy of impulse.

In [2] author present alternative three often used characteristics:

1. Magnitude, where the magnitude is either the maximum voltage or the maximum voltage deviation from the normal sine wave.
2. Duration, where the duration is harder to define, as it often takes a long time before the voltage has completely recovered. Possible definitions are:
   a) the time in which the voltage has recovered to within 10 % of the magnitude of the transient overvoltage;
   b) the time-constant of the average decay of the voltage;
   c) the ratio of the Ut-integral defined below and the magnitude of the transient overvoltage.
3. U_t-integral: the U_t-integral is defined as:

$$U_t = \int_0^T U(t)dt \tag{1}$$

where: t – time, T – appropriate value of time, U – voltage.

The start of the event begins at t=0 and an appropriate value is chosen for T, e.g., the time in which the voltage has recovered to within 10 % of the magnitude of the overvoltage. The voltage $U(t)$ can be measured either from zero or as the deviation from the normal sine wave. We can classify overvoltages according to the duration in:

- very short, corresponding to transient and self-restoring events;
- short, corresponding to automatic restoration of the pre-event situation;
- long, corresponding to manual restoration of the pre-event situation;
- very long, corresponding to repair or replacement of faulted components.

Knowing the magnitude and duration of an overvoltage event – recorded e.g. by a monitor over a certain period, it can be represented as one point in the magnitude-duration plane [2].

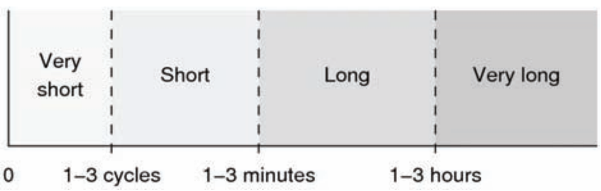

Fig.1. Classification of overvoltages magnitude events [2]

Both IEC and IEEE give different names to overvoltage events in some of the regions of the magnitude-duration plane. This method – using the magnitude-duration plane –, is useful and has a lot of information and knowledge about power quality. However, in many application of the overvoltage field the overvoltage factor is used. The overvoltage factor k is calculated as a ratio of the amplitude of overvoltage and p. u. constant, see equation (2).

$$\mathrm{k} = \frac{U_{\mathrm{mo}}}{p.\,\mathrm{u.}} \tag{2}$$

where: k – overvoltage factor, U_{mo} – amplitude of overvoltage, p. u. – per unit constant.

For three phase systems the p. u. constant is calculated as a ratio of the amplitude of the system voltage divided by square root of 3, see equation (3).

$$p.\,\mathrm{u.} = \frac{U \times \sqrt{2}}{\sqrt{3}} \tag{3}$$

where: $p.\,u.$ – per unit constant, U – system voltage.

A sudden change in the electrical conditions of any circuit will cause a transient voltage to be generated from the energy stored in circuit inductance and capacitance. The rate of change in current di/dt in an inductor L will generate a voltage U equal to:

$$U = L \cdot \frac{di}{dt} \tag{4}$$

where: L – circuit inductance, i – current, t – time.

This effect accounts for most switching overvoltages. It occurs as commutating spikes in power conversion circuits, when switching loads and under fault conditions. The simple effect of one switching operation can be repeated several times during a switching sequence, so that cumulative effects can be significant.

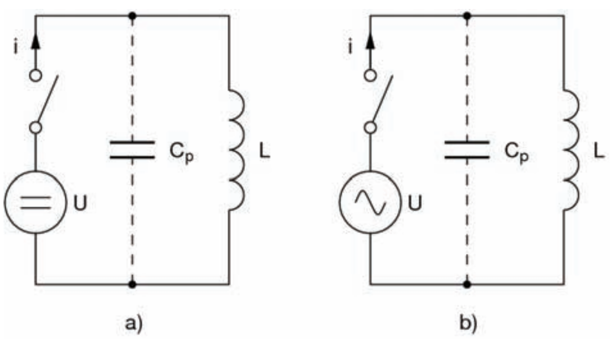

Fig.2. Disconnecting of circuit with inductor

After breaking circuit with inductor, current flow through inductor can enclose via stray capacitances C_p, (fig.2). Inductor current i then charges stray capacitances up to the breakdown voltage of the atmosphere between the contacts (for air, it occurs at 30 kV/cm in homogeneous electric field). The capacitance discharges and recharges repeatedly until all the energy is dissipated. The high initial charging current will oscillate in the inductance and capacitance at a high frequency. Considering at specific time all electrostatic energy accumulated in capacitance, neglectlosses, the amplitude of overvoltage reach

$$\frac{C_p \cdot U_{\max}^2}{2} = \frac{L \cdot I^2}{2} \tag{5}$$

where: C_p – stray capacitance, L – circuit inductance, $U_{\max}$ – amplitude of voltage, I – current.

In circuits with alternating current the transient voltage is superimposed to power frequency system voltage. Single conductor can be modelled with resistance and inductance in serial, capacitance (stray capacitance) to ground and shunt conductance. In the three-phase systems the mutual capacity between supply conductors of power cable should be considered. Short power cables usually are modelled with lumped parameters – resistance and inductance in serial for low voltage and middle voltage power systems. Over long distances, power cables are fairly low loss transmissions lines of about 150÷200 Ω characteristic impedance up to about 10 MHz [4].

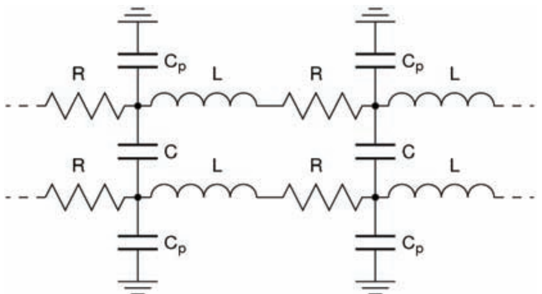

Fig.3. Equivalent circuit of long two-wire cable

In the figure 3 an equivalent circuit with distributed parameters of long cable with two conductors is shown. Both conductors have the same diameter and are made from the same material. In the presented equivalent circuit C represents capacitance between conductors and C_p stray capacitance to ground. However, voltage sources, loads and power cables connected each other develop together complex system.

As an example we can consider deenergizing the transformer primary. The opening of the primary circuit of a transformer generates voltage transients, especially if the transformer drives a high impedance load. Interrupting the transformer magnetizing current, and the resulting collapse of the magnetic flux in the core, couples a high voltage transient into the transformer secondary winding. Unless a low-impedance discharge path is provided, this burst of transient energy appears across the load.

Overvoltage measurement

In order to investigate of occurrence of overvoltages (mainly switching) in low voltage network the measurement in transformer station 22/0.4 kV were performed. Performed on-line measurement of overvoltages lasted six days in one phase of three phase voltage system. On the figure 4 the place of connection to voltage system by voltage probe is shown. The place of connection is marked by letter „A“.

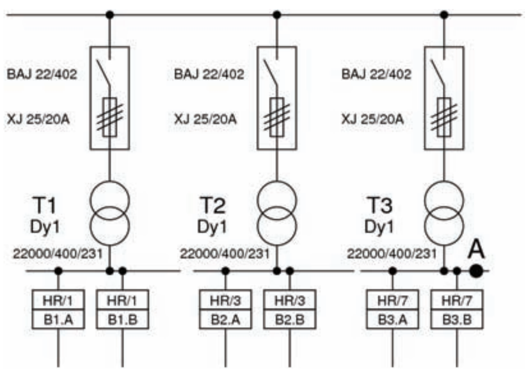

Fig.4. Connection point of measurement system

The measuring system consists of two basic units: digital scope which record overvoltage events and personal computer controlling the scope. Start conditions of the scope enable store all overvoltage events with amplitude higher than 360 volts. The level of triger was approximately 10 % higher than the amplitude of phase to ground voltage. Moreover, the personal computer performed data recording and data archives of measured events. Overvoltages were measured by the probe with the ratio 1 000:1. After generation of overvoltage personal computer record this event in time domain, date of event, time of event and the amplitude of overvoltage (its positive and negative amplitude), see table 1. Every one record of the event last 100 ms. Measuring system was adjusted so that total recorded data of one event consists of one period before beginning of the event (20 ms) and four periods after beginning of the event. In order to record detailed behaviour of overvoltage events 1 MS/s sample rate for digital converter of the scope was adjusted.

Table 1. List of overvoltage events

No.	Date	time	positive amplitude	negative amplitude
1	Thu, 10 Nov	16:34:38	+1 180	–1 500
2	Thu, 10 Nov	17:24:25	+540	–400
3	Thu, 10 Nov	23:14:22	+500	–380
4	Fri, 11 Nov	16:38:31	+520	–1 440
5	Fri, 11 Nov	20:59:52	+480	–380
6	Sat, 12 Nov	16:15:24	+500	–400
7	Sat, 12 Nov	18:04:43	+440	–400
8	Sun, 13 Nov	00:10:41	+500	–380
9	Sun, 13 Nov	01:46:41	+440	–380
10	Sun, 13 Nov	16:17:19	+460	–760
11	Mon, 14 Nov	13:00:46	+460	–380
12	Mon, 14 Nov	16:10:12	+1 180	–760
13	Mon, 14 Nov	19:01:15	+400	–360
14	Tue, 15 Nov	08:25:55	+420	–380
15	Tue, 15 Nov	08:26:39	+460	–380
16	Tue, 15 Nov	08:27:32	+620	–380
17	Tue, 15 Nov	08:29:21	+880	–380
18	Tue, 15 Nov	08:30:37	+460	–640
19	Tue, 15 Nov	08:31:19	+740	–380
20	Tue, 15 Nov	08:37:00	+660	–640

During six days we achieved completely 20 records. Last 7 records represent switching overvoltages activated by planned operation (switch-on and switch-off) with switch device, see data listed above in the table 1. The maximal recorded amplitude of overvoltage is –1 500 V which is 4.59 multiple of amplitude of the phase to ground voltage. Here the per unit (p. u.) of the system nominal voltage phase to ground crest equals 326.6 V. Overvoltage factor is calculated as a ratio of the amplitude of overvoltage and p. u. constant, see equation (2).

The results obtained from the measurements of overvoltages were analysed in the time domain. After data analysis we can conclude that:

1. overvoltages with the overvoltage factor higher than 2 have impulse shape with aperiodic behaviour. The front time of impulses lasted about ten microseconds and the time to half-value lasted to one hundred microsecond, see figure 5 and figure 6. In the figure 5 it is seen that during three periods seven overvoltage events occurs. In the figure 6 aperiodic behaviour of switching overvoltage in the time domain is evident where magnified part of time window of the figure 2 is shown;
2. overvoltages with overvoltage factor less than 2 can attribute to damped oscillation. The front time of impulses and the time to half-value are comparable with overvoltages with factor higher than 2 described above. The total duration of switching overvoltages is longer. It is approximately *n*-times longer in

comparison with aperiodic shape of impulses, where n is the number of halfcycles of damped oscillation.

Planned manipulation – man-made overvoltages was realised as follows (records No. 14–20). Before begining of manipulation two transformers T1 and T3 were in normal parallel operation.

The manipulation begins by switch-of of transformer T3 then the transformer T2 was switch-on so two transformers T1 and T2 in parallel operated. After while change to parallel operation of transformers T1 and T3 by switch-off T2 and next switch-on T3 was realised.

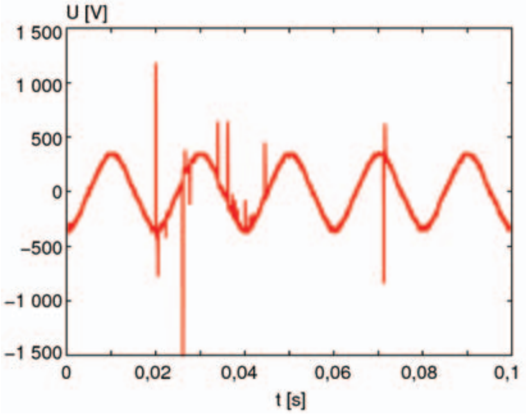

Fig.5. Overvoltage behaviour in time domain, no. 1

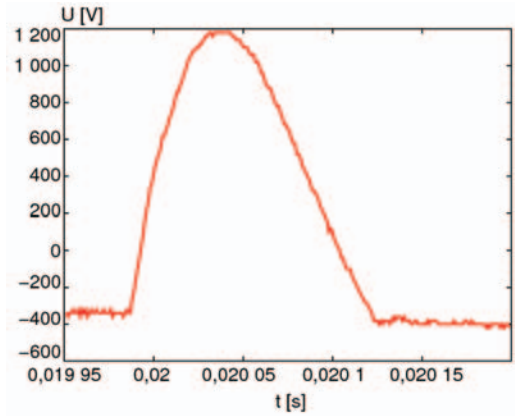

Fig.6. Overvoltage behaviour in time domain – detail , no. 1

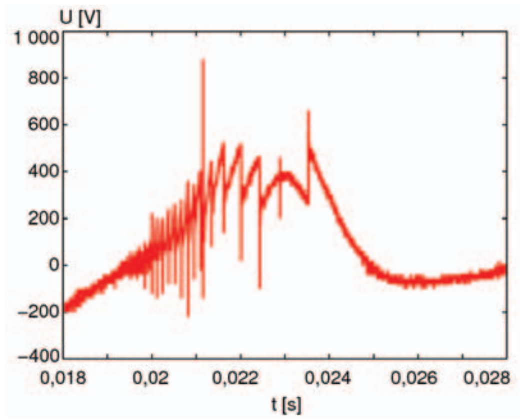

Fig.7. Switch-off transformer on primary – detail, no. 17

From figure 7 it is clear that in addition to overvoltage caused by switch-of transformer on primary short following voltage impulses due to recovery voltage on contacts of the circuit breaker originated.

These voltage impulses with relatively low amplitude are not very dangerous for insulation of the electric equipment. However, from the electromagnetic compatibility point of view these voltage impulses cause interference in power system and in addition decrease the quality of the system voltage.

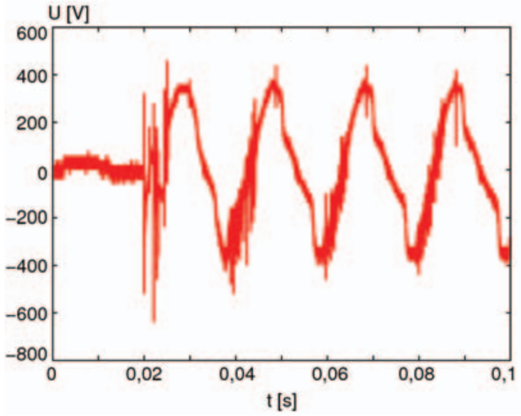

Fig.8. Switch-on MV/LV transformer on primary, no. 18

From the electromagnetic immunity point of view some electric equipment (e.g. power source for PC) are sensitive to these voltage impulses and can cause incorrect operation especially when galvanic coupling exist.

In the figure 8 it is clear that switch-on transformer on primary cause disturbing pulses superimposed to power voltage. These impulses originated from repetitive arc ignition and arc suppression between contacts of circuit breaker. Moreover, distortion of power voltage due to higher harmonic after switch-on transformer originated.

Except on-line overvoltage measurement in low voltage system some additional measurements of overvoltage occurrence on electric equipments with relatively low power e.g. single-phase transformer, personal computer, drilling machine, refrigerator, incandescent lamp, and fluorescent lamp were performed. Man made overvoltages on mentioned electric equipments by switching-on and switching-off of the circuit breaker were realised. The place of connection to voltage system by voltage probe with the ratio 1 000:1 near the load was realised.

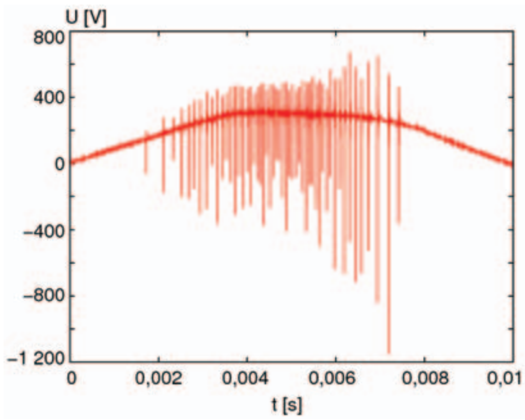

Fig.9. Operation of drilling machine – detail

The amplitudes of measured overvoltages range from values just above normal voltage to some kilovolts (1÷3 kV). In the figure 9 overvoltages measured during operation of drilling machine in time domain are shown. Switch-on of drilling machine with push-button switch was realised. The amplitude of repeated voltage impulses reached up to 2 kV. These voltage impulses except voltage stress on insulation of electric equipments effect disturbing voltages by means of galvanic or electromagnetic coupling in low voltage system.

An interesting result with the incandescent lamp which represents resistive load were obtained. Overvoltages up to 1 kV were achieved. The amplitudes of overvoltages depend on the design of the circuit breaker and electrical properties of the electric circuit.

Switching personal computer results in small amplitude of the overvoltage. Switching single-phase transformer with no-load and single-phase motor develop overvoltages up to 2 kV.

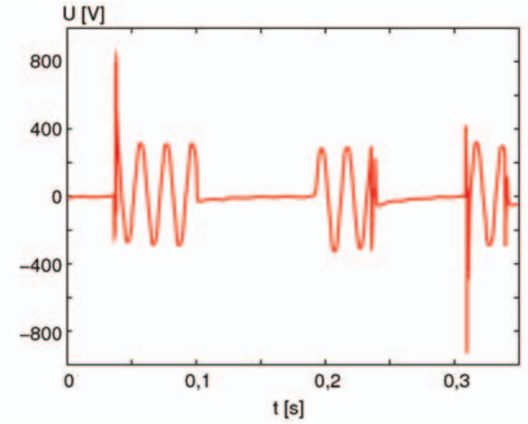

Fig.10. Switch-on of incandescent lamp

Conclusion

We performed on-line measurement of overvoltages in order to investigate occurrence of overvoltages in low voltage system. Measurement lasted six days in the transformer station 22/0.4 kV supplying the office building of the railway station. We apply digital measurement technique controlled by personal computer.

According to our defined start conditions we record 20 overvoltage events with maximal overvoltage factor 4.59. Some overvoltage events caused voltage impulses due to recovery voltage on contacts of circuit breaker.

Because loads connected to measured electric circuit are distance some hundreds meters from transformer station it would be advisable to realise on-line measurement of overvoltages on more locations at the same time. In this way it would be possible to investigate the influence of damping of cables on the overvoltage impulses.

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