GROUND'2010

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4th LPE

International Conference on Grounding and Earthing
&
4th International Conference on Lightning Physics and Effects

Salvador - Brazil November, 2010

PROTECTIVE LEVELS AT EQUIPMENT TERMINALS FOR VARIOUS SPDs

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Abstract – selection rules for SPDs based on lead length, distance between equipment and SPD and protective levels are given in standards. Some of them are simplified and some others are more complex. But all of them are ignoring some effects. If the 10 m maximum distance between equipment and SPD is now well known, the effect of oscillation can exist even for shorter distance than 10 m. The way of connecting the SPD and the type of SPD has also some importance in the protection offered by the SPD. Combined SPD types may change the rate of rise at the output of the SPD and this rate of rise is also to be considered. Two ports SPD, with their capability to reduce the steepness of the incoming surge allow more flexibility in terms of SPD installation as well as providing very low protective levels.

1 - INTRODUCTION

It is clear in standards that SPDs have a protective level defined at its terminals (named UP) that may differ from what appears at the protected equipments terminals. This is explained in IEC 61643-12 [1] as well as in IEC 62305-4 [2]. Parameters that have influence are :

- lead length from active conductors to SPD, from SPD to its disconnector (if any) and from disconnector to ground terminal
- distance between the SPD and the equipment to be protected
- technology of the SPD (1 port : parallel SPD, 2 ports : parallel and series SPD ...)

Many of these parameters are described in the standards but sometimes in a non physical way. For example, the maximum allowed distance between SPD and equipment is 10 m. After 10 m, the protective level is doubled. But what happen between 1 m and 10 m ? The evolution, even if not linear is not an abrupt increase from UP up to 9,9 m and the 2 times UP after 10 m ! We will show on examples that the voltage at the equipment terminal is depending on the equipment-SPD distance and the equipment characteristics in an increasing even if not a linear way.

In addition, some SPD technologies have capability to reduce the dependency between SPD-equipment distance and voltage at equipment terminals.

A project was introduced in SPD standards at early stage to cover specificities of two ports SPDs (for example SPD with filter). The du/dt at the output of two ports SPD was supposed to be measured. This could have been an interesting parameter which is now missing to characterize the effect of theses SPDs to reduce the effect of the distance between the SPD and the equipment to be protected.

The paper will conclude with recommendations for the standards (application and product standard) and for the users.

2 - WITHSTAND VOLTAGES AND IMMUNITY LEVELS

The withstand voltage of equipment is defined in IEC 60664-1 [3]. It should be noticed immediately a few things regarding the withstand voltage Uw. This is obtained by a test with a voltage impulse having a 1,2/50 µs waveshape. It is tested between phase or neutral and ground. For equipment having to earthing terminal the reference is a metallic foil wrapped around the product. IEC 60664-1 has a pilot function but is not mandatory. Each committee developing product standard have the possibility to include such a test in its standard or not. It appears that at the end of the day it is very difficult to get such a value Uw for all equipments inside a facility. IEC TC64 (electrical installation inside buildings) has then developed categories to insure insulation coordination. IEC 60364-4-443 [4] gives a table reproduced below. This table allows selecting equipments based on his use assuming that it complies with IEC 60064-1.

Table 44B – Required rated impulse withstand voltage of equipment

Nominal voltage of the installation [a] V		Required impulse withstand voltage for kV [c]			
Three-phase systems [b]	Single-phase systems with middle point	Equipment at the origin of the installation (overvoltage category IV)	Equipment of distribution and final circuits (overvoltage category III)	Appliances and current-using equipment (overvoltage category II)	Specially protected equipment (overvoltage category I)
–	120-240	4	2,5	1,5	0,8
230/400[b] 277/480[b]	–	6	4	2,5	1,5
400/690	–	8	6	4	2,5
1 000	–	12	8	6	4

[a] According to IEC 60038.

[b] In Canada and USA, for voltages to earth higher than 300 V, the impulse withstand voltage corresponding to the next highest voltage in column one applies.

[c] This impulse withstand voltage is applied between live conductors and PE.

Figure 1 – Overvoltage categories

The situation is in fact a little more complex, as the insulation withstand Uw is not enough to describe equipment sensibility to surges. IEC 6100-4-5 [5] one of the EMC standard has defined immunity for equipment. This includes withstand between phase and neutral, which is much more relevant than insulation withstand, but also gives other values for the withstand between active cable (phase or neutral) and earth. Reason, for this discrepancy, is double : first of all, EMC deals with malfunction and not only damage. Second, the testing generator is no more an impulse voltage but a combination wave (a generator that deliver a 1,2/50 µs voltage impulse when the equipment behaves like an open circuit or a 8/20 µs current wave when the equipment behaves like a short-circuit). This lead to another table reproduced below :

Selection of generators and test levels

The selection of the test levels shall be based on the installation conditions. For this purpose table A.1 should be used, together with information and examples given in B.3 of annex B where:

Class 0:	Well-protected electrical environment, often within a special room.
Class 1:	Partly protected electrical environment.
Class 2:	Electrical environment where the cables are well separated, even at short runs.
Class 3:	Electrical environment where cables run in parallel.
Class 4:	Electrical environment where the interconnections are running as outdoor cables along with power cables, and cables are used for both electronic and electric circuits.
Class 5:	Electrical environment for electronic equipment connected to telecommunication cables and overhead power lines in a non-densely populated area.
Class x:	Special conditions specified in the product specification.

Additional information is given in figures B.1 to B.3 of annex B.

To demonstrate the system level immunity, additional measures relevant to the actual installation conditions, e.g. primary protection, should be taken.

Figure 2 – EMC immunity levels

It should be noticed that, a group of five IEC committees (SPDs, insulation coordination, electrical installation, lightning protection and EMC) met to try combing these two tables but failed to do so. We will then not try to do so in the present study but will just conclude that this is making the task of surge protection engineers difficulty especially when it is noticed that to declare such values is already not mandatory for all products.

3 - COMPARISON BETWEEN IEC 62305-4 AND IEC 61643-12 STANDARD

Situation in IEC 61643-12 is rather simple. The lead length is to be below 50 cm. The protective level of the SPD is used by taking into account a 20%¨margin in order to tolerate some variation in installation rules, surge characteristic (magnitude or waveshape) or even, SPD protective characteristics degradation. Then a possible voltage doubling is introduced after 10 m of cable distance between SPD and equipment to be protected. Of course, this double voltage is depending on equipment characteristic (mainly capacitance at high frequency) and cable type (mainly inductance). For simplicity sake the rule is simple, below 10 m , the 20% margin is sufficient and above 10 m, a double protective level is to be considered. Protection at equipment terminal is then either 1,2 times UP (UP being the declared protective level of the SPD,) if distance between SPD and equipment is less than 10 m or 2 times (1,2 * UP) if the distance is greater than 10 m). Very often this last rule is simplified in 2 times UP. By the way, experience over a very large quantity of SPDs is showing that these simple rules work and are enough to cover most of the phenomena. Why simple rules are needed ? Because, in real word, many different situation occurs and in order to be sure that rules are applied and understood they need to be simple. Over more than 25 years of experience worldwide not a single case of damage to equipment has been reported to the authors for SPD following IEC 61643-12 rules.

IEC 62305-4 introduced moiré accurate rules. They are summarized below :

First of all, 62305-4 introduces the effective protection level, UP/f that takes into account the inductive voltage drop ΔU of the connecting conductors when the SPD is carrying partial lightning current,. UP/f is then defined as the voltage at the output of the SPD resulting from the protection level and the wiring voltage drop in the leads/connections. For voltage-limiting type SPDs (varistor based SPD for example) UP/f = UP + ΔU. For voltage-switching type SPDs (spark gap based SPDs) UP/f = max (UP, ΔU). The arc voltage that may be as high as some hundreds of volts should be added as well. For combination type SPDs, more complex formulas may be needed, but they are not provided in the standard .ΔU = 1 kV/m of lead conductor should be assumed. A minimum safety margin of 20 %, should be used when the length of the connection conductors is lower than 0,5 m. When the SPD is carrying induced surges only, Δ*U* can be neglected.

The doubling of voltage due to oscillation phenomenon presented above is also introduced but relates to UP/f and not to 1,2 times Up as per 61643-12. In this standard the protection distance *l*po is defined as the maximum length of the circuit between the SPD and the equipment, for which the SPD protection is still adequate taking into account oscillation phenomena and capacitive load. This depends on the SPD technology, the installation rules and the load capacity. If the circuit length is less than 10 m or UP/f < Uw /2, the protection distance lpo may be disregarded. In the opposite case lpo = [Uw–UP/f]/25.

But 62305-4 also introduces the induction protection distance *l*pi to take care of lightning flashes to the structure or to ground nearby the structure, which can induce an overvoltage in the circuit loop between the SPD and the equipment, which adds to Up and thereby reduces the protection efficiency of the SPD. The induction protection distance lpi is the maximum length of the circuit between the SPD and the equipment, for which the protection of the SPD is still adequate (taking into account the induction phenomena). The magnetic field and the induction effects can be reduced by spatial shielding of the building or of the rooms inside the building, by cable routing or even line shielding (use of shielded cables or cable ducts). When these precautions are followed, the induction protection distance lpi can be disregarded. If it is not the case, the induction protection distance *l*pi can be estimated using the following equation: *l*pi (in m) = [Uw–UP/f]/h where is depending of the shielding efficiency.

4 - APPLICATION OF SPDs INSTALLATION RULES ON PROTECTIVE LEVEL PROVIDED TO EQUIPEMENT VC

4.1 - OSCILLATION PHENOMENON VERSUS DISTANCE BETWEEN SPD AND EQUIPMENT

The real behavior of a simple R, L and C circuit is not a simple rule such as the oscillation phenomenon doubles the peak voltage after 10 meters and has no effect on the peak voltage before.
All electrical parameters have their impact. The values of the resistance, of the capacitance and of the inductance are of course main parameters of the circuit, but the Input signal characteristics are also part of calculation for simulation. The new parameter to consider here compare

to Standard rules will be the voltage/time variation of the impulse voltage.

In the following paragraphs, the effect of each parameter will be recalled and assumptions will be fixed.

In a power distribution circuit, the R an L parameters are both linked to the cable length. The arrangement of the cable impacts the inductance value and this is linked to the installation. The value for the inductance per meter is commonly fixed to 1µH per meter. This is the value we will also use in our simulations.
The cross section of the cables impacts as well these 2 parameters but mainly the resistance is concerned (we assume that the cables are made of copper). In other hands, if we consider the cross section of a power cable is around 3mm² and can vary from 1mm² (AWG 17) to 16mm² (AWG 5), the resistance per meter varies from 1 to 16 Ohms and compare to the effect of the inductance, we can assume that fixing the cross section to an average of 3,3mm² (AWG 12) will lead to usable results independently of the size of the cable. In consequence the resistance per meter is fixed to 5 mΩ/m.
The capacitance is also linked to the size, the length and of course the arrangement of the cable but also mainly to the internal input of the device. For simplification, in our simulation, we will consider that this capacitance is fixed and is depending of the loads itself. The capacitance is fixed to 5nF.

The estimation of U_{osc}, the added voltage to the protective level Up has been simulated with the assumption that the SPD protecting the power cable is a limiting type SPD. Thus the injected voltage shape is a square signal with defined rise time and maximum value.

In this part, the front time of the impulse voltage is fixed to 1,5kV in 0,6µs which is a du/dt equal to 2,66kV/µs

To observe the impact of the cable length, several simulations have been performed with simulated cable length as describe above. The interesting area was fixed from 0 meter to 10 meters.

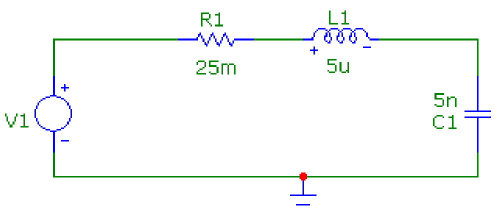


Figure 3 - Circuit used for the simulations

The figure 4 shows a simulation for 5 meter. The maximum value measured at the capacitor terminal U_{cmax} is equal to 2,224 kV. Table 1 summaries the results of all simulations made from 0 to 10 meters. The last line of this table express the voltage rise in % of Up (Up=1,5kV), with U_{cmax} = Up + U_{osc} = (1+k) * Up

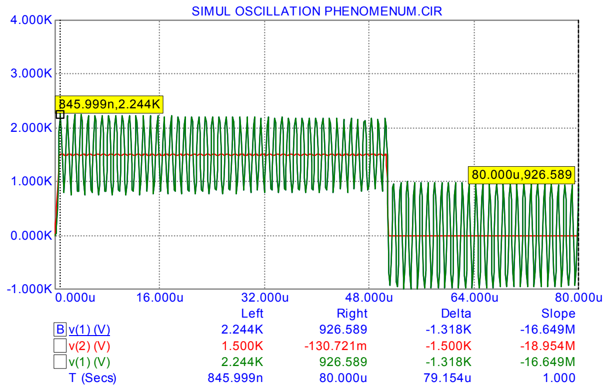


Figure 4 - Example of simulating results

Value	Distance between SPD and equipement											
Lenght	0	1	2	3	4	5	6	7	8	9	10	meter
R	0	5	10	15	20	25	30	35	40	45	50	mΩ/m
L	0	1	2	3	4	5	6	7	8	9	10	µH
Ucmax	1,50	1,77	1,66	1,94	2,11	2,24	2,35	2,43	2,46	2,49	2,51	kV
%	0%	18%	10%	29%	41%	50%	57%	62%	64%	66%	67%	%

Table 1 – effect of distance between SPD and equipement length

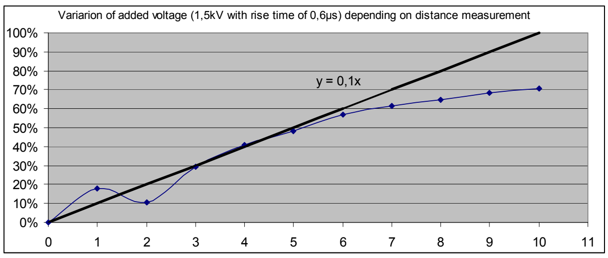


Figure 5 – curve k versus distance SPD-equipment

We can see that an approximate value for the added voltage U_{osc} is given in the following formula when L is lower than 10m:

$$U_{osc} = U_P \cdot \frac{L}{10}$$

When L is greater than 10m, the formula becomes of course:

$$U_{osc} = U_P$$

This simplified formula is usable for residual voltage estimation at the place of the equipment to protect when the power line is protected by a limiting type SPD.

4.2 - OSCILLATION PHENOMENON DEPENDING ON THE FRONT TIME OF THE IMPULSE VOLTAGE

We made an estimation of the front time when the power circuit is protected by a limiting type SPD such as a MOV. Figure 6 shows record of surge current and residual voltage on a SPD MOV based. The current was set at 5kA with a 8/20 wave shape and the front time of the residual voltage was measured.

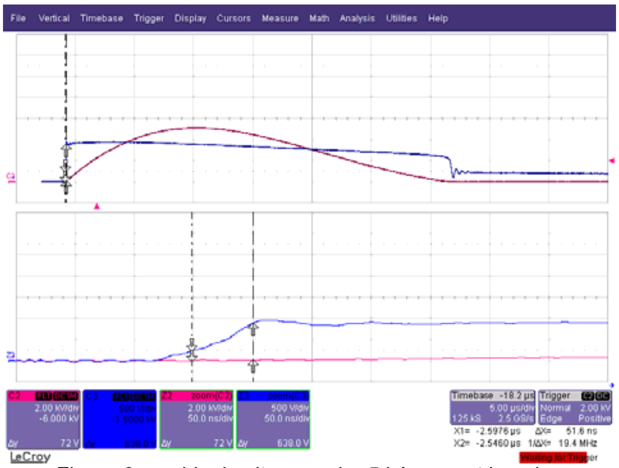


Figure 6 –residual voltage under 5 kA current impulse

Several measurements have been performed under different current values. See Table 2 for the results.

I	3	5	10	20	kA 8/20
Δu/Δt	13,06	12,36	16,90	20,27	kV/µs

Table 2 – front time .vs. magnitude of the surge

In this table we can notice a slight progression of the voltage variation with the maximum surge current. This is logical as the MOV time reaction is fast enough to follow the current rise and thus the residual voltage is depending on the current rise. The interesting point is that in a wide range of usual current rises, the front time of the pulse voltage stays in a range of 10 to 20 kV/µs.

In case of switching type SPD the front time is simply linked to the surge rise time with or without SPD and are linked to many parameters.

In addition 2 ports SPDs contain non linear components in order to decrease this front time and thus its value can be dropped down to a value much lower than the one usually measured with one port SPDs.

This leads us to consider several front time durations in order to analyze the front duration impact on the oscillation phenomenon.

Three rise times have been simulated on MOV based SPDs. The first time is set to 0,1 µs, the second to 1 µs and the last one to 10µs. These rise times correspond to a voltage variation to respectively 15 kV/µs, 1,5 kV/µs and 150 V/µs.

The circuit simulates a distance of 10m between the SPD location and the location of the device to protect (R=50mΩ, L=10mH and C=5nF))

The figures 7 to 9 shows simulations with the 3 different rises time and indicate the maximum value measured at the capacitor terminal U_{cmax}. The table 1 summaries the results of these 3 simulations and the last line of this table express the voltage rise in % of Up (Up=1,5kV).

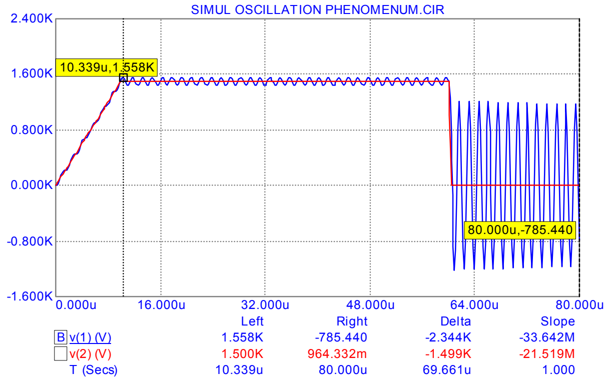


Figure 7 - R=50mΩ, L=10mH, C=5nF R and Δu/Δt=0,15kV/µs

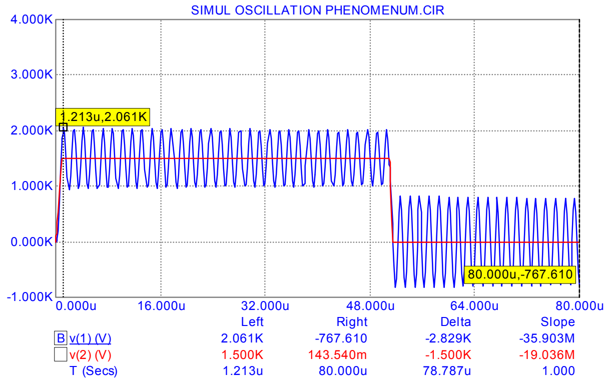


Figure 8 - R=50mΩ, L=10mH, C=5nF R and Δu/Δt=1,5kV/µs

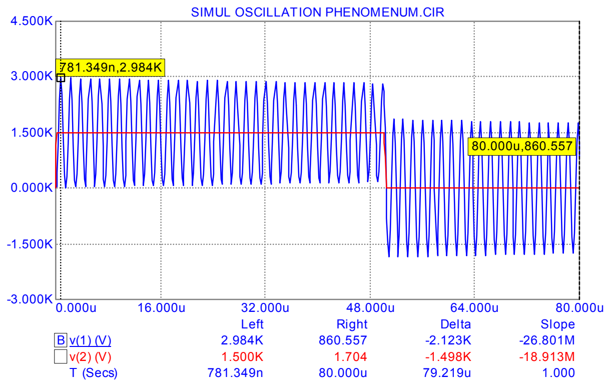


Figure 9 - R=50mΩ, L=10mH, C=5nF and Δu/Δt=15kV/µs

Value	Rise time from SPD			
Δu/Δt	0,15	1,5	15	kV/µs
Ucmax	1,56	2,06	2,98	kV
%	4%	37%	99%	%

Table 3 – Front time effect

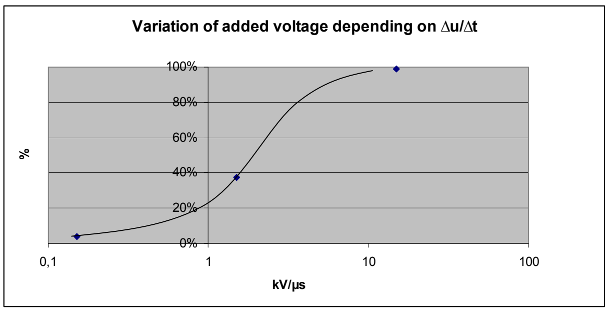


Figure 10 – U_{cmax} .vs. du/dt

From these simulations we can observe that the rise time of the voltage is a major characteristic to predict the overvoltage that the device will have to withstand without break down.
As well we can see that the simplified formula given in 4.1 is based on a voltage variation less than 3kV/µs. This is a bit optimistic considering the observation of the residual voltage under 8/20 wave shape current.

In case of slow rise time of the residual voltage provided by a 2 port SPD (150V/µs) even if the distance is as long as 50m, the voltage is far from to be doubled. But in this case, other effects can be taken in consideration depending on pure installation and field coupling effect
A 50m limit can be fixed for normal installation protected by 2 port SPDs and not using shielding solution.

4.4 - APPLICATION DEPENDING ON 1 PORT SPD CABLING AND TYPE OF EQUIPMENT

Combining the standard rules about the residual voltage created by the current flowing into the lead length, the simplified formulas defined in the previous parts of this paper we can make some calculation to estimate the protection distance of an SPD.

It is interesting to see the effect on the protection if the equipment to protect is a class 1 or class 2. As a reminder, class 1 equipment (or installation) means that there is only a functional insulation between active cable and ground and the envelope of this equipment is connected to the ground (PE) whereas, for the class2 equipment (or installation) the envelope is not connected to ground and all parts connected to active cables are under the double insulation concept.
When class 2 equipment is used, the dangerous voltage to not reach in between active cables and ground is set to 6kV. For the differential mode, it is the same as for class 1 equipment.

The following examples will consider the residual voltage between active cables themselves called differential mode protection (DM) and the residual voltage between active cable and ground., called common mode (CM).

The following assumptions are used.
ΔU = 1000V/m at the entrance SPD for one cable carrying the full lightning current. In our example, we selected 0,2m for the cable connecting the SPD to the ground. This conduct to add 200V to the protection voltage Up of the SPD.
ΔU = 1000V/m / n at the entrance SPD for ‘n’ cables sharing the current (depending on common mode or differential mode, calculation of ‘n’ may varies: n = number of Lines or n = number of Lines + Neutral). In our example, we consider only one phase and the neutral and we selected 0,2m for these 2 cables. This conduct to add 100V to the protection voltage for common mode and 200V for differential mode
Residual voltage can be gradually doubled from 0 to 10m as presented above: $U_{osc} = U_P \cdot \frac{L}{10}$

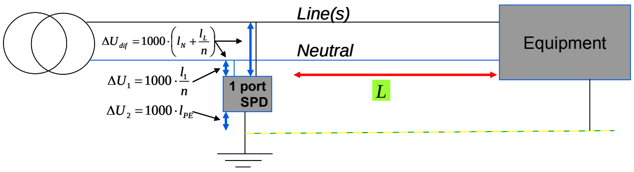
Cabling loops are considered as negligible (installation following SPD standard, electrical installation and lightning protection standard rules)

The SPDs are of limiting types with a Up equal to 1,2kV. The equipment is category II and this leads to consider 2,5 kV as the withstand voltage Uw.

The back up protection protecting the SPD in case of fast end of life is not considered in this paper but can be easily integrated in the calculation if the user knows its behavior under surge current condition.

A few examples were studied and only usual combinations are presented below.

- Example 1: 1 ports



Used Formulas for estimation of the overvoltage protection:

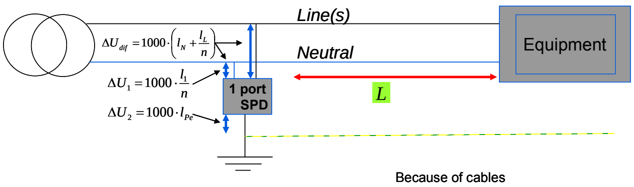
- For differential Mode (DM)

$$U_P + \Delta U_{dif} + U_{osc} \leq 2{,}5kV$$

- For Common Mode (CM)

$$U_P + \Delta U_1 + \Delta U_2 + U_{osc} \leq 2{,}5kV$$

- Example 2 : 1 ports + Class II Equipment (Insulated system)



Used Formulas for estimation of the overvoltage protection:

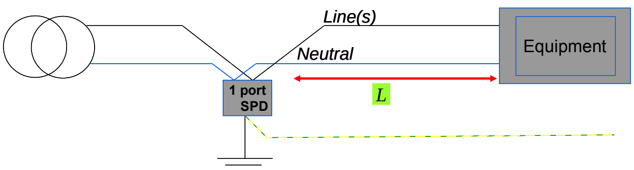
- For differential Mode (DM)

$$U_P + \Delta U_{dif} + U_{osc} \leq U_W$$

- For Common Mode (CM)

$$U_P + \Delta U_1 + \Delta U_2 + U_{osc} \leq 6kV$$

- Example 3 : 1 ports V wiring (L, N & PE) + Class 2 Equipment (Insulated system)



Used Formulas for estimation of the overvoltage protection:

- For differential Mode (DM)

$$U_P + U_{osc} \leq U_W$$

- For Common Mode (CM)

$$U_P + U_{osc} \leq 6kV$$

See in table 4 the result of the calculation using respective formulas.

Example	Mode	0	1	2	3	4	5	6	7	8	9	10
1	CM	1,80	1,95	2,10	2,25	2,40	2,55	2,70	2,85	3,00	3,15	3,30
	DM	1,90	2,05	2,20	2,35	2,50	2,65	2,80	2,95	3,10	3,25	3,40
2	CM	1,80	1,95	2,10	2,25	2,40	2,55	2,70	2,85	3,00	3,15	3,30
	DM	1,90	2,05	2,20	2,35	2,50	2,65	2,80	2,95	3,10	3,25	3,40
3	CM	1,50	1,65	1,80	1,95	2,10	2,25	2,40	2,55	2,70	2,85	3,00
	DM	1,50	1,65	1,80	1,95	2,10	2,25	2,40	2,55	2,70	2,85	3,00

Residual voltage at the equipment location depending of distance (in m)

Table 4 - Synthesis of the 3 examples for one port SPDs

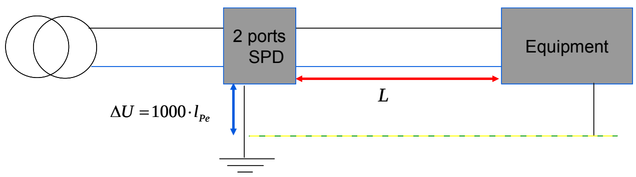
Considering the calculation it is obvious that the protective distance of a one port SPD can be considered as low. Even the V wiring which is more effective than usual wiring has a protection distance of less than 7 m (Up=1,5 and Uw=2,5)
It is interesting to see than the use of class II equipment gives a safe margin on the common mode protection but no effect on the differential mode of protection

4.5 - ADVANTAGES OF USING A TWO PORTS SPDs TO FACILITATE INSTALLATION RULES

With the exception of the increasing of the residual voltage because no oscillation phenomenon are possible, the assumptions and comments made in part 4.4 are identical.

Two examples are presented to highlight the benefit of using 2 ports SPDs.

- Example 1 : 2 ports



Used Formulas for estimation of the overvoltage protection:

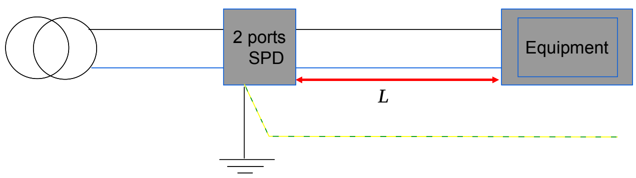
- For differential Mode (DM)

$$U_P \leq 2{,}5kV$$

- For Common Mode (CM)

$$U_P + \Delta U \leq 2{,}5kV$$

- Example 2 : 2 ports + Class 2 Equipment (Insulated system)



Used Formulas for estimation of the overvoltage protection:

- For differential Mode (DM)

$$U_P \leq 2{,}5kV$$

- For Common Mode (CM)

$$U_P \leq 6kV$$

Example	Mode	0	1	5	10	20	30	40	50
1	CM	1,70	1,70	1,70	1,70	1,70	1,70	1,70	1,70
	DM	1,70	1,70	1,70	1,70	1,70	1,70	1,70	1,70
2	CM	1,50	1,50	1,50	1,50	1,50	1,50	1,50	1,50
	DM	1,50	1,50	1,50	1,50	1,50	1,50	1,50	1,50

Residual voltage at the equipment location depending of distance (in m)

Table 5 - Synthesis of the 2 examples for two ports SPDs

Considering the calculation it is obvious that the protection distance of two ports has nothing to compare to one port SPD.
We have to point out that this result is linked to the hypothesis that the installation between the SPD and the equipment to protect is perfectly realized. As the protective distance if high this will lead to a higher risk of coupling effect able to create a dangerous overvoltage. But following the installation rules described in the various standards dealing with surge protection installation this can be avoided.
We recall as well the precaution rules consisting in limiting the protective distance to 50m.

Suggestion for consistency with the formula proposed for one port SPD. A second formula can be used to determine the added voltage to be considered in case of 2 port SPDs:

$$U_{osc} = U_P \cdot \frac{L}{50}$$

When L is greater than 50m, the formula becomes of course:

$$U_{osc} = U_P$$

In that case, the protective distance of the 2 ports SPDs is reduced but still much better than one port SPDs.
See the following graph comparing the one port examples and the 2 port SPDs with this last suggested formula.

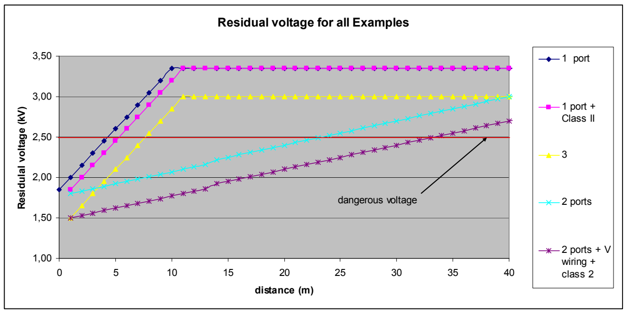


Figure 11 – comparison between one and two port SPDs

5 - CONCLUSIONS

The installation rules for SPDs are generally considering a 10 m distance between SPD and equipment to be protected as the limit above which the equipment is not properly selected. Calculations have shown that 10 m can be reduced to only a few meters depending on equipment type, SPD type and front of the wave. On the reverse, the two ports SPD, with their capability to reduce the steepness at the output of the SPD, are much more flexible regarding installations rules and in particular distance between SPD and equipment to be protected. For a time the 61643-11 draft standard has considered inclusion of a new parameter being the steepness of the wave at the output of the SPD. This is probably the right time to reconsider this proposal. In the mean time the distance between SPD and equipment to be protected can be extended between compared to a one port SPD.

6 - REFERENCES

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