Characteristics of Overvoltage Protection with Cascade Application of Surge Protective Devices in Low-Voltage AC Power Circuits

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***Abstract*—Surge Protective Devices (SPDs) are widely used for protection of the equipment in low-voltage AC power circuits against wide variety of surges. Cascade application of SPDs starting at the service entrance of a building and downstream toward near sensitive equipment is intended to ensure optimal energy distribution among installed SPDs, as well as proper equipment protection against surges. Characteristics of overvoltage protection with two-stage application of SPDs have been analyzed in the paper through performed measurements, followed by simulations and numerical modeling using the ATP/EMTP and MATLAB Simulink. Parametric analysis of the protection's characteristics in wide range of influencing factors has been performed in order to define a set of applicable solutions for proper selection and performance of SPDs.**

Index Terms—arresters, high-voltage techniques, insulation testing, surges, surge protection.

I. Introduction

Many changes occurred in residential and industrial power circuits in the last decade, such as smart grid environment, penetration of solar and fuel cells, electrical vehicles chargers etc. imply application of advanced electric and electronic devices [1]. Such devices installed in low-voltage AC systems require a reliable mains-voltage supply [2], as well as appropriate protection against voltage and current surges. These surges can be periodic or random events and can appear in any combination of line, neutral, or grounding conductors with different amplitudes, durations and waveforms according to the database of published surveys (recorded events as well as experiments and computations), anecdotes and observed failure rates summarized in IEEE C62.41.1 standard [3]. Lightning is one of the major sources of these voltages and currents and in this paper lightning surges impinging at the service entrance of the building will be considered.

Protection of the equipment in low-voltage AC power circuits against surges is based on wide application of Surge Protective Devices (SPDs). Location and selection of SPDs depend on characteristics of voltage and current surges which can be expected or evaluated in different location categories and exposure levels according to IEEE C62.41.1 standard [3], and installation categories according to IEC 60664-1 standard [4]. In low-voltage AC power systems two types of surge protection schemes can be found: one-stage protection schemes and cascade (mostly two-stage) protection scheme.

One stage protection scheme assumes installation of only one group of SPDs on the distribution panel at service entrance, for which many users assumes to protect all equipment in the building [5]. Cascade application of SPDs starting at the service entrance of a building and toward near sensitive equipment is intended to ensure optimal energy distribution among installed SPDs, as well as proper equipment protection against surges [6], [7], [8]. In existing practice most common situation is application of two-stage cascade protection with SPDs located at the service entrance of the building and relatively near protected equipment. Here is worthwhile to point on fact that many household appliances, especially electronic appliances, have been equipped with voltage-dependent resistors (VDRs or varistors) to suppress transient overvoltages [9]. Varistors could limit overvoltages at the entrance of an appliance. However, compared with SPDs, build-in varistors have a relatively lower energy absorption capability, and may not survive under a high voltage surge [9]. Therefore, in this study only external SPDs are taken into account.

There are number of parameters that have influence on overvoltage protection performances: characteristics of SPDs and their coordination [7], [8], [10], [11] types of applied voltage and current surges [12], [13], length and characteristics of lines between protection stages [14], [15], type of equipment under test [15], [16] and so on. It is obvious a lack of comprehensive analysis that takes into consideration the impact of all mentioned parameters. Neglecting some of them or keeping it on constant level could lead to wrong conclusions and inappropriate overvoltage protection. To that end, the aim of researches in this paper is to overcome perceived lack through conducting analysis of all influencing parameters on SPDs performances in two-stage arrangement in low-voltage AC power circuits. The overvoltage protection characteristics have been analyzed through performed measurements, followed by simulations and numerical modeling using the ATP/EMTP and MATLAB Simulink. Parametric evaluation of the protection's characteristics in wide range of influencing factors has been performed in order to define a set of applicable solutions for proper selection and performance of SPDs.

II. System Model

The aim of equipment and/or SPDs surge testing is to obtain their response (regarding upset or damage for equipment or protection level and energy capability for

Digital Object Identifier 10.4316/AECE.2015.03022

SPDs) to surge environment. Surge environment in low-voltage AC power circuits can be facilitated by a reduction of wide variety of surges to a few representative stresses [17] which can be used for surge testing purposes.

Single phase TN-C-S system with nominal voltage of 230V and two-stage application of SPDs (Fig. 1.) is observed for the analysis of protection performances. In general terminology, upstream SPD is usually called "arrester", while SPD located near equipment (as stand-alone device) is usually called "suppressor".

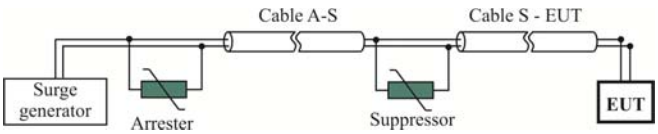

Figure 1. Model of the observed system.

Equipment under test (EUT) is load connected via cable S-EUT at one socket of single power line. Due to continuous miniaturization trend in an industry, advanced electric and electronic devices have weak surge withstand capability. Therefore it is assumed that analyzed EUT belongs to the equipment of the overvoltage category I according to IEC 60664-1 standard [4]. This overvoltage category involves equipment with withstands impulse voltage level of 1.5kV and it is the most rigorous requirement for the protection effect of SPD.

SPDs are selected from manufacturer's catalogue with maximum continuous operating voltage 275V, and protection voltage 1250V for arrester and 800V for suppressor, which are lower than equipment withstand voltage of observed overvoltage category I [4]. Arrester is SPD type 2 according to IEC 61643-11 standard [18], designed for mounting on sub-distribution board, with maximal discharge current I_{max} (8/20μs) of 15kA which corresponds energy absorption capability of 328J. Suppressor is SPD type 3 according to IEC 61643-11 standard [18], designed for socket mounting, with value of combination wave open circuit voltage of U_{OC}=6kV (I_{SC}=3kA), which corresponds energy absorption capability of 42J. It is taken that cables that connect the SPDs with phase line have length of 1m and inductance of 0.5μH [19]. V-I curves of used SPDs in interpolated log-log plot can be represented as in Fig. 2.

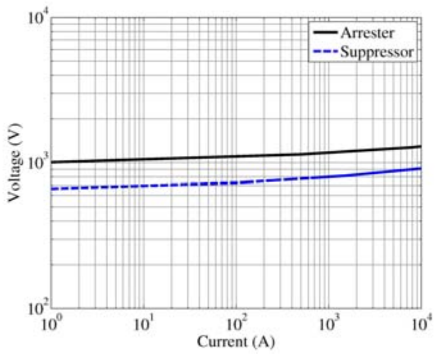

Figure 2. V-I curves of used SPDs for arrester and suppressor.

Cables between arrester and suppressor (cable A-S) and between suppressor and EUT (cable S-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.

A. Surge characteristics

International standards [17], [20] recommend application of representative surge waveforms for surge testing in low-voltage AC power circuits. The one of the waveforms recommended by IEEE C62.41.2 standard [17] and IEC 61000-4-5 standard [20] for representation of surges impinging at the service entrance of the building is 1.2/50μs–8/20μs Combination Wave. Combination Wave surge is delivered by a Combination Wave generator (CWG) that applies a 1.2/50μs voltage wave across an open circuit and an 8/20μs current wave into a short circuit. In case of EUT surge testing, exact voltage and current waveforms depend on the generator and the EUT's impedance to which the surge generator is connected.

Surge is applied without connection of observed system to power network, ie. with surge direct coupling between lines to neutral [21]. Values of amplitudes of voltage and current surges delivered by CWG in open circuit and short circuit are 6kV and 3kA, which corresponds to location category B [17], [21].

III. Measurements and Simulation Model

Analysis of overvoltage characteristics in case of cascade application of SPDs is performed by measurement of EUT and SPDs response in case of surge testing in observed system. In addition, simulation model in the ATP/EMTP and MATLAB Simulink is developed for parametric analysis of influencing parameters.

A. Experimental results

Commercial CWG that delivers open circuit voltage and short-circuit current waveforms according to IEEE C62.41.2 standard [17] and IEEE C62.45 standard [21] is used for experimental surge testing of observed system given in Fig. 1. taking into account cases with different EUT, cable A-S length and with cable S-EUT length of 1m. Instead of specific household devices, frequency independent high voltage resistors and capacitors are used as EUT. The measurements were performed by using oscilloscope with sampling rate of 500 MSamples/s and resistive voltage attenuator probes in differential connection.

For illustration of measurement results, cases with cable A-S length of 80m, cable S-EUT length of 1m and resistive load of 400W (R=121Ω) and capacitive load of 114VAr (C=7.5μF) are used in experiments. Recorded voltage waveform across EUT with the resistive load is given in Fig. 3., while for the capacitive load is given in Fig. 4.

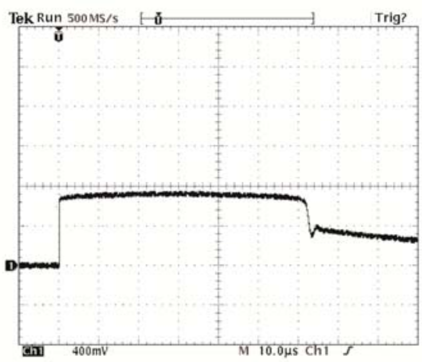

Figure 3. Recorded voltage waveform across EUT for case of resistive load with P=400W, cable A-S length of 80m and cable S-EUT length of 1m.

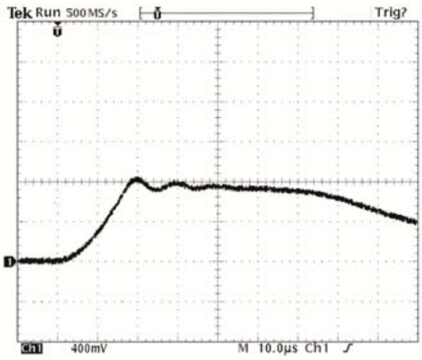

Figure 4. Recorded voltage waveform across EUT with capacitive load of Q=114VAr, cable A-S length of 80m and cable S-EUT length of 1m.

B. Simulation results

For the purpose of simulation's model verification and comparison of obtained results, an electrical scheme of CWG for location category B is developed [22] and given in Fig. 5. Parameters of elements for proposed realization of CWG are: U=6.247kV, C_1=12.5μF, L_1=2.45μH, L_2=4μH, R_1=5.83Ω, R_2=1.41 Ω. The CWG delivers 1.2/50μs open-circuit voltage and 8/20μs short-circuit current with specifications regarding waveforms and amplitudes according to IEEE C62.41.2 standard [17].

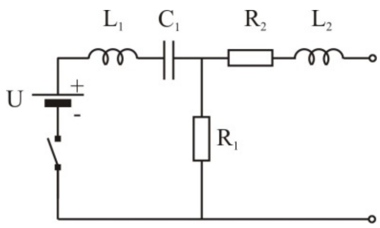

Figure 5. Electrical circuit of CWG.

Cables between arrester and suppressor and between suppressor and EUT are modeled as distributed lines.

Obtained simulation results for the same input data as in experiments, i.e. cases with cable A-S length of 80m, cable S-EUT length of 1m and resistive load of 400W and capacitive load of 114VAr are given in Fig. 6.

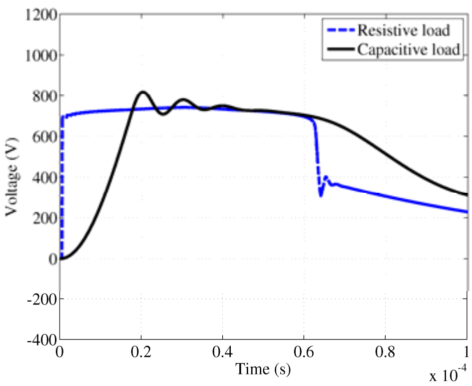

Figure 6. Simulation voltage waveform across EUT with resistive load of P=400W, cable A-S length of 80m and cable S-EUT length of 1m.

By comparing curves given in Figs. 3., 4., and 6. it can be concluded that the measurements results and simulation results correspond very well. Differences of less than 2.5% can be observed in case of detailed comparison of amplitudes. Therefore, the simulation model can be further used to analyze the influence of different parameters in wide range of their values on the two-stage overvoltage protection's characteristics.

IV. Analysis of Protective Characteristics

Simulations of surge testing of different EUT types and values of load power that can be found in real residential and/or industrial low-voltage AC power circuits were performed in ATP/EMTP and MATLAB.

As it is already mentioned, in two-stage protection common practice is that arrester is located at the service entrance of the building, while suppressor is located relatively near protected equipment. Therefore, in performed analysis it is taken that length of cable between suppressor and EUT is short and that it can has length up to 10m. Justification for this can be found in IEC 62305-4 standard [23] where is stated that protective distance, of SPD is 10m. Cable length between arrester and suppressor is varied in range of 10m up to 100m.

Maximal values of voltages that appear across EUT load and deposited energy in SPDs are monitored because of their main influence on protective characteristics regarding EUT response and SPDs performance.

Color-maps and color-bars besides graph in figures presenting obtained results in following sub-chapters are defined according to green-yellow-red principle considering allowed selected equipment withstand voltage or selected SPDs energy absorption capability.

A. Resistive load as EUT

In the case of EUT with resistive load, analysis is performed in range of load power between 0.5W and 4000W. Length of cable S-EUT of 1m is taken into account.

Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 7., while energy deposited in arrester and suppressor are given in Fig. 8. and Fig. 9. respectively.

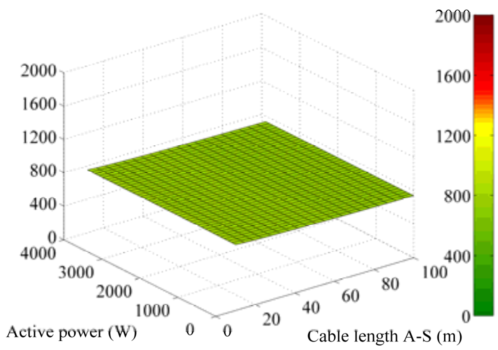

Figure 7. Maximal voltage across EUT with resistive load for case of cable S-EUT length of 1m.

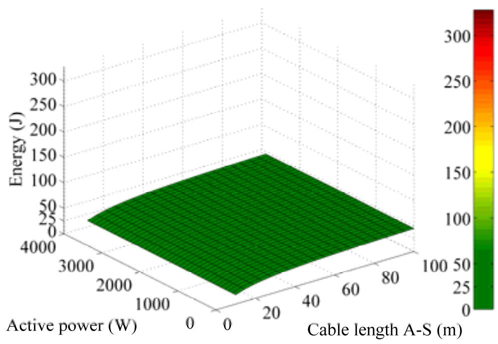

Figure 8. Energy deposited in arrester in case of EUT with resistive load and cable S-EUT length of 1m.

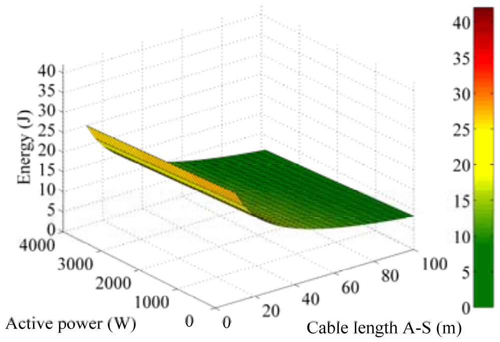

Figure 9. Energy deposited in suppressor in case of EUT with resistive load and cable S-EUT length of 1m.

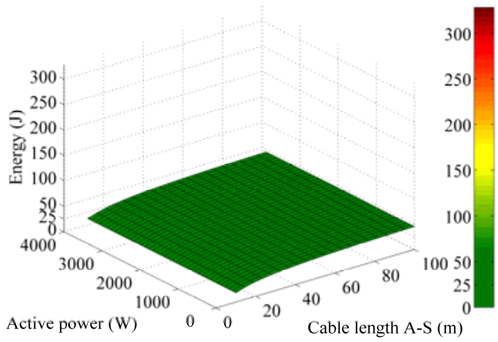

Figure 11. Energy deposited in arrester in case of EUT with resistive load and cable S-EUT length of 10m.

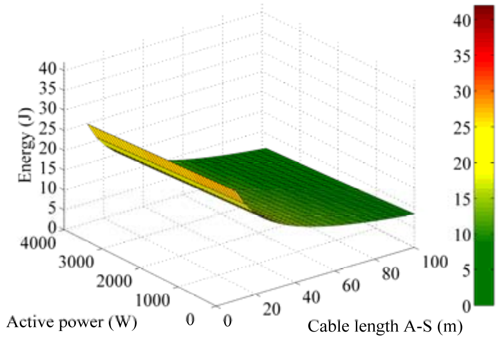

Figure 12. Energy deposited in suppressor in case of EUT with resistive load and cable S-EUT length of 10m.

From Fig. 7. it can be noticed that for all EUT load power maximal voltages across EUT are lower than suppressor protection voltage. This is consequence of very short cable S-EUT of 1m which causes attenuation of voltage reflection at the load resistance in case when load resistance has larger value than characteristic impedance of the cable [6]. From Fig. 8. it can be concluded that energy deposited in arrester 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. This is consequence of fact that SPDs of type 3 selected for suppressor has significantly lower energy absorption capability in comparison with SPDs of type 2. Energy deposited in arrester and suppressor mainly depends on length of cable A-S, and not on load power value. From Figs. 8. and 9. it can be noticed that for short cable A-S energy deposited in arrester is smaller than energy deposited in suppressor, and vice versa. 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·di/dt) and resistive (R·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.

In order to investigate possible influence of cable S-EUT length on obtained results, analysis is performed with this cable length of 10m, which is maximum allowed length of the cable according to IEC 62305-4 standard [23]. Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 10., while energy deposited in arrester and suppressor are given in Fig. 11. and Fig. 12. respectively.

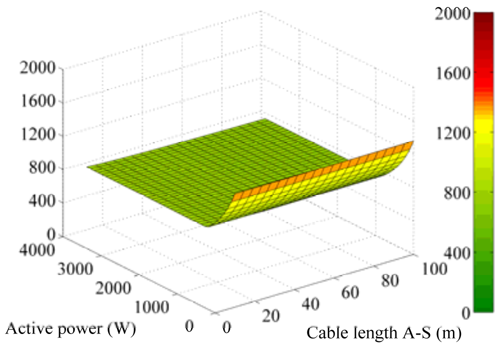

Figure 10. Maximal voltage across EUT with resistive load for case of cable S-EUT length of 10m.

From Fig. 10. can be noticed that in case of longer cable S-EUT and for smaller value of EUT load power, maximal voltages across EUT are larger than suppressor protection voltages. This is consequence of reflection of traveling voltage and current wave at large value of load resistance (small resistive power). However, these maximal values of voltages are still smaller than equipment withstands impulse voltage level of 1.5kV.

By comparison of Fig. 8. and Fig. 11., as well as Fig. 9. and Fig. 12. it can be concluded that there are no difference between distribution of energy deposition in corresponding SPDs for different cable S-EUT lengths. Reason for this is that the most part of surge energy is deposited in arrester and suppressor, while very small part of the energy is let-troughed toward EUT. For example, distribution of surge energy between arrester, suppressor and EUT as function of time in case of resistive load with 1000W, cable A-S length of 100m and cable S-EUT length of 1m are given in Fig. 13.

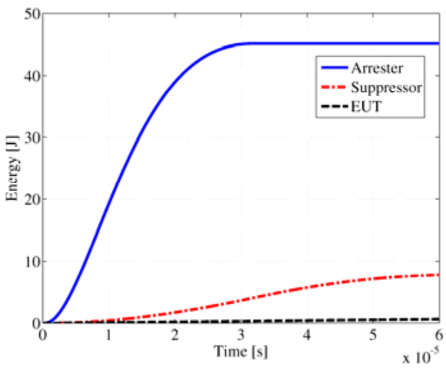

Figure 13. Example of energy distribution between arrester, suppressor and EUT as function of time for case of resistive load with 1000W, cable A-S length of 100m and cable S-EUT length of 1m.

In order to verify these conclusions further analysis are performed with assumed length of cable S-EUT of 100m, and the same results are obtained. Therefore, it can be concluded that energy through arrester and suppressor depends only on cable A-S length, and there are no dependence neither on EUT load power or cable S-EUT length. This is very important conclusion for energy coordination of SPDs in cascade applications.

B. Inductive load as EUT

In the case of EUT with inductive load, analysis is performed in range of load power between 0.5VAr and 1000VAr and with length of cable S-EUT of 1m.

Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig.14., while energy deposited in arrester and suppressor are given in Fig. 15. and Fig. 16. respectively.

By comparing Figs. 14., 15. and 16., with corresponding Figs. 7., 8. and 9. in case of resistive load, it can be concluded that there are no differences in obtained results regardless of these types of EUT load. Therefore, in case of very short cable S-EUT the same conclusions can be made both for resistive as well as inductive EUT's load.

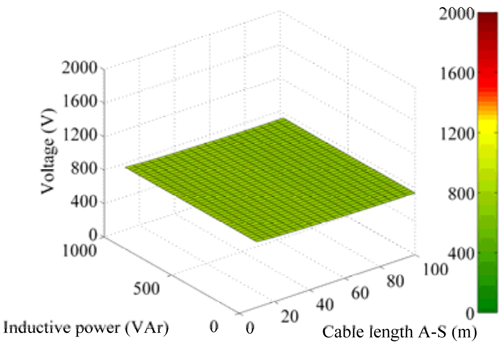

Figure 14. Maximal voltage across EUT with inductive load for case of cable S-EUT length of 1m.

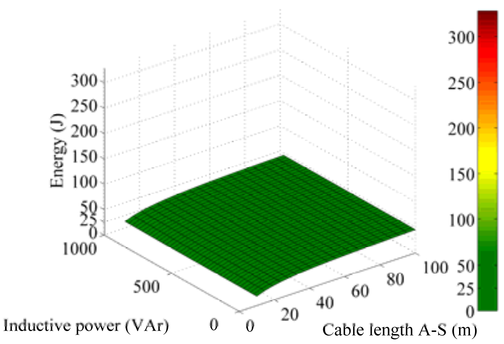

Figure 15. Energy deposited in arrester in case of EUT with inductive load and cable S-EUT length of 1m.

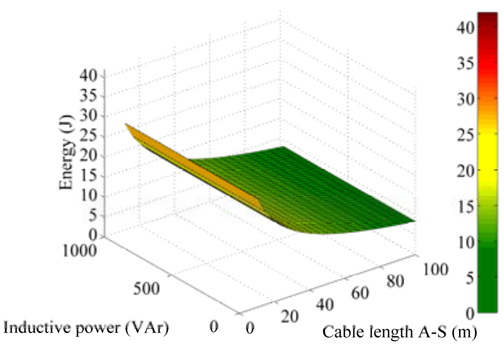

Figure 16. Energy deposited in suppressor in case of EUT with inductive load and cable S-EUT length of 1m.

In order to investigate influence of cable S-EUT length on obtained results in case of inductive load, analysis is performed with this cable length of 10m. Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 17., while energy deposited in arrester and suppressor are given in Fig. 18. and Fig. 19. respectively.

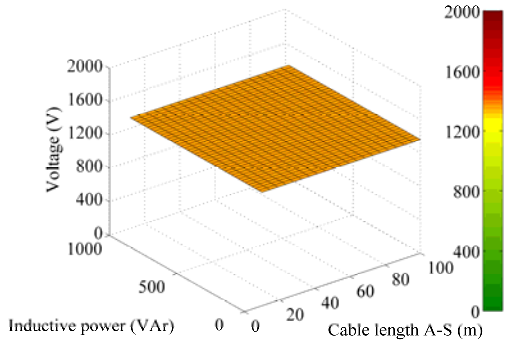

Figure 17. Maximal voltage across EUT with inductive load for case of cable S-EUT length of 10m.

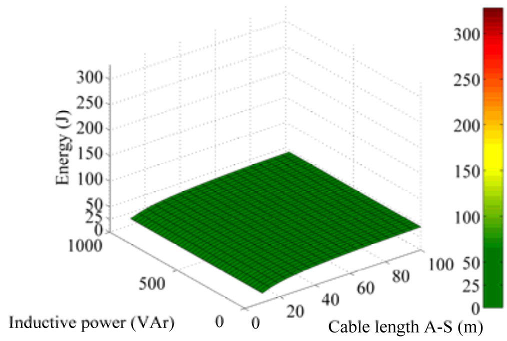

Figure 18. Energy deposited in arrester in case of EUT with inductive load and cable S-EUT length of 10m.

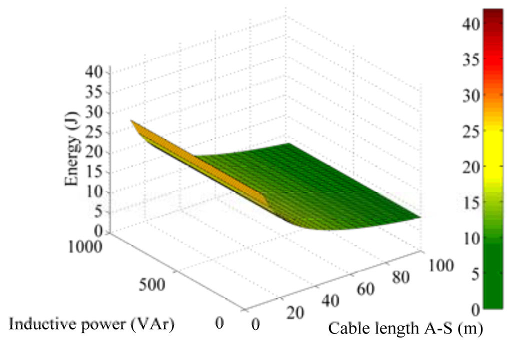

Figure 19. Energy deposited in suppressor in case of EUT with inductive load and cable S-EUT length of 10m.

From Fig. 17. it can be noticed that maximal voltages across EUT don't depend on values of inductive load power and/or cable A-S length. The maximal voltages across EUT have value of 1357V. This is consequence of traveling wave reflection on impedance of EUT with inductive load. This impedance is very large because of high frequencies at rise time of current surge impinging at the EUT node. In order to verify previously stated conclusions, further analysis is performed with assumed length of cable S-EUT of 100m, and the similar results are obtained but with maximal voltage values across EUT up to 1450V. Illustrations of these reflections are given in Fig. 20., which presents voltages waveforms across EUT with 500VAr for case with cable A-S length of 100m and cable S-EUT lengths of 1m (no reflections) and 100m (very pronounced reflections).

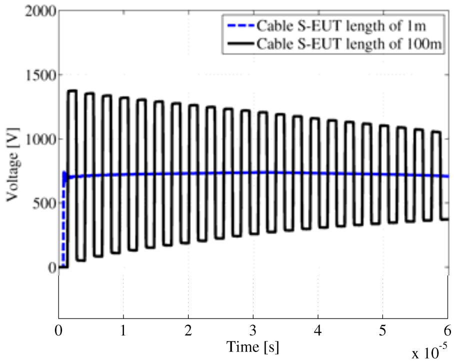

Figure 20. Voltage waveforms across EUT with inductive load for cases with different cable S-EUT lengths.

One more important conclusion can be made by analysis of the obtained results considering energies deposited in arrester and suppressor. Namely, by comparing Figs. 8., 11., 15. and 18., which present energy deposited in arrester for resistive or inductive load with cable S-EUT length of 1m or 10m, it can be noticed that there are no differences in obtained results. This also applies for energy deposited in suppressor (Figs. 9., 12., 16. and 19.).

C. Capacitive load as EUT

In the case of EUT with inductive load, analysis is performed in range of load power between 0.5VAr and 200VAr and with length of cable S-EUT of 1m. Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 21., while energy deposited in arrester and suppressor are given in Fig. 22. and Fig. 23. respectively.

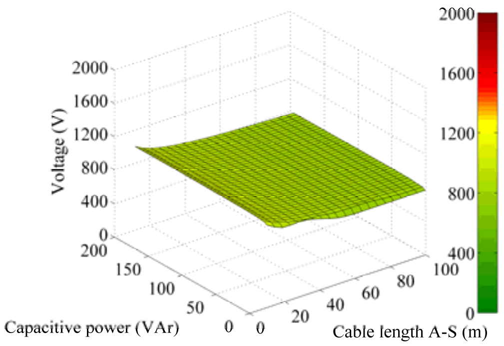

Figure 21. Maximal voltage across EUT with capacitive load for case of cable S-EUT length of 1m.

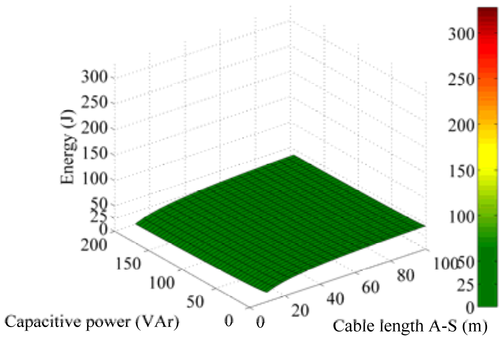

Figure 22. Energy deposited in arrester in case of EUT with capacitive load and cable S-EUT length of 1m.

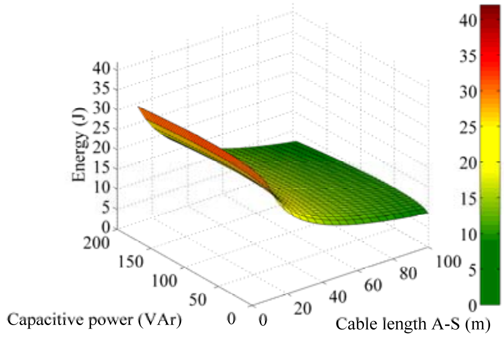

Figure 23. Energy deposited in suppressor in case of EUT with capacitive load and cable S-EUT length of 1m.

From Fig. 21. it can be noticed that even for very short cable S-EUT and relatively short cable A-S, maximal voltages across EUT are higher than suppressor protection voltage. This is consequence of voltage oscillations across EUT due to processes of capacitor charging. Illustration of voltage waveform across EUT for capacitive load power of 200VAr, cable A-S length of 10m and cable S-EUT length of 1m is given in Fig. 24.

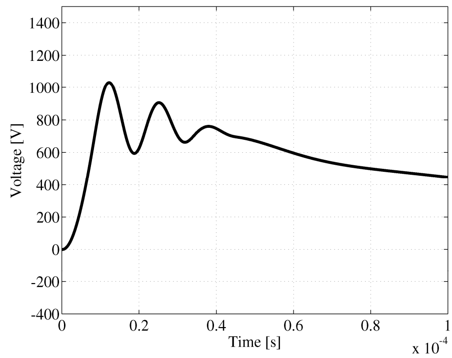

Figure 24. Voltage oscillations across EUT with capacitive load of 200VAr in case of cable A-S length of 10m and cable S-EUT length of 1m.

From Figs. 22. and 23. it can be noticed that energy distribution pattern is similar but very slightly different than in case of resistive and inductive load.

In order to investigate influence of cable S-EUT length on obtained results in case of inductive load, analysis is performed with this cable length of 10m, which is maximum allowed length of the cable according to IEC 62305-4 standard [23]. Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 25., while energy deposited in arrester and suppressor are given in Fig. 26. and Fig. 27. respectively.

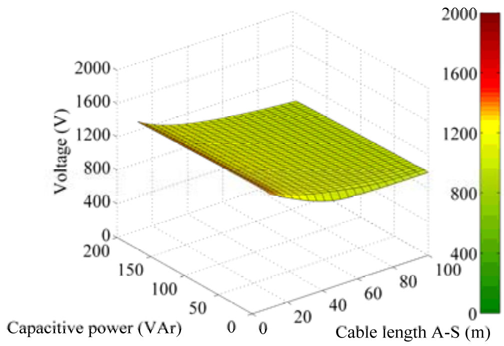

Figure 25. Maximal voltage across EUT with capacitive load for case of cable S-EUT length of 10m.

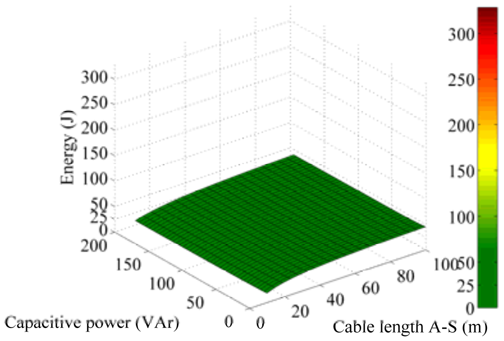

Figure 26. Energy deposited in arrester in case of EUT with capacitive load and cable S-EUT length of 10m.

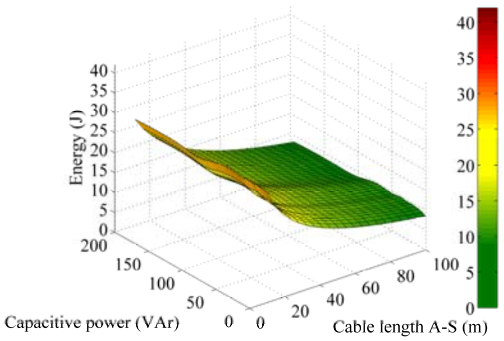

Figure 27. Energy deposited in suppressor in case of EUT with capacitive load and cable S-EUT length of 10m.

From Fig. 25. it can be noticed that for all cable A-S lengths and all load capacitive power maximal values of voltages across EUT are higher than suppressor protection voltage. From Fig. 27. it can be noticed that distribution of energy deposited in suppressor is slightly changed than in case of cable S-EUT length of 1m. Reason for this is changes in energy let-trough toward EUT.

As it can be seen from Fig. 21. and Fig. 25. maximal voltages across EUT increase with increasing of cable S-EUT length. In order to confirm this, further analysis with assumed cable S-EUT length of 100m are performed. Maximal voltages across EUT as function of load power and length of cable A-S are given in Fig. 28.

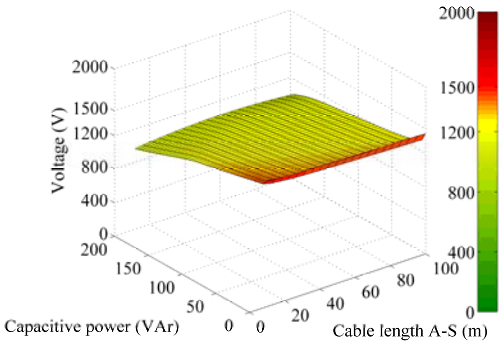

Figure 28. Maximal voltage across EUT with capacitive load for case of assumed cable S-EUT length of 100m.

From Fig. 28. it can be noticed that for small capacitive load power maximal voltages across EUT are even higher than 1500V i.e. equipment withstand voltage.

V. Analysis of Obtained Results

Obtained results in performed simulations considering characteristics of overvoltage protection with two-stage application of SPDs can be summarized as follows:

1. In case of a very short cable S-EUT maximal voltages across EUT are lower than suppressor protection voltage in case of resistive and inductive load regardless of its power and/or cable A-S length. This is expected performance of suppressor. However, in the case of capacitive load maximal voltages across EUT are higher than suppressor protection voltage even for short cable S-EUT of 1m. Indeed, these values of maximal voltages are still lower than equipment withstand voltage, but only because protection voltage of suppressor is selected much lower than the equipment withstand voltage. The most of stand-alone SPDs of type 3 or type 2 [18] (which can be used as suppressor located near protected equipment) have protection voltages in range of 1250V to 1500V, which selection and application, according to obtained results, can endanger equipment with capacitive load which commonly characterized sensitive electronic equipment. Namely, this equipment with switch power supply unit can be modeled as capacitor-charging circuits in the analysis of lightning surges, particularly for the discussion of load effect [24]. With increase of cable S-EUT length up to 10m (which is maximum allowed length of the cable according to IEC 62305-4 standard [23]) maximal voltages across EUT increases and have values higher than value of suppressor protection voltage. For resistive load this is notable only in case of small resistive load power (which in most cases refers to sensitive equipment), while it is true for all values of inductive and capacitive load power and/or cable A-S lengths.

2. Energy deposited in arrester and suppressor for all types of load has dependences only on cable A-S length, regardless of EUT load power and/or cable S-EUT length. This is because the most of surge energy is deposited in arrester and suppressor, while energy let-through toward EUT is very low due to energy and insulation coordination of the selected arrester and suppressor. For short cable A-S energy deposited in arrester is smaller than energy deposited in suppressor, and vice versa. However, it should be kept on mind that this energy coordination it is not granted, i.e should to be verified and confirmed for every combination of selected SPDs in two-stage protection.

3. Energy deposited in arrester and suppressor is smaller than their energy absorption capability. However, safety margin for suppressor is very narrow. This is because selected arrester is SPD type 2 according to IEC 61643-11 standard [18] (which have high energy absorption capability), while selected suppressor is SPD of type 3 which has significantly lower energy absorption capability in comparison with SPDs of type 2. Possible solution is application of SPDs of type 2 for suppressor. But, as already mentioned, SPDs of type 2 have higher protection voltage and, although energy absorption capability would be increased, overvoltage protection might be inappropriate especially in case of sensitive equipment with low withstand voltages.

VI. Conclusion

Protection of equipment against the prospective surges in low-voltage AC power circuits is based on wide application of SPDs. In existing practice the most common situation is application of two-stage cascade protection with SPDs located at the service entrance of the building and relatively near protected equipment. Analysis of SPDs performances arranged in two-stage protection scheme is conducted through performed measurements and simulations using the ATP/EMTP and MATLAB Simulink. Surge testing is performed with Combination Wave as representative surge according to IEEE and IEC standards. This paper is an attempt aimed at overcoming the lack of a comprehensive analysis of the characteristics of two-stage protection by applying research of the protection's performance with a wide range of influencing parameters. Obtained results show that special attention should be given to selection of SPDs protection voltages in order to confirm their energy, as well as insulation coordination. This is very important for protection of equipment with capacitive load character, in which case values of maximal voltages higher than SPD' s protection voltages appears even for small cable lengths between SPD and equipment. Having on mind that advanced electrical and electronic devices are commonly equipped with switch power supply units (that can be modeled as capacitor-charging circuits) and that they normally have low impulse withstand voltage level, obtained conclusions become particularly significant. We find this as a good base for further researches which should analyze overvoltage protection in low-voltage AC power circuit with application of other representative surges according to standards, as well as analysis of overvoltage protection for specific devices modeled with frequency depended parameters.

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