Surge protection of resistive loads in low voltage power installations

Vladan M. Radulović, Vladan R. Durković***

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Abstract: Advanced electric equipment widely used nowadays both in residential as well as in industrial low-voltage power systems have weak surge withstand capability. The electromagnetic sensitivity of these devices requires an appropriate protection against voltage and current surges. Analysis of protection performances of surge protective devices arranged in one-stage and two-stage protection system will be given in the paper for case of resistive load. Analysis will be performed using MATLAB for different values of resistive load's active powers widely used in low voltage power installations. Performed analysis should to point on possibilities and limitation for proper overvoltage protection.

1. INTRODUCTION

Electrical and electronic devices and systems installed in residential, business and office buildings, or industrial factories have a very low withstand impulse voltage level. Therefore, lightning is one of the major sources of electrical overstresses that can cause failure, permanent degradation, or temporary malfunction of these devices and systems [1].

In order to ensure uninterruptible power supply and/or survival of equipment under lightning surges it is necessary to apply adequate lightning protection system (LPS), which is consisting of the external and the internal lightning protection installation [2]. Components of the external LPS are the air termination system, the downward conductor system, and the earth termination system. The functions of the external LPS are to intercept the lightning flash, to conduct the lightning flash safely to earth, and to disperse it to the earth. Components of the internal LPS are the lightning equipotential bonding and the separation distance between the external LPS and the volume to be protected. The function of the internal lightning protection is to prevent dangerous sparking within the structure. The LPS does not provide sufficient protection for the electrical and electronic equipment installed inside the structure [3]. The adequate protection of the apparatus requires a

* Vladan M. Radulović (corresponding author) is with Faculty of Electrical Engineering, University of Montenegro, Montenegro (phone: 382-69-537605; e mail: vladanra@ucg.ac.me).

** Vladan R. Durković is with Faculty of Electrical Engineering, University of Montenegro, Montenegro (phone: 382-68-893973; e mail: vladan.d@ucg.ac.me)

lightning electromagnetic impulse (LEMP) protection measures according to IEC standard 62305-4 [4]. The protection against LEMP is based on the lightning protection zones (LPZs) concept. Successive zones are characterized by a significant reduction of the LEMP severity. This significant reduction is provided mainly by installation of different types of Surge Protective Devices (SPDs) at the boundaries of the different LPZs [4]. SPDs have to fulfill two major tasks: first, to divert a large amount of the surge energy to the ground (which refers to SPD's energy absorption capability) and second, to clamp the surge voltage to the level below withstand impulse voltage level of protected device(s) (which refers to SPD's protection voltage) [5].

However, protection performances highly depend on proper selection and installation of SPDs in low voltage power systems. Many factors such as characteristics of the protected elements, length of cables between SPDs and equipment to be protected, and the characteristics of the SPDs affect the protection performances of SPDs.

Devices with resistive load are very common in low-voltage power systems of residential and industrial objects. Although insulation of these devices is equally subjected to effects of overvoltages, there is not enough attention given to the overvoltage protection of such devices in comparison with the protection of modern electronic devices. Namely, devices with resistive load usually do not have built-in surge protective devices, and their overvoltage protection completely relies on installation of SPDs throughout a power installation.

Analysis of protection performances of SPDs arranged in one-stage and two-stage protection system will be given in the paper for case of resistive load. Analysis will be performed using MATLAB for different values of resistive load's active powers widely used in low voltage power installations. Performed analysis should to point on possibilities and limitation for proper overvoltage protection.

2. ONE-STAGE OVERVOLTAGE PROTECTION SYSTEM

Transient response of electrical devices with resistive load in cases of surges propagating into electrical installations from service entrance can be analyzed with simple system given in Fig. 1. The system represents one-stage protection scheme with installation of only one SPD, usually at distribution board.

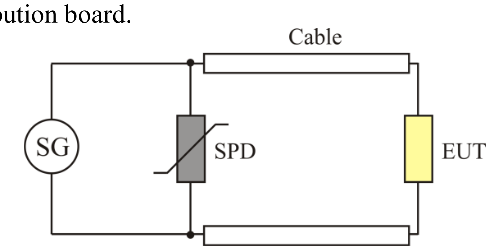


Fig. 1. Model of overvoltage protection system

Equipment under test (EUT) is device within low voltage installation with resistive load. Capabilities of electrical and electronic devices to withstand overvoltages are determined with their insulation level i.e. with their withstand impulse voltage. According to IEC standard 60664-1 [6], devices are classified into four overvoltage categories (I - IV). It will be assumed that EUT belongs to overvoltage category I for which withstand impulse voltage is 1500V.

Large number of field tests show that surges with different waveforms, amplitudes and steepness occur in low-voltage installations. However, in order to determine influence of surges to equipment through analytical or experimental approach, as well as necessary protection measures, wide variety of surges should be modelled with few representative surges. IEEE standard C62.41.2 [7] defines representative surges, which characteristics regarding waveforms and amplitudes depend on location categories. In this paper, Combination Wave, as one of the representative surge, is used as surge delivered by surge generator in Fig. 1. Combination Wave is consisting of two waveforms: 1.2/50 μs open circuit voltage waveform, and 8/20 μs short circuit current waveform. Amplitudes of these waveforms are selected for location category B and their values are 6 kV for open circuit voltage waveform and 3 kA for short circuit current waveform [7]. Model of surge generator is given in Fig. 2 [8].

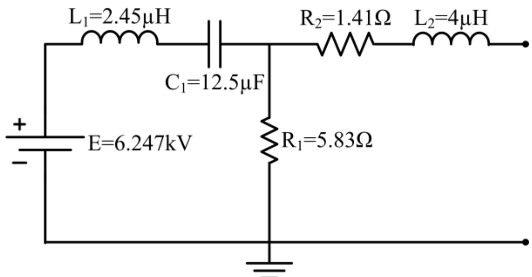


Fig. 2. Model of the Combination Wave generator

SPD is arrester of type 2 according to IEC 61643-11 standard [9], designed for mounting on sub-distribution board with protection voltage of 1250 V, which is lower than withstand impulse voltage of observed equipment.

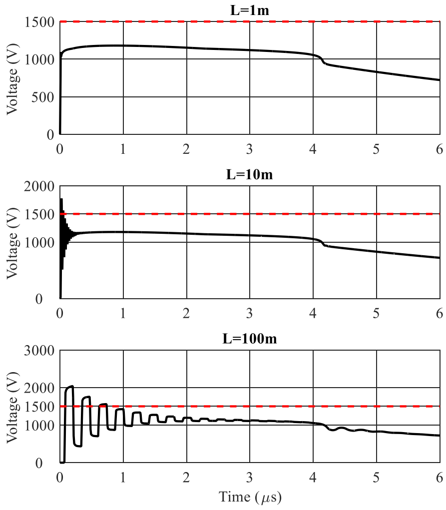
Voltage values across EUT depends on EUT's impedance (Z_{EUT}) and length of cable between SPD and EUT (the influence of the cable length is through travelling time of voltage surge along the cable, which depend on cable length). Therefore, in following analysis, active power of EUT and cable length will be observed as influencing parameters.

Three cases with active power of 100W, 400W and 2000W are taken into analysis, as representative powers of resistive loads in low-voltage power installations. Analysis is performed through simulations in MATLAB Simulink.

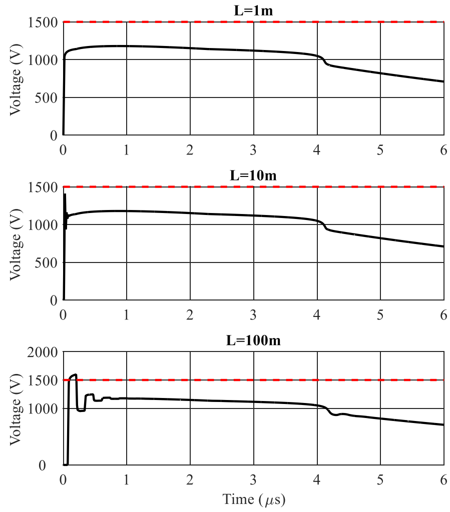
Transient voltages across EUT with resistive load for cable lengths of 1m, 10m and 100m is given in Fig. 3. Fig. 3.a) represents voltage across EUT with active power of 100W, Fig. 3.b) for active power of 400W and Fig. 3.c) for active power of 2000W.

Voltage oscillations for cases of longer cables and load active powers of 100W and 400W are consequence of voltage wave reflections at the point of load connection. Namely, resistance (impedance) of the EUT with active power of 100W and 400W are Z_{EUT}=484Ω and Z_{EUT}=121Ω, respectively. These values are higher than characteristic impedance of the cable (which value is Z_C=49.3Ω). This causes increase of voltage at EUT after each reflection of voltage surge. From Fig. 3.a) and Fig. 3.b) it can be concluded that for longer cables (typically in industrial buildings) maximal value of voltage across EUT exceeds its withstand impulse voltage. For shorter cables, effect of voltage oscillations is suppressed with vicinity of SPD i.e. maximal values of voltages are closer to value of SPD protection voltage.

Impedance of EUT with active power of P=2000W is Z_{EUT}=24.2Ω and it is less than characteristic impedance of cable. Therefore, there is no reflection of the overvoltage wave that arrives at EUT load node, regardless of cable length.



a)



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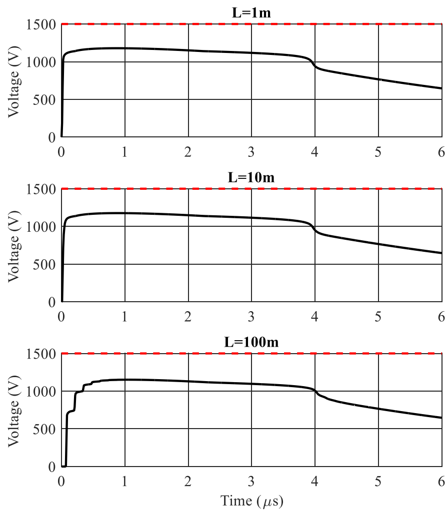


c)

Fig. 3. Voltages across resistive load with a) 100W, b) 400W and c) 2000W for different cable lengths

In order to analyze possibilities for proper overvoltage protection of EUT with resistive load, calculations of maximal values of voltages across EUT are performed for wide range of values of active powers and cable lengths. The results are presented in Fig. 4 in form of zones. Zone boundaries represent percent values of EUT withstand impulse voltage.

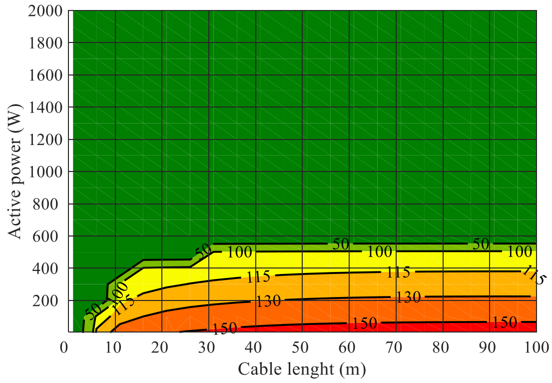


Fig. 4. Zones with different voltage levels across EUT

From Fig. 4 it can be concluded that for resistive load with values of active power larger than 550W SPD fulfills its protective role for each value of cable length. However, for smaller values of active power and relatively longer cables, voltage across load can be higher than device's withstand impulse voltage, which can lead to insulation failure.

Therefore, it can be concluded that one-stage protection system does not provide adequate protection for smaller values of active power. In order to provide adequate protection against surges for these resistive loads, it is necessary to apply multi-stage protection system.

3. TWO-STAGE OVERVOLTAGE PROTECTION SYSTEM

Multi-stage protection system assumes cascade application of SPDs starting at distribution board toward protected equipment inside low-voltage power installation. This arrangement of protection system is intended to ensure optimal distribution of surge energy among installed SPDs, as well as proper equipment protection against surges [5]. In existing practice, most common realization of multi-stage protection system is two-stage cascade protection with SPDs located at the (sub) distribution board of the building and relatively near protected equipment (Fig. 5).

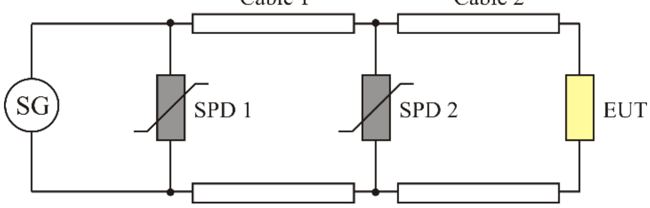


Fig. 5. Model of two-stage protection system

SPD 1 is arrester of type 2 according to IEC 61643-11 standard [9] designed for mounting on (sub) distribution board with protection voltage of 1250 V and energy absorption capability of 340J. SPD 2 is arrester of type 3 designed for socket mounting, with protection voltage of 800V and energy absorption capability of 50J. Cables between protection stages and EUT are PVC-insulated cables 3x2.5mm^2 with electric parameters: R=0.00561Ω/m, L=0.324μH/m, C=0.1368nF/m, G=0s/m. Two cases with active power of 100W and 400W are taken into analysis, because for case of active power of 2000W satisfactory protection performances can be achieved with one-stage protection system.

Transient voltages across EUT with resistive load of 100W for different lengths of cable 1 and cable 2 with values of 1m, 10m and 100m is given in Fig. 6. Fig. 6.a) represents case with cable 1 length of 1m, Fig. 6.b) for case of cable 1 length of 10m and Fig. 6.c) for length of cable 1 of 100m.

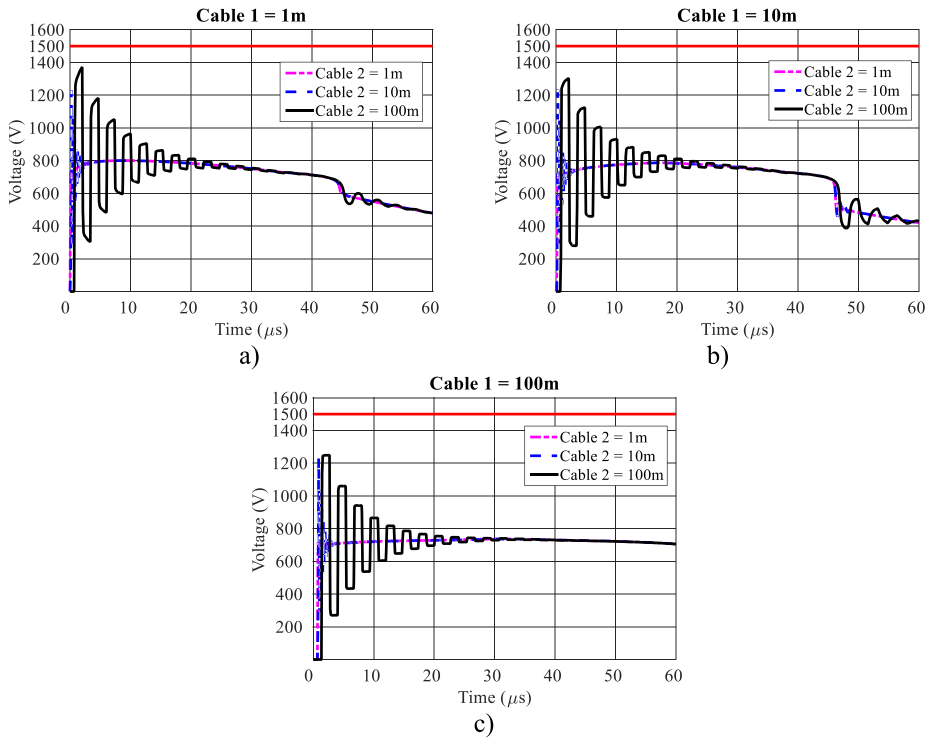


Fig. 6. Voltage across resistive load with 100W for different lengths of cables 1 and 2: a) cable 1 length of 1m, b) cable 1 length of 10m and c) cable 1 length of 100m

Transient voltages across EUT with resistive load of 400W for different lengths of cable 1 and cable 2 with values of 1m, 10m and 100m is given in Fig. 7. Fig. 7Fig. 6.a) represents case with cable 1 length of 1m, Fig. 7.b) for case of cable 1 length of 10m and Fig. 7.c) for length of cable 1 of 100m.

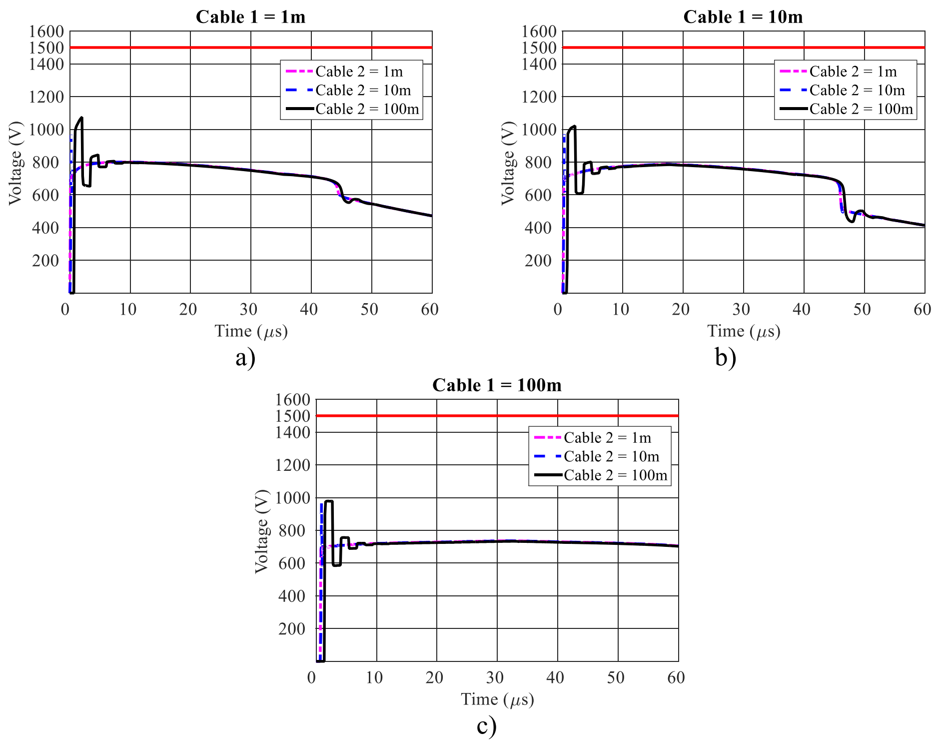


Fig. 7. Voltage across resistive load with 400W for different lengths of cables 1 and 2: a) cable 1 length of 1m, b) cable 1 length of 10m and c) cable 1 length of 100m

From Fig. 6 and Fig. 7 it is obvious that maximal voltages across EUT is below 1500V for every combination of analyzed cables lengths, both for load's active power of 100W and 400W. Therefore, it can be concluded that only application of multi-stage protection system ensures proper overvoltage protection for all situation that can be found in low-voltage power installation regarding resistive loads.

On the other hand, multi-stage protection system arises issue of energy coordination of installed SPDs in power installation. Energy coordination should to provide that part of surge energy deposited in each SPD is below its energy absorption capability. Otherwise, it can lead to energy overstress of the SPD and its destruction.

Distribution of energy between individual SPDs for case of resistive load with active power of 100W and different lengths of cable 1 and cable 2 is given in Fig. 8. Fig. 8.a) represents deposited energies for case of cable 1 length of 1m, Fig. 8.b) for case of cable 1 length of 10m and Fig. 8.c) for case of cable 1 length of 100m.

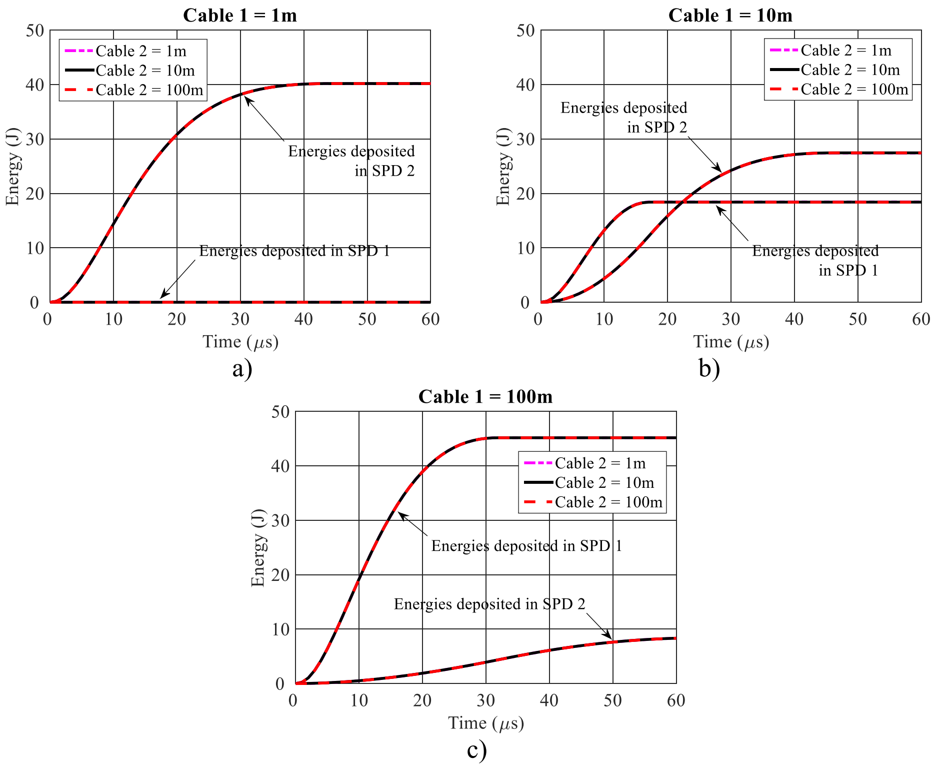
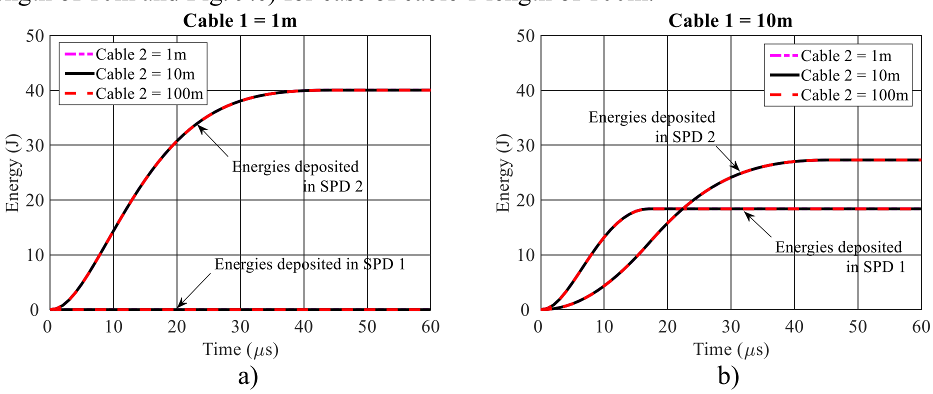
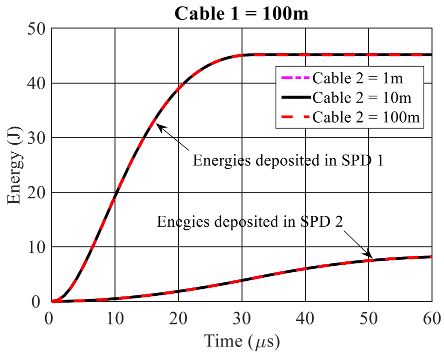


Fig. 8. Energies deposited in SPD 1 and SPD 2 for active power of 100W and different lengths of cable 1 and cable 2: a) cable 1 length of 1m, b) cable 1 length of 10m and c) cable 1 length of 100m

Distribution of energy between individual SPDs for case of resistive load with active power of 400W and different lengths of cable 1 and cable 2 is given in Fig. 9. Fig. 9.a) represents deposited energies for case of cable 1 length of 1m, Fig. 9.b) for case of cable 1 length of 10m and Fig. 9.c) for case of cable 1 length of 100m.





c)

Fig. 9. Energies deposited in SPD 1 and SPD 2 for active power of 400W and different lengths of cable 1 and cable 2: a) cable 1 length of 1m, b) cable 1 length of 10m and c) cable 1 length of 100m

From Fig. 8 and Fig. 9 it can be concluded that energies deposited in individual SPDs do not depend neither on value of cable 2 length, neither on value of active power. Values of deposited energies depend only on value of cable 1 length. For very short cable 1 of 1m energy deposited in SPD1 is equal to zero (Fig. 8.a) and Fig. 9.a)). For relatively longer cable 1 of 10m (Fig. 8.b) and Fig. 9.b)), energy deposited in SPD1 is higher than energy deposited in SPD2, but only during front time of incoming voltage and current surges. After that, during tail time of incoming surges, energy deposited in SPD2 becomes higher than energy deposited in SPD1. For very long cable 1, energy deposited in SPD1 is much higher than energy deposited in SPD2 (Fig. 8.c) and Fig. 9.c)).

The reason for this is inductive voltage drop along cable 1. Namely, voltage across SPD1 is equal to sum of protection voltage across SPD2 (around 800V) and the voltage drop along cable 1. In case of short cable 1, the value of voltage drop along cable 1 is small, and therefore voltage across SPD1 is below its protection voltage (1200V). Because of that, SPD1 cannot go to the conduction state. This can represents problem in cases when energy absorption capability of SPD2 is smaller than energy deposited in this SPD. In this case, SPD2 can be destroyed due to energy overstress. In observed system (Fig. 5), energy absorption capability of SPD2 is 50J and it is larger than maximal energy deposited in SPD2 of about 40J (in cases when length of cable 1 is 1m - Fig. 8.a) and Fig. 9.a)).

4. CONCLUSION

Protection of electrical and electronic devices against the voltage and current surges in low-voltage AC power circuits is based on wide application of surge protective devices (SPDs). Devices with resistive load are very common in low-voltage power systems of residential and industrial objects. Overvoltage protection of these devices completely relies on installation of SPDs throughout a power installation.

Analysis of performances of one-stage and two-stage protection systems in cases of resistive load is given in the paper. The obtained results show that in case of one-stage protection system there are combinations of cable lengths and relatively small values of active powers for which SPD doesn't fulfill its protective role due to the fact that maximal values of voltage across load are higher than its withstand impulse voltage.

In order to provide adequate surge protection of resistive loads, it is necessary to apply multi-stage protection system. Performed analysis in case of two-stage protection system show that proper protection is ensured for all values of active power of resistive loads. Precautions should be taken into account because of surge energy distribution between installed SPDs, especially in case of short cable between SPDs, in which cases SPD with low energy absorption capability may be energy overstressed.

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