Coordination of surge protective devices in low voltage AC power installations

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Abstract

The surges protection in low-voltage AC power circuits is commonly realized by Surge Protective Devices (SPDs). These devices divert a large amount of the surge energy to the ground and reduce the surge voltage to the level acceptable for protected device(s). Adequate protection performances are provided by applying multiple-stage protection assuming cascade deployment of SPDs starting from distribution board toward equipment in an installation. Therefore, SPDs coordination, (i.e. selection of SPDs parameters as well as determination of necessary distance between stages) becomes of great importance and the paper deals with this issue. The proper SPDs coordination is significant for both protected equipment and SPDs themselves (their survival during surges). The paper provides an analysis of the SPDs coordination for case of two-stage protection system. The influence of different lengths of cables between protection stages, as well as influence of type and parameters of load on SPDs protection characteristics have been analyzed and discussed with the purpose of determination of requirements for proper surge protection and coordination of applied SPDs.

Keywords Low voltage AC power installations · Surges · Surge protective devices · Coordination

1 Introduction

Electric and modern electronic equipment widely used in industrial and residential objects have become strongly dependent upon the continuous availability and quality of electrical power. Recent studies have shown that industrial and digital business enterprises are having financial losses due to power interruptions and poor power quality.

Power quality or more specifically, a power quality disturbance is generally accepted as any change in the power (voltage, current, or frequency) that interferes with normal operation of electrical equipment and which can result in mal operation or failure of equipment. Taking the wave shape as a criteria, the IEEE Standard 1159 [1] defines seven categories of power quality disturbances based on the wave shape: transients, interruptions, sag/undervoltage, swell/overvoltage, waveform distortion, voltage fluctuations, frequency variations. Transients are

potentially the most damaging type of power disturbance. They fall into two subcategories: impulsive and oscillatory transients. Impulsive transients or surges are sudden high peak events that raise the voltage and/or current levels. The consequences of surges can range from the loss (or corruption) of data to physical damage of equipment.

Duration of surges in low voltage–power installations do not exceed one-half period of the supply voltage waveform. They are random events which appear in any combination of line, neutral, or grounding conductors. The origin of surges occurring in low-voltage ac power circuits are lightning and switching. A third phenomenon that needs to be taken into account is the occurrence of surge voltages resulting from interactions between different systems, such as the power system and a communications system [2].

Surge Protective Devices (SPDs) are used to provide protection against the surges in low-voltage AC power

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circuits. 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) [3].

Numerous studies and research reports have shown that application of only one group of SPDs, usually at the distribution board, (i.e. one-stage protection system) doesn't provide proper overvoltage protection of equipment [4–7]. Namely, for equipment with small values of active powers as well as for equipment with capacitive character of load SPDs must have very low protection voltage in order to provide adequate protection. At the same time they must have high energy absorption capability. These demands are in contradiction because of the fact that SPDs with relatively high energy absorption capability have higher protection voltages and vice versa [7].

In order to achieve adequate protection of equipment against surges it is necessary to apply multiple-stage protection which assumes cascade placement of SPD starting from distribution board toward equipment in an installation [8]. This approach should to provide gradually decreasing of the protection level of SPDs in the stages, as well as the appropriate distribution of surge energy between stages. Therefore, SPDs coordination, (i.e. selection of SPDs parameters as well as determination of necessary distance between stages) becomes of great importance and the paper deals with this issue.

Analysis of the SPDs coordination for case of two-stage protection system is given in the paper. The influence of different lengths of cables between protection stages, as well as influence of type and parameters of load on SPDs protection characteristics have been analyzed and discussed with the purpose of determination of requirements for proper surge protection and coordination of applied SPDs. Simulation of surge testing is performed by using ATP/EMTP and MATLAB Simulink software with application

of the Combination Wave as one of the representative surges according to relevant standards.

2 Model of two-stage protection system

Cascade protection system assumes application of two or more SPDs starting at distribution board toward protected equipment. Protection performances as well as coordination of SPDs can be performed with analysis of two-stage protection scheme given in Fig. 1.

The purpose of the surge testing is to assess response of equipment to the known or unknown surge environment and/or to determine characteristics of SPDs. Therefore, the first decision or assumption that must be made in planning a surge test addresses the nature of the surge environment [9].

2.1 Surge environment and characteristics

The surges with different characteristics regarding their polarity, duration and wave amplitudes can occur in low-voltage AC power systems [2]. This variety of surges can be reduced to few representative stresses for the purpose of surge testing and determination of protection performances. IEEE and IEC standards define Combination Wave as one of the representative surge waveforms used for surge testing of equipment which impedance is not known in advance and which can change during time. Combination Wave is surge which consists of two waveforms: 1.2/50 μ s open circuit voltage waveform and 8/20 μ s short circuit current waveform [9]. Selection of amplitudes of these waveforms depends on location categories to which observed circuit belongs. The concept of location category, proposed in IEEE C.62.41.1 [2], rests on the considerations on dispersion and propagation of surge currents and surge voltages. IEEE C62.41.1 [2] recognizes three location categories: A, B and C. Location category A applies to the parts of the installation at some distance

Fig. 1 Two-stage protection scheme

from the service entrance. Location category C applies to the external part of the structure, extending some distance into the building. Location category B extends between Location categories C and A [2].

It will be assumed that circuit in Fig. 1 belongs to location category B. For this category values of open circuit voltage and short circuit current amplitude of the Combination Wave surge are 6 kV and 3 kA, respectively [9]. The model of surge generator delivering Combination Wave with mentioned parameters is given in Fig. 2 [10]. Parameters of Combination Wave model generator for location category B are: $U = 6.247$ kV, $C_1 = 12.5$ μ F, $L_1 = 2.45$ μ H, $L_2 = 4$ μ H, $R_1 = 5.83$ Ω , $R_2 = 1.41$ Ω [10].

Surge is applied with method of direct coupling between lines to neutral, according to IEEE Std. C62.45 [9]. Surge generator is connected directly between neutral conductor and power line. This situation represents un-powered testing, that is direct connection between un-powered equipment under test and the test surge generator.

2.2 Model parameters

SPDs used in the model (Fig. 1) are selected from the manufacturer catalogue with following technical parameters: SPD marked as arrester (A) has protection voltage of 1250 V. It is SPD of type 2 according to IEC 61643-11 [11], designed for mounting on distribution board, with maximal discharge current I_{max} (8/20 μ s) of 15 kA, which corresponds energy absorption capability of 328 J. SPD marked as suppressor (S) is SPD type 3 according to IEC 61643-11 [11], designed for socket mounting, with protection voltage of 800 V, and value of combination wave open circuit voltage of $U_{OC} = 6$ kV ($I_{SC} = 3$ kA), which corresponds energy absorption capability of 42 J.

Equipment under test (EUT) in analyzed circuit is load connected via cable at a socket of single power line. It is assumed that analyzed EUT belongs to the equipment of the overvoltage category I according to IEC 60664-1 [12]. This overvoltage category involves equipment with withstands impulse voltage level of 1.5 kV and it is the most rigorous requirement for the protection effect of SPD [3].

Fig. 2 Model of combination wave generator

Cables between arrester and suppressor (cable A–S) and between suppressor and EUT (cable S–EUT) are PVC-insulated cables 3×2.5 mm² with electric parameters: $R = 0.00561$ Ω /m, $L = 0.324$ μ H/m, $C = 0.1368$ nF/m, $G = 0$ s/m. It is taken into account that SPD connecting leads (between power and neutral conductors) have length of 0.5 m. These connecting leads cause inductive voltage drop along them, which can have strong influence on the performances of protection system.

3 Protection performances

Protection performances of the circuit given in Fig. 1 are analyzed by simulations in MATLAB Simulink and ATP/EMTP. Maximal values of voltages across EUT and deposited energy in SPDs are measured and used as criteria for assessment of protection performances and energy coordination of SPDs for cases with different parameters of circuit elements with values which can be found in real household and industrial low-voltage–power systems [13].

Simulations are performed for three types of EUT load: resistive, inductive and capacitive, and for cases with different lengths of cable A–S and cable S–EUT. For resistive load two values of active power $P = 100$ W and $P = 2000$ W, while for inductive and capacitive character of load two values of reactive power $Q = 10$ VAR and $Q = 100$ VAR are taken into account.

3.1 Influence of cable A–S length

According to the common practice in two stage protection system the arresters are supposed to be located at the service entrance, while suppressor is located near protected equipment. Therefore, for the analysis of the influence of cable A–S length it is taken that cable S–EUT has length of 1 m. Maximal values of voltage across EUT for different values of cable A–S length in range of 1–100 m are given in Figs. 3, 4 and 5 for resistive, inductive and capacitive character of EUT's load respectively.

From Figs. 3, 4 and 5 it can be concluded that values of maximal voltages across EUT don't depend or very little depend on value of EUT's load power. In case of resistive (Fig. 3) and inductive (Fig. 4) load maximal values of voltages across EUT are close to or lower than suppressor protection voltage (800 V). This is consequence of very short cable S–EUT with length of 1 m and short SPDs connecting leads, which causes attenuation of voltage reflection at the load impedance even in case when load impedance has larger value than characteristic impedance of the cable. However, in the case of capacitive load (Fig. 5) maximal values of voltages across EUT are higher than suppressor protection voltage for cases of lower capacitive power,

Fig. 3 Maximal voltages across EUT's resistive load with different values of active power and for cable A-S length in range of 1–100 m

Fig. 4 Maximal voltages across EUT's inductive load with different values of reactive power and for cable A-S length in range of 1–100 m

Fig. 5 Maximal voltages across EUT's capacitive load with different values of reactive power and for cable A-S length in range of 1–100 m

regardless the fact of short cable S-EUT. The reason for this is voltage oscillations across load impedance with capacitive power. The illustration of these oscillations is given in Fig. 6 for case of capacitive load with power of 10 VAr, cable A-S length of 1 m and cable S-EUT length of 1 m.

Fig. 6 Transient voltage across EUT's capacitive load with power of 10 VAr for cable A-S length of 1 m and cable S-EUT length of 1 m

Fig. 7 Energy deposited in arrester for case of EUT's resistive load with different values of active power and for cable A-S length in range of 1–100 m

Fig. 8 Energy deposited in suppressor for case of EUT's resistive load with different values of active power and for cable A-S length in range of 1–100 m

Energies deposited in arrester and suppressors for case of resistive load of EUT (with conditions: active powers of 100 W and 2000 W, different values of cable A-S length in range of 1–100 m and cable S-EUT length of 1 m) are given in the Figs. 7 and 8.

Energies deposited in arrester and suppressors for case of inductive load of EUT (with conditions: reactive powers

Fig. 9 Energy deposited in arrester for case of EUT's inductive load with different values of reactive power and for cable A-S length in range of 1–100 m

Fig. 11 Energy deposited in arrester for case of EUT's capacitive load with different values of reactive power and for cable A-S length in range of 1–100 m

Fig. 10 Energy deposited in suppressor for case of EUT's inductive load with different values of reactive power and for cable A-S length in range of 1–100 m

Fig. 12 Energy deposited in suppressor for case of EUT's capacitive load with different values of reactive power and for cable A-S length in range of 1–100 m

of 10 VAr and 100 VAr, different values of cable A-S length in range of 1–100 m and cable S-EUT length of 1 m) are given in the Figs. 9 and 10.

Energies deposited in arrester and suppressors for case of capacitive load of EUT (with conditions: reactive powers of 10 VAr and 100 VAr, different values of cable A-S length in range of 1–100 m and cable S-EUT length of 1 m) are given in the Figs. 11 and 12.

From the results presented in Figs. 7, 8, 9, 10, 11 and 12 it can be concluded that values of energy deposited in arrester and suppressor don't depend or very little depend on value of EUT's load power. However, they strongly depend on length of cable between arrester and suppressor. In case of very short cable between arrester and suppressor, almost all surge energy is diverted through suppressor, and very small amount through arrester. This is because short length of cable A-S causes small voltage drop on the cable during rise time of current surge. Voltage across arrester is equal to sum of voltage across suppressor, and inductive ($L \cdot di/dt$) and resistive ($R \cdot i$) voltage drop on cable A-S. This voltage across arrester isn't

enough to causes conduction of large current through it and therefore the most part of surge current flows through suppressor.

Energy deposited in arrester for all types of load is much smaller than its energy absorption capability. Although energy deposited in suppressor is lower than its energy absorption capability, safety margin is very narrow.

3.2 Influence of cable S-EUT length

Influence of cable S-EUT length on protection performances and energy coordination of SPDs is performed with assumption of cable A-S length of 10 m. The reason for this are results obtained for influence of cable A-S length, from which can be concluded that this is minimal length of cable A-S which provides value of energy deposited in suppressor below its absorption capability with appropriate safety margin. Maximal values of voltage across EUT for different values of cable S-EUT length in range of 1–100 m are given in Figs. 13, 14 and 15 for

Fig. 13 Maximal voltages across EUT's resistive load with different values of active power and for cable S-EUT length in range of 1–100 m

Fig. 14 Maximal voltages across EUT's inductive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

Fig. 15 Maximal voltages across EUT's capacitive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

resistive, inductive and capacitive character of EUT's load respectively.

Obtained results given in Figs. 13, 14 and 15 show that maximal voltages across EUT depend both on cable S-EUT length as well as on value of EUT's power.

For resistive load, maximal values of voltage across EUT are higher in cases of EUT with smaller values of

Fig. 16 Transient voltage across EUT with active power of 100 W, cable A-S length of 10 m and cable S-EUT length of 100 m

Fig. 17 Transient voltage across EUT with active power of 2000 W, cable A-S length of 10 m and cable S-EUT length of 100 m

active power. Reason for this is voltage oscillations across EUT with smaller values of active power, which consequently have larger input impedance. This causes voltage reflections at the point of EUT connection to the grid. In order to illustrate these oscillations, transient voltage across EUT with active power of 100 W and for case cable A-S length of 10 m and cable S-EUT length of 100 m is given in Fig. 16. Although maximal value of voltage across EUT is lower than its selected withstand impulse voltage, it is obvious that maximal voltage is higher than suppressor protection voltage (800 V), which is consequence of voltage oscillations. Observed oscillations can be suppressed by decreasing the length of cable between suppressor and EUT.

For case of EUT with active power of 2000 W and for case of cable A-S length of 10 m and cable S-EUT length of 100 m (Fig. 17) there are no voltage oscillations due to the fact that load input impedance is smaller than characteristic impedance of cable S-EUT. Therefore, maximal value of voltage across EUT is lower than suppressor protection voltage.

In case of inductive load (Fig. 14) maximal voltages across EUT don't depend on value of inductive reactive power. Namely, due to high frequencies at the surge rise

Fig. 18 Transient voltage across EUT with inductive power of 10 VAR, cable A-S length of 10 m and cable S-EUT length of 100 m

Fig. 20 Transient voltage across EUT in case of capacitive power of 100 VAR, cable A-S length of 10 m and cable S-EUT length of 1 m

Fig. 19 Transient voltage across EUT in case of capacitive power of 10 VAR, cable A-S length of 10 m and cable S-EUT length of 1 m

Fig. 21 Transient voltage across EUT in case of capacitive power of 10 VAR, cable A-S length of 10 m and cable S-EUT length of 100 m

time, EUT's load input impedance is higher than characteristic impedance of the cable for every value of load inductive power. This causes voltage oscillations. Example is given in Fig. 18 for case of EUT with inductive power of 10 VAR, cable A-S length of 10 m and cable S-EUT length of 100 m.

In case of capacitive load (Fig. 15) maximal voltages across EUT depend both on capacitive power of EUT as well as on cable S-EUT length. In case of shorter cable S-EUT maximal values of voltages are lower, but still higher than suppressor protection voltage, as consequence of voltage oscillations. Examples of transient voltage are given in Figs. 19 and 20 for cases of EUT with capacitive power of 10 VAR and 100 VAR (respectively) when cable A-S length is 10 m and cable S-EUT length is 1 m.

In case of longer cable S-EUT maximal voltages across EUT depend on capacitive power of EUT. Examples of transient voltages are given in Figs. 21 and 22 for cases of EUT with capacitive power of 10 VAR and 100 VAR (respectively) when cable A-S length is 10 m and cable S-EUT length is 100 m.

Energies deposited in arrester and suppressors for case of resistive load of EUT (with conditions: active

Fig. 22 Transient voltage across EUT in case of capacitive power of 100 VAR, cable A-S of 10 m and cable S-EUT of 100 m

powers of 100 W and 2000 W, different values of cable S-EUT length in range of 1–100 m and cable A-S length of 10 m) are given in the Figs. 23 and 24.

Energies deposited in arrester and suppressors for case of inductive load of EUT (with conditions: reactive powers of 10 VAR and 100 VAR, different values of cable S-EUT length in range of 1–100 m and cable A-S length of 10 m) are given in the Figs. 25 and 26.

Fig. 23 Energy deposited in arrester for case of EUT's resistive load with different values of active power and for cable S-EUT length in range of 1–100 m

Fig. 26 Energy deposited in suppressor for case of EUT's inductive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

Fig. 24 Energy deposited in suppressor for case of EUT's resistive load with different values of active power and for cable S-EUT length in range of 1–100 m

Fig. 27 Energy deposited in arrester for case of EUT's capacitive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

Fig. 25 Energy deposited in arrester for case of EUT's inductive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

Fig. 28 Energy deposited in suppressor for case of EUT's capacitive load with different values of reactive power and for cable S-EUT length in range of 1–100 m

Energies deposited in arrester and suppressors for case of capacitive load of EUT (with conditions: reactive powers of 10 VAr and 100 VAr, different values of cable S-EUT length in range of 1–100 m and cable A-S length of 10 m) are given in the Figs. 27 and 28.

Obtained results given in Figs. 23, 24, 25, 26, 27 and 28 show that energy deposited in arrester and suppressor don't depend on value of cable S-EUT length or load power, except in case of capacitive load. This is

consequence of voltage oscillations across capacitive load with different time constants.

4 Requirements for energy coordination

From the obtained results shown in the previous chapter it can be concluded that energy coordination between SPDs in cascade protection scheme is not fulfilled for cases when cable between protection stages is short. This implies that larger amount of surge energy is diverted through SPD with lower protection voltage (suppressor). Having on mind that SPDs with lower protection voltages inherently have lower energy capability, this situation can lead to thermal destruction and failure of SPDs. The situation is most likely to happen in cases when equipment contains built-in varistors and it is located near distribution board. Also, the problem may emerge in cases when it is necessary to decrease value of protection voltage level for equipment with additional set of SPDs with lower protection voltages.

In order to avoid these dangerous situations, it is necessary to provide minimal cable length between protection stages. This minimal length strongly depends on value of SPD energy absorption capability and characteristics of cable between stages.

In cases when this approach isn't possible, it is necessary to apply inductive bridges between protection stages. Inductance of these bridges has to be high enough to increase voltage drop between protection stages during surges, but small enough in order not to causes high value of voltage drop in normal operating state.

5 Conclusion

Adequate protection against surges in low-voltage AC installations requires application of surge protective devices arranged in multi-stage protection system. Protection performances of such systems depend on proper selections of surge protective devices characteristics as well as on their appropriate location in the installation. These conditions determine protection level of surge protective devices and values of their energy absorption.

Analysis of two-stage protection system given in the paper has shown that energy coordination of installed surge protective devices in individual stages is necessary in order to ensure proper distribution of surge energy between stages and survival of surge protective devices with lower protection level and lower energy absorption

capability under prospective surges. In order to achieve this goal, it is necessary to provide impedance between protection stages with different protection levels. This impedance can be accomplished either with cable of sufficient length between stages, or with insertion of inductive bridges.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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