Transient Behaviour of Low Voltage Distribution Systems

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Abstract: IEC and EN standards describing testing requirements for surge protective devices (SPDs) connected to low voltage power distribution systems emphasise the energy level that is expected to pass through each SPD type without giving much importance to the expected overvoltage levels. In high energy SPD technology, which is mainly based on spark gaps, the voltage protection level partly depends on the prospective overvoltage that will be applied across their terminals. In this paper a number of 3-phase low voltage distribution systems including the customer supply network are analysed. Energy and overvoltage levels are recorded for various case studies and the surge protection is evaluated for various methods/devices.

Keywords: Low voltage distribution system, SPDs, voltage protection level, lightning current distribution

1. Introduction

Previous research [1-4] and International standards [5] suggest that in case of a direct lightning strike on a building, high energy lightning currents may flow through the electrical installations that equip the building. Moreover experience and research [6] on lightning protection proves that the most important point that should be protected against the bulk of these generated overvoltages/currents is the main electrical distribution board where the LV distribution supply is connected to the building.

Depending on the earthing type of the low voltage distribution system that connects the building with the electricity supply (i.e. TN S, TN CS or TT), the expected overvoltages and lightning/surge currents may vary. For the purpose of this paper only the TN CS system, which is the most common LV distribution system for residential and industrial areas in the UK [7], will be examined in order to distinguish the level of the initial prospective overvoltages and the resulting lightning/surge current.

Figure 1 describes an arrangement of how a typical LV distribution system looks like from the distribution transformer up to the customer load. The LV cable provides the link between the MV-LV transformer and the customer’s installation. At the customer supply point an optional additional earth might be used. Inside the customer premises all the earthed parts including the electrical protective earth (PE) and the lightning protection earthing system (considering a structure that has an external LPS installed) have a common reference point. Live connections (i.e. electric and telecom conductors) should also be connected to the same reference point as all the earthed parts, through surge protective devices. This reference point may be for example a potential equalisation-bonding bar or similar providing that it has one or more [8] short connections to the LPS earthing system.

2. Transient Behaviour of LV Systems – Theory

When lightning strikes the external LPS of a building, the local earth (i.e. LPS earthing system) rises in potential causing a high potential difference between conductors or components connected to it and others that are not referenced to it (i.e. live conductors of energy and telecom lines). A practical example is the PE conductor, which is directly connected to the LPS earthing system with respect to the phase conductors, which have as a reference to earth the earthing system of the MV-LV substation. By providing equipotential bonding between earthed and live conductors through SPDs this high potential difference can be reduced. But due to the conduction of the SPDs, partial lightning current flows towards them through the transformer site via the phase and the neutral conductors.
For primary protection either spark gaps or heavy-duty metal oxide varistors are mainly used. If the SPD is based on varistor technology the voltage protection level of the SPD partly depends on the lightning/surge current that will pass through it. If the SPD is based on a spark gap technology then the voltage protection level of it partly depends on the prospective overvoltage, which will cause the initial breakdown of the gap.

3. Modelling Issues

Two general cases will be considered, one with a single customer been fed of the LV cable, which is common for industrial sites and a second with three customers, which will provide a fundamental understanding of the multicomponent network. All the case studies were modelled and simulated by using the EMTP-ATP algorithm [9] in order to define the prospective overvoltages in absence of SPDs and partial lightning current that may flow through the SPDs in the case of a direct lightning strike to the customer installation. Each simulation model consists of; the distribution transformer, the supply cable(s), the customer(s) supply point(s) and the earthing system(s).

**Transformer:** The distribution transformer model contained a leakage reactance (50µH), series resistance (0.5Ω) and shunt capacitance (1nF) on each phase. The values were measured on a 300kVA transformer 11/0.433kV.

**Cable:** The underground supply cable was modelled in ATP based on J. Marti's method for calculation of transients on frequency dependant transmission lines [10]. ATP features make possible the simulation of belted cables and materials with different permittivity and permeability values, which allows modelling of 3 and 4-phase cables, the sheath and the insulation materials of the cable with greater accuracy.

All the results may be taken as a valid reference if the PEN conductor was supplied either by a fourth core or by the sheath of the cable as long as both are made out of a material with low permeability (aluminium or copper). If they are made out of materials with different permeability values, for example the core is made out of copper and sheath is made out of steel and both are used (i.e. core for the phases and sheath for PEN) different results than the ones that are presented may occur since the permeability influences the inductance, which will then change the surge impedance of certain conductors during transient studies.

**Earthing System:** In many national [11] and international standards [12], which specify design principles for lightning protection earthing systems, the term of the impedance is neglected. The impedance of the earthing system is an important parameter to be modelled since the reactance will interact with the high frequency components of the lightning stroke, giving high total impedance, while the DC resistance value dominates for the low frequency components [13]. As it has been suggested by other researchers [14], a “π” equivalent circuit used in EMTP - ATP is accurate with small error during the calculation process. The earthing system, which was used, was composed of parallel single ten metre long electrodes. The soil for all the simulations was taken to have a resistivity of 5000Ωm.

**Lightning source:** The lightning source is simulated as a double exponential waveform with a rise time of 5.5µs and a tail time of 70µs, by using a surge type current source, which satisfies the double exponential equation,

\[ I = I_0 \times \left( e^{-\alpha t} - e^{-\beta t} \right) \]

For the 5.5/70µs \( \alpha=10910 \) and \( \beta=785500 \), efficiency = 0.93 These values were selected as average values for first return strokes according to research that was done by Berger in 1975 [15]. The magnitude was chosen to be between 5kA and 200kA since according to Berger data only 5% of recorded first return strokes had a lower or higher magnitude. Subsequent strokes and long duration (DC current) components were not included in the case studies.

4. Single Customer – Industrial Site Example

In the first case study a single customer will be considered. This is common for industrial sites with high loads where the MV-LV transformer supplies one site only. The main supply cable (4 x 95mm²) from the MV-LV transformer to the customer electrical supply was selected to be 40m. The DC resistance for the neutral point earthing system at the distribution transformer for such cases does not usually have a lower value than the LPS earthing system (considering that the structure has an external LPS). The neutral earthing system at the transformer had a total DC resistance of 10Ω and the LPS earthing system had a DC resistance of 3Ω. Figure 2 describes the case study that was examined. Two simulations were performed, one with and one without SPDs. The SPDs where modelled with a simplified spark gap model. Without the SPDs installed the prospective overvoltage was recorded (Figure 3), while as with the SPDs installed the partial lightning current that may flow through them was also recorded (Figure 4).

From the results, the need of surge protection device is as shown necessary due to high potential difference between live and earthy parts. In such cases where the substation is near the customer, the SPDs are not subjected to high-energy lightning currents.

A similar real case has been described in [16] and indeed the SPDs, which have been installed, have discharged over 35 lightning impulses of more than 500A and none has suffered any overstress over a quite long period of service and in a high ground flash density environment.
The current flowing through the PEN conductor is about three – four times higher (energy and peak) than the current flowing through the phases. The current is limited in the phases due to the transformer inductance. If the neutral is provided by the cable’s sheath and the sheath is made out of a high permeability material, then its inductance will also be higher causing an alteration to the current distribution than in the previous case where phases and neutral were supplied by the cable’s cores.

Additional statistical simulation results are summarised in table 1, appendix 1.

5. Multi Customer – Residential Area Example

Realistic low voltage distribution systems are quite complex, which makes difficult to understand their behaviour during transient studies. The aim of this section is to explain the lightning current distribution in a simple low voltage network, which contains three customers connected to it. This will explain the danger that neighbouring houses may be under if one is struck by lightning.

The simulation model including the cables sizes and lengths is shown in Figure 5. All the structures have a low local impedance earthing system of 3Ω. In residential areas it is common to earth the neutral at multiple points to achieve a low DC resistance value. For these simulations the total neutral DC resistance was set to be 0.5 Ω. The attachment point of the lightning stroke was set to be the middle structure for all the case studies.

Three case studies are described, in the first one all the structures had SPDs installed, in the second case only the structure that is struck by lightning had SPDs installed and in the third none had SPDs installed. In the first case the lightning current distribution through all the SPDs was evaluated (Figure 6), whereas in the second and third case study the overvoltage levels in the neighbouring structures were recorded (Figure 7 & 8). The overvoltage levels at the neighbouring structures are higher if customer 2 has SPDs installed. This doesn’t mean that by not installing SPDs the overvoltage level will be reduced because in all the cases the level of the generated overvoltages can cause damage to equipment connected to the network and should be limited.
Figure 5: Example of a residential LV supply system – case 1 SPDs installed in C1, C2 and C3 – case 2 SPDs installed only in C2 – case 3 no SPDs installed

Figure 6: Case 1 – Current distribution in customer 1, 2 and 3 with SPDs installed in all structures - % of total energy

Figure 7: Case 2 – Overvoltage level without SPDs at customer 1 and 3

Figure 8: Case 3 – Overvoltage level at customer 1, 2 and 3 without SPDs at any customer

Additional statistical simulation results are summarised in table 1, appendix 1.

6. Discussion & Conclusions

The purpose of installing SPDs is to provide equipotential bonding during transient conditions between live and earthy parts of an electrical system/equipment and therefore protect it from undesired transient overvoltages and to divert lightning and surge current away from it.

For primary protection and in order to fulfil the current-testing requirements of IEC 61643-1 Class I [17], the main SPD design should be based on spark gaps since common varistor technology cannot, yet, cope with the energy that the above standard recommends for Class I testing method.

The selection of the SPD depends on the expected lightning current that it should discharge and on the overvoltage category of the equipment that is to be protected. Knowing the overvoltage category the selected SPDs should have a lower voltage protection level in order to provide sufficient surge overvoltage protection.

For the case studies that were previously described only the origin of the electrical installation is taken into consideration. Equipment at the origin of the installation according to IEC 60364-4-44 [18] are classified in overvoltage category IV and for 230-400V systems the required impulse withstand voltage level is 6kV. Therefore the upstream SPDs should provide a voltage protection level of less or equal to 6kV.

In order to define the voltage protection level of an SPD based on spark gap in a realistic situation, three SPDs based on spark gap technology with different voltage protection levels were tested in the laboratory by applying a sequence of impulse voltages similar to those that were recorded during the simulations. Depending on the initial lightning stroke the rate of rise of the overvoltage may vary. Figure 9 describes the probability of the lightning current exceeding a given value. Based on this figure and on the simulation results, Figure 10 shows the probability...
of the prospective overvoltage for different lightning strokes and the voltage protection level of the three spark gap SPDs after been tested with a similar waveform as the prospective overvoltage.

The spark gaps were tested with the standard lightning impulse (1.2/50μs) since most of the recoded overvoltages had a rise time between 850ns and 1.3μs, which are within the ±30% tolerance [17] of the front for the standard lightning impulse. Since for most of the applied impulses the breakdown of the spark gap was during the front, the tail time was not taken into consideration. It is clear that for a wide range of lightning currents, none of the spark gaps could provide the desired voltage protection level of less or equal of 6kV.

When the spark gaps were highly overvolted with values of high dV/dt (i.e. 100kV/μs) the spark gap conduction may occur few nanoseconds after the overvoltage has exceeded the DC breakdown voltage of the gap. Although this delay is only few nanoseconds, the let through voltage as it is showing in Figure 10 has an appreciable level, which might cause disturbances to equipment connected downstream the spark gaps. Additional voltage limiting devices should be installed and co-ordinated with the spark gaps in order to limit the let through voltage of the spark gaps.

For impulse voltages with high steepness (i.e. more than 40kV/μs) the step response of the digital measurement unit due to its bandwidth and response time has given attenuation to the measured signal.

Further work is currently been undertaken to improve all the simulation models and to perform more detail analysis of the entire system.

7. References

[7] IEE wiring regulations for electrical installations
[12] IEC 62305-3, Protection against lightning, Part 3: Physical damage to structures and life hazard
[17] IEC 61643-1, Surge protective devices connected to low-voltage power distribution systems, Part 1: Performance requirements and testing methods
[18] IEC 60364-4-44, Electrical installations of buildings, Part 4-44: Protection for safety – Protection against voltage disturbances and electromagnetic disturbances
8. Appendix 1

<table>
<thead>
<tr>
<th>Current peak &amp; Charge distribution for a single connection – industrial site</th>
<th>Phase SPDs (L₁ L₂ L₃)</th>
<th>PEN</th>
<th>LPS earthing system</th>
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<tr>
<td></td>
<td>Ipk (kA)</td>
<td>Q %</td>
<td>Ipk (kA)</td>
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<th>Current peak &amp; Charge distribution for multiple connections – residential area (See Figure 5)</th>
<th>Phase SPDs @ C₂ (L₁ L₂ L₃)</th>
<th>*PEN @ C₂</th>
<th>LPS earthing system @ C₂</th>
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4 x 95mm² – Cu
25m of 3 x 185mm² – Cu & 2.5mm thick sheath wires for PEN - Cu
15m of 4 x 16mm² – Cu, connection cable
200kA, 5.5/70µs total Q = 100%

Table 1: Current distribution for single and multi connections in a LV network with variable parameters – *Note: PEN is connected directly to earth at each supply point and not through SPDs