International Symposium on Lightning Protection (XV SIPDA), São Paulo, Brazil, 30th September – 4th October 2019.

Coordinated Surge Protection System in a TT Wiring System: A Comprehensive Analysis of Performance

Chandima Gomes
School of Electrical and Information Engineering,
University of the Witwatersrand, 2050, Johannesburg,
South Africa
E-mail: chandima.gomes@wits.ac.za

Ashen Gomes
School of Electrical Engineering and Computer Science,
KTH, Royal Institute of Technology, Stockholm,
Sweden
E-mail: ashen.gomes@gmail.com

***Abstract*—This paper delineates that the protection provided by a system of coordinated surge protection devices (SPDs) in a low voltage TT wiring network strongly depends on many selection and installation parameters. The outcomes provide a comprehensive guidance for both the designers of protection systems and the end user to understand the realistic scenarios of protection. Two connection configurations and four cases of lightning transient interception have been considered. The information inferred from the analysis clearly shows that the efficiency of the SPDs, even if they are connected under zonal concept, will depend on site-specific factors such as wire lengths between SPDs at different zones and the wire length from the final set of SPDs to the load, resistance values of the neutral earth at the substation and the consumers' earth. The three line to neutral and neutral to earth configuration is preferred over the three lines and neutral to earth configuration. SPDs may or may not operate in the ascending order of their voltage protection level. The substation earth could significantly affect the probability of equipment damage or reduction of the SPD life-time at a consumer facility.**

Keywords—SPD, voltage protection level, impuse current, surge, impulse withstanding voltage

I. Introduction

Surge protective devices (SPDs) play a significant role in protecting equipment and systems from transient over voltages and over currents. However, due to the inability of checking the correctness of selection and installation of SPDs in a given low voltage (LV) network there are many cases where lightning protection providers have disappointed the protection seeker [1]. This is evident as there are many failures of surge protection systems of LV systems that have been reported in India, Sri Lanka and Malaysia (in South and South East Asia) where authors have personal experience as lightning protection consultants.

The installation and production/testing criteria of surge protective devices (SPDs) in low voltage power systems are well documented in many IEC Standards [2] – [7]. General issues that will be encountered by a design engineer of lightning surge protection systems and the rules of thumb to be used are detailed in several studies in the literature [8, 9]. Some system specific installation concerns of SPDs have been discussed in several other studies; Protection of solar photovoltaic systems [10, 11], railway systems [12, 13], naval systems [14] etc.

None of the above mentioned documents have made a comprehensive analysis on the operational criteria of SPDs in a coordinated arrangements that are recommended by the standards. Such information is vital for the analysis of the effectiveness of SPDs installed at a given LV network. This study is an attempt to analyze the response of an array of SPDs connected under zonal concept in the event of various lightning transient interception with the LV system. We considered only the TT wiring system in this case, which is mostly practiced in South and South East Asia.

In this paper, we use the term "operate" when an SPD transforms from high impedance mode (ideally open circuit) to low impedance mode (ideally short circuit).

II. Connection and Operation

The connection of SPDs may differ based on the low voltage wiring system practiced in a given country, region or installation. Therefore, it is important to discuss their operation with respect to the wiring system. Generally, there are four main LV wiring systems practiced in most countries; TT, TNS, TNC and TNCS. In this paper we only consider the TT wiring system where the neutral point of the secondary (star connection) of the transformer is earthed and a separate earth is provided at the subscribers premises.

A. 3LN + NE connection in a TT wiring system

Connection of each of the 3 phases or lines to neutral and the neutral to earth at each zone is typically denoted by 3LN + NE. Figure 1 shows this arrangement, however for the convenience of demonstration only a single phase to a single load is depicted in the diagram. The points A, B and C are far apart from one another thus the potential of one point does not influence that of the other. Point C is considered as the reference point where it is at zero potential at all times (i.e. $V1 = 0$).

We assume that

$x_1 = x_2 = x_9 = x_{10}$

Usually, as the cables of the wiring system runs together;

$\boldsymbol{x_3 = x_8 = x_{12}}$

$\boldsymbol{x_4 = x_7 = x_{11}}$

$x_5 = x_6$

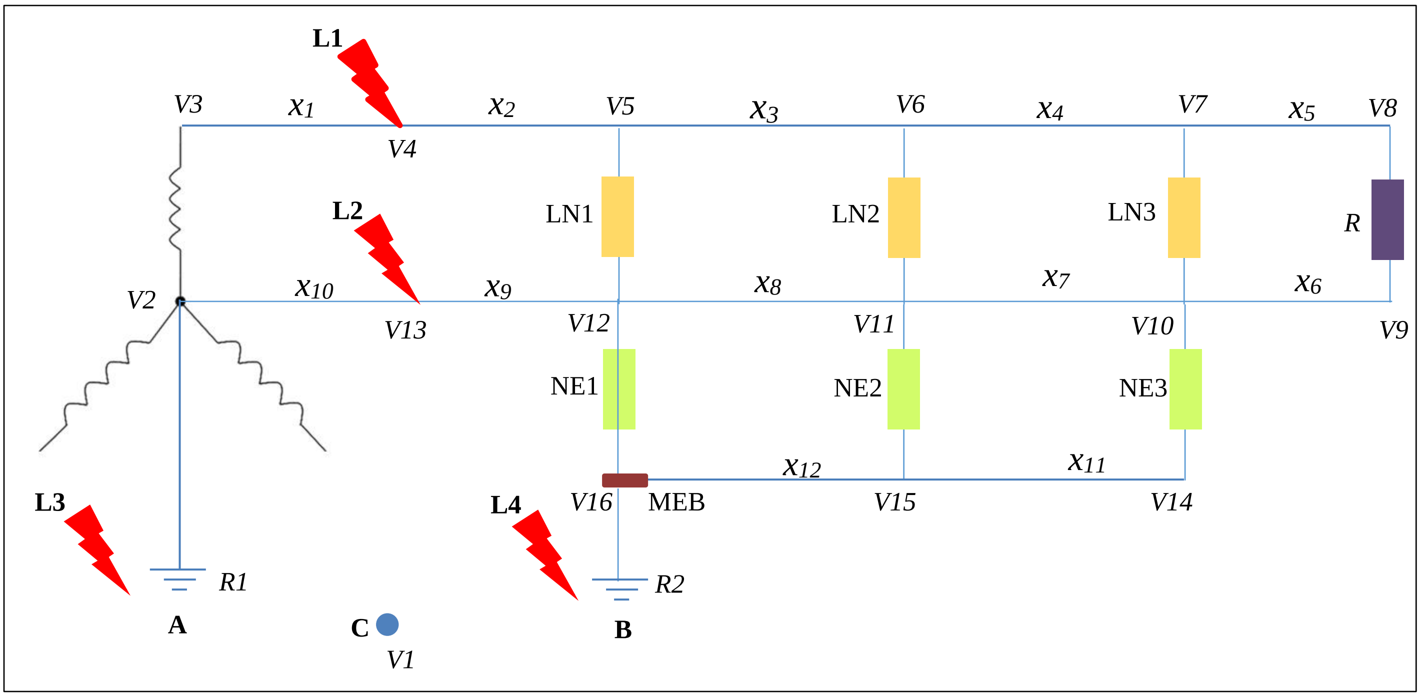

Figure 1. The 3LN + NE configuration of SPD connection in TT wiring system. MEB: main earth bar

Let's assume that the wiring system, made of copper, can deliver 50 A (rms) under operational frequency. Thus, the cross-section of the wires is approximately 6 mm^2.

Thus, the resistance per unit length (R') is calculated by

$$R = \frac{\rho\, l}{A}$$

$R' = 2.8 \times 10^{-3}$ [Ω/m]

Note that R' is the DC or low frequency resistance, which we assume to be applicable to the transient analysis as well.

The self-inductance per unit length (L') is calculated by

$$L = 2l\left\{\ln\left[\left(\frac{2l}{d}\right)\left(1+\sqrt{1+\left(\frac{d}{2l}\right)^2}\right)\right] - \sqrt{1+\left(\frac{d}{2l}\right)^2} + \frac{\mu}{4} + \left(\frac{d}{2l}\right)\right\}$$

$L' = 1.3 \times 10^{-6}$ [H/m]

In a TT wiring network there are four cases of coupling lightning energy into the system; strike to a line, the neutral, a point near the transformer earth and a point near the consumer's earth (Figure 1). In this paper we exclusively analyze the most complex case, i.e. striking a point on the line (labelled as L1) and explain the other cases qualitatively.

We adopted the Heidler function to represent the lightning current waveform. The functional parameters were set to obtain the 8/20 μs standard test current waveform *i(t)*, with an approximate peak value of 12.5 kA (Minimum current handling capacity specified in [3]). Figure 2 depicts this current waveform. Note that as we do not analyze the energy handling capacity of SPDs in this study, the selection of 8/20 μs waveform over 10/350 μs does not have any significant influence.

For the case of L1, we consider that initially, the total current flows through the load (no current across the transformer winding), due to the very high inductance of the winding.

In the presence of the impulse current *i(t)*, the voltage across a unit length of the wire is given by

$$v(t) = 2.8 \times 10^{-3} \times i(t) + 1.3 \times 10^{-6} \times \frac{di(t)}{dt}$$

Where *i(t)* is in A and *v(t)* is in V/m.

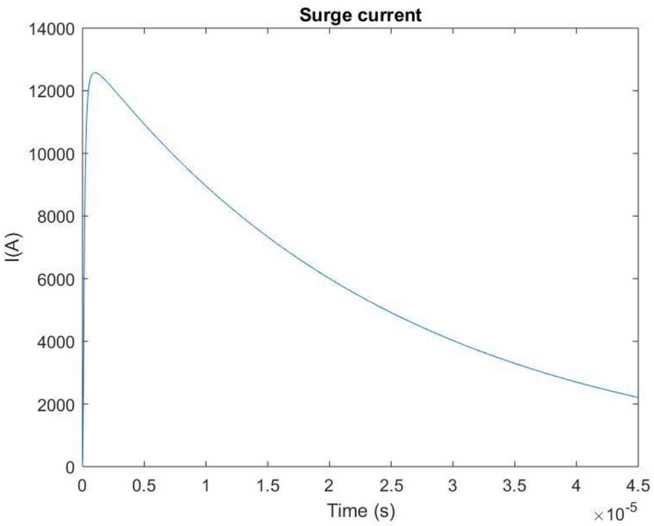

Figure 2. Current waveform generated by Heidler function

Figure 3 depicts the $v(t)$ waveform appear at any point in the line or neutral in the absence of SPDs or line/neutral to earth arcing.

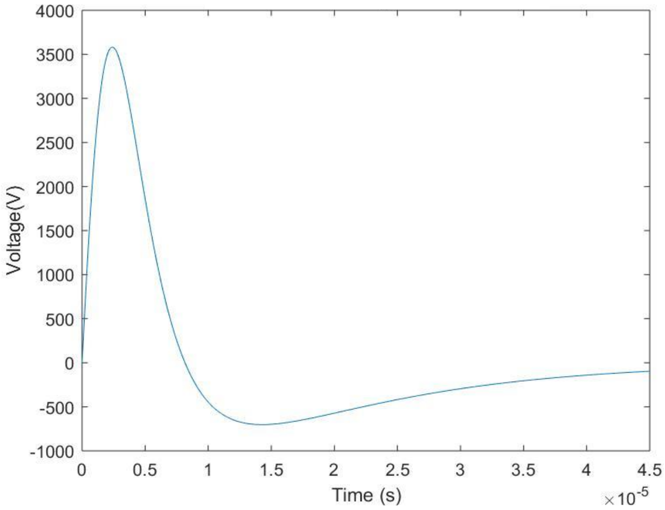

Figure 3. Voltage per unit wire length, $v(t)$.

Thus, the voltage at each point, along the wire could be given by the following equations, as the lightning current enters the wire,

$V2 = i(t)\,R1$

$V12 = V2 + v(t) \times x_9$

$V11 = V12 + v(t) \times x_8$

$V10 = V11 + v(t) \times x_7$

$V9 = V10 + v(t) \times x_6$

$V8 = V9 + i(t) \times R$

$V7 = V8 + v(t) \times x_5$

$V6 = V7 + v(t) \times x_4$

$V5 = V6 + v(t) \times x_3$

Figure 4 shows the potentials along the line and neutral in the absence of any of the SPDs. The following values have been considered in the calculations. Note that $R1$ is the total earth resistance up to the neutral point in the transformer (at which the potential is $V1$).

$R1 = 10\ \Omega$; $R = 20\ \Omega$.

$x_2 = 100$

$x_3 = x_4 = x_5 = x_6 = x_7 = x_8 = 10$ m

For any equipment to be protected by SPDs the impulse withstanding voltage (Uw) should be significantly higher than the lowest voltage protection level (Up) of the array of SPDs. In this analysis, we assume that each SPD starts operating when the voltage across it reaches its Up value.

For LN3 to operate, $(V7 - V10)$ should exceed Up of LN3 ($Up_{(LN3)}$); where $(V7 - V10) = v(t) \times 2 \times x_5 + (i(t) \times R)$. Therefore, the function of LN3 depends on both R and x_5.

In the presence of SPDs, for the load to be protected under transient condition, the voltage across the load, $(V8 - V9)$, should not exceed Uw of the load; where $(V8 - V9) = i(t) \times R$.

The let through voltage of LN3 (assumed to be the same as $Up_{(LN3)}$; i.e. assuming that the wire lengths from lines to the SPDs are zero); where

$(V7 - V10) = 2 \times x_5 \times v(t) + (V8 - V9)$.

As $(V8 - V9) < Uw$ for the protection of the load

$Up_{(\mathrm{LN3})} < Uw + (2 \times x5 \times v(t))$

Thus, the margin of protection of LN3 is effectively increased by a factor of $(2 \times x5 \times v(t))$. For an example if the Uw value of the load is 1 kV, then $(V8 - V9)$ should be clamped at a voltage less than 1 kV to protect the load. $(V8\text{-}V9)$ reaches 1 kV value approximately at 0.43 μs (Figure 5). At this time $v(t)$ is approximately 1.2 kV/m (extracted from the data set of Figure 3). Thus, if the SPD LN3 is installed 1 m away from the load, then theoretically, if $Up_{(\mathrm{LN3})} < 3.4$ kV, then the SPD can protect the load. The message to be emphasized here is that the required protection of the SPD could be delivered even if the Up is significantly higher than the Up value if the distance from the load to the SPD is at least a meter apart. However, it is customary to recommend a sizable margin between this critical value of Up and the actually selected value, due to the practical wire length between the line to the SPD if it is done through a "T" connection. However in a "V" connection, the voltage drop along this wire length from line to SPD could be treated as zero, thus no potential drop. This, scenario is applicable to the connection from the NE SPD to earth bar as well. The Figure 6 clearly depicts this scenario.

Figure 6(a) shows the T connection of wires. The distance $d2$ is negligible as the connection is done inside the SPD block itself. The distance d1 and d3 negatively affect the performance of $SPD_{(LN)}$ and $SPD_{(NE)}$ as they contribute in increasing the let-through voltage. The distance D positively affects the performance of SPDs as they allow a higher value for Up to get the same load protection. In the V connection (Figure 6(b)) the distances $d1$ and $d3$ becomes effectively zero.

For LN2 to operate; $(V6 - V11)$ should exceed $Up_{(LN2)}$; where $(V6 - V11) = v(t) \times 2 \times (x_5 + x_4) + i(t) \times R$

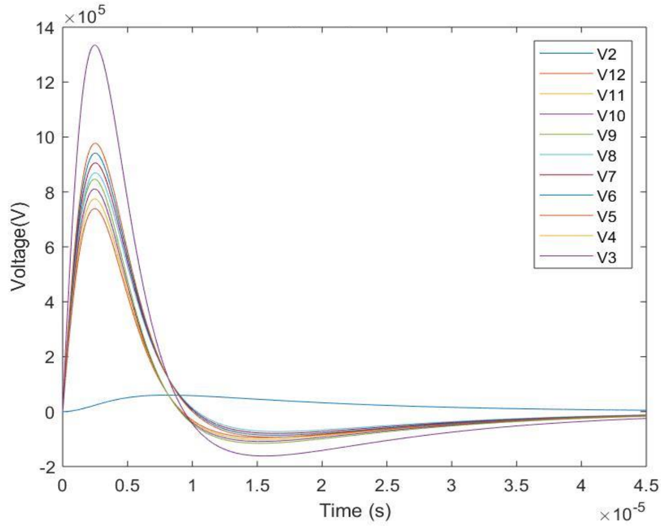

Figure 4. Voltage at various points in the current path

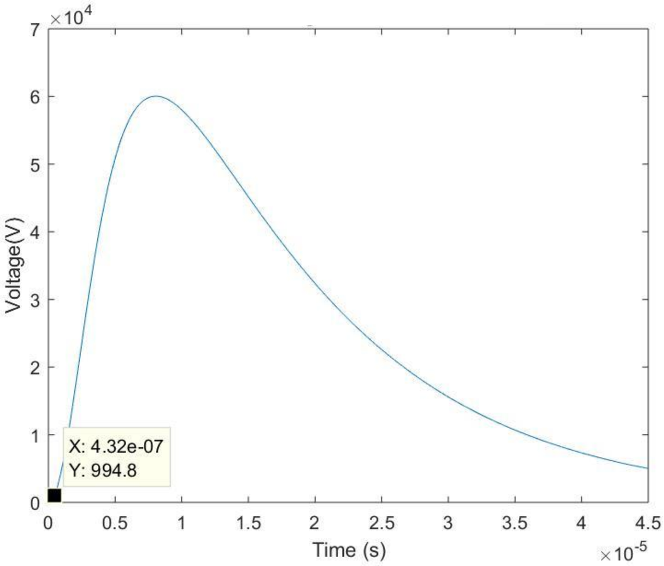

Figure 5. Voltage drop across the load *R*, *(V8-V9)*.

The trade-off between LN2 and LN3 depends apparently on x_4 and x_5. For a given current waveform, if x_4 exceeds a certain critical length, LN2 will operate before LN3, while protecting the load. Under this condition;

$(V6 - V11) > Up_{(LN2)}$ and

$(V7 - V10) < Up_{(LN3)}$

By the substitution of terms for the two expressions;

$v(t) \times 2 \times (x_5 + x_4) + i(t) \times R > Up_{(LN2)}$

$v(t) \times 2 \times x5 + i(t) \times R < Up_{(LN3)}$

By combining these expressions;

$Up_{(LN3)} + v(t) \times 2 \times (x_5 + x_4) + i(t) \times R < Up_{(LN2)} + v(t) \times 2 \times x_5 + i(t) \times R$

$Up_{(LN3)} + 2\, v(t)\, x_4 < Up_{(LN2)}$

$Up_{(LN2)} - Up_{(LN3)} < 2\, v(t)\, x_4$

$x_4 > [Up_{(LN2)} - Up_{(LN3)}] / 2\, v(t)$

Thus, which SPD will operate first depends on the tradeoff between x_4 value and the ratio between the difference of their *Up* values and twice the voltage gradient. Thus steeper the current wave front greater the *v(t)*, thus smaller the distance required between LN2 and LN3 to make the LN2 operate while LN3 remains non-operative.

Similarly LN1 to operate; *(V5-V6)* should exceed $Up_{(LN1)}$. It can be shown that at the critical value of x_3 LN1 will operate suppressing the operation of both LN3 and LN2 or either of them for a given voltage gradient and *Up* values.

It is quite interesting to analyze the potential rise at the point of strike at the wire (*V4*) and its effect on the transformer winding. The inductance of a transformer coil is quite high compared with the total impedance along a circuit with wires and resistive loads. Thus, it is highly improbable that initially the current flowing across the transformer winding. Thus, *V3 = V4.*

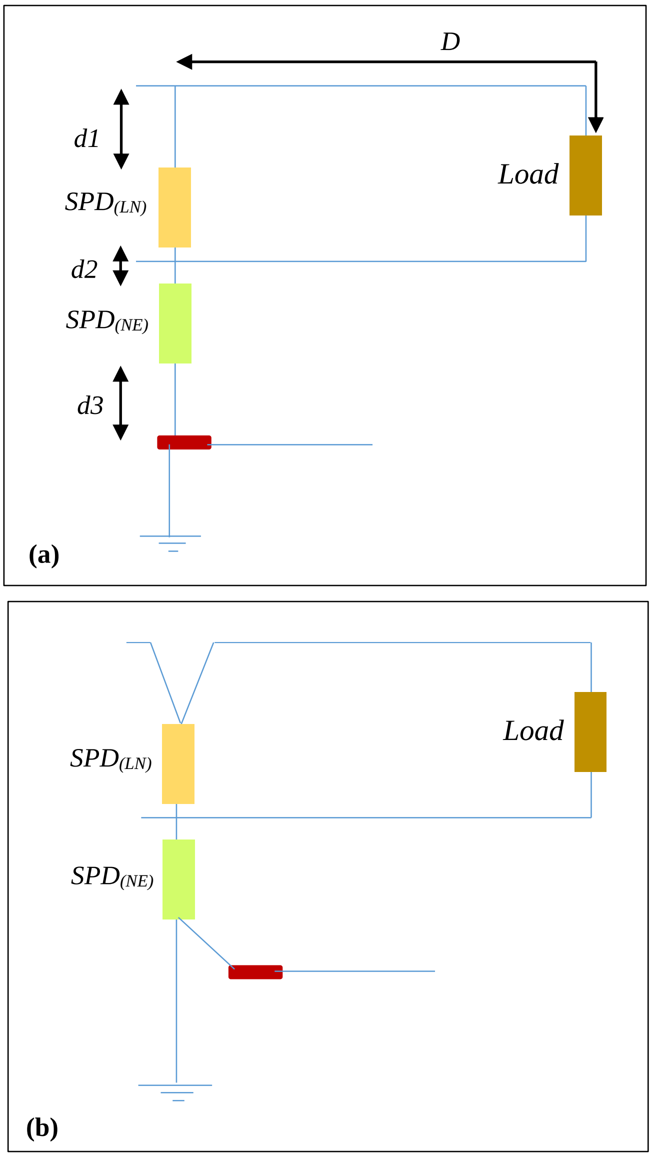

Figure 6. (a) T-connection of wires and (b) V connection of wires

As such, the voltage appearing across the winding is given by *(V4 – V2)*. In the absence of any operational SPDs this voltage may reach to a peak value about 1.3 MV (Figure 4) for the 12.5 kA peak current. If this voltage difference exceeds the insulation level, internal arcing will happen in the transformer either across the winding or from line to body. If LN1 operates, this voltage difference will drop to a load independent lower value given by (assuming that the total current flows through LN1)

$(V4 - V2) = Up_{(LN1)} + v(t) \times (x_2 + x_9 + x_{10})$.

When EN1 also operates, the voltage drop *(V4 – V2)* will drop even further as the current is now divided between the two earthing systems. The lower the resistance of the consumer's earth the lesser the voltage drop across the transformer winding. This implies that the installation of SPDs at consumer's end could lower the chances of having internal arcing in the substation.

The operation of the NEs depends on the voltage drop across the neutral wire with respect to the potential at the consumer's earth.

For NE3 to operate *(V10 – V14)* should exceed $Up_{(EN3)}$; where $(V10 – V14) = i(t) \times R1 + v(t) \times (x_9 + x_{10} + x_8 + x_7)$

Note that $V14 = 0$ as none of the NEs are in operation.

The fact that whether LNs or NE3 will operate first depends on many parameters such as the load, substation earth resistance and wire lengths. Even if NE3 operates first before LNs, one of the LNs will operate before the voltage across the load exceeds its line-to-neutral *Uw* value as per the discussion above.

If an LN operates first before the NE3, despite which LN it is, the first NE to operate (even if all NEs have the same *Up*) is NE3 (as *V10* is always larger than *V11* or *V12*).

While LN3 and NE3 are operating, if LN2 also starts operating, the current through LN2 also flows in to consumer's ground, first through the NE3, as it is already in operation (via wire length x_7). Then once *(V11-V15)* exceeds the $Up_{(NE2)}$, it will also starts operating. Similarly operation of NE1 also starts if the potential drop across that *(V12-V16)* is large enough to exceed $Up_{(NE1)}$.

In the case of lightning strike L2, the current will first flow into the substation earth (A), generating a potential rise at *V13* due to the substation earth resistance *R1* and the wire length x_{10}, where;

$$V13 = i(t) \times R1 + v(t) \times x_{10}$$

Thus *V13* strongly depends on the substation earthing system. This same potential will initially appear all along the wire in the load direction, right up to *V3* as there is no transient current ideally flowing in that direction. Thus, if *V13* exceeds $Up_{(NE3)}$, then it will start operating, sending a part of the lightning current into the consumer's earth at B. The division of current into the two earthing system depends on *R1* and *R2,* where R2 is the total earth resistance up to the MEB. If the substation earthing system is much poorer and that at the consumer's end ($R1 >> R2$), then a sizable current will flow into the consumer's earth stressing the operational NEs. Thus, in such case, if there are no SPDs at consumers end it is highly likely that neutral to earth arcing taking place at consumer's end (either at a panel or inside an equipment). Thus, in regions where TT wiring system is practiced it is strongly advised to keep a low earth resistance at the substation for the benefit of the consumers.

In the event of a lightning in the proximity of the transformer earth (L3), the outcome is similar to the lightning that strikes the neutral. In this case an earth potential rise (EPR) occurs at A where this potential appears all over the line up to *V3*. This potential rise depends on *R1*, the lightning current waveform (both profile and amplitude) and the proximity of lightning current injection point to the earthing system. The operation of NEs and arcing at consumer's end in the absence of SPDs occur similar to that in the case of lightning striking to the neutral. In this scenario too large value of *R1* results in larger EPR, which in turn drive more current into the consumer's earth.

A lightning in the proximity of consumer's earth (L4) results in the rise of potential at main earth bar similar to the case of lightning close to the substation earth. In this case too based on the value of potential *V16* the NEs will operate starting from NE3. In the absence of SPDs there is a possibility of arcing at the consumer's end (at a panel or equipment) that sends a current into the substation earth. In this case if ($R1 >> R2$) the current that flows into substation will be smaller, however, it creates a large step potential in the vicinity of the consumer's earthing system.

B. (3L+N)E connection in a TT wiring system

In this case, the 3 lines and the neutral are connected to the earth via SPDs (Figure 7). The IEC 62305-4 [7] approves both 3LN + NE and (3L+N)E for TT wiring system.

In this arrangement, in the case of L1, the voltage across LE3 becomes *(V7-V14)*. As $V14 = 0$ until one of the SPDs operates, $(V7-V14) = V7$; where

$$V7 = i(t) \times R1 + v(t) \times (x_{10} + x_9 + x_8 + x_7 + x_6 + x_5) + i(t) \times R$$

This value, which depends on substation earth, load and the wire lengths, will be higher than the voltage across NE3, *V10*, where;

$$V10 = i(t) \times R1 + v(t) \times (x_{10} + x_9 + x_8 + x_7)$$

Thus, LE3 will usually operates before NE3 if they have similar *Up* values. The operation of the LE3 alone could not guarantee the protection of the load as the let through voltage of LE3 and the voltage across the load *(V8-V9)* are not the same.

NE3 will operate if $(V10 – V14) > Up_{(NE3)}$.

However, *(V10-V14)* under the operation of LE3 depends on several parameters such as *R1, R2, R,* $Up_{(LE3)}$ and respective wire lengths. Thus it is not easy to develop a simple fixed set of coordination parameters to ensure the operation of NE3 at a particular time instant. In the event that NE3 operates the let through voltage that appears across the line and neutral of the load, *(V8-V9)* is given by

$$(V8\text{-}V9) = Up_{(LE3)} + Up_{(NE3)}$$

Thus in this case *(V8-V9)* will most often be twice as much as the let through voltage appearing across the line and neutral of the load in the case of 3LN + NE.

Similar arguments could be developed in the case of the operation of other LEs and NEs.

In the event of L2, L3 and L4, as well, the operation of the SPDs are somewhat different to the same cases in the 3LN + NE configuration.

In the events of lightning incident L2 or L3, either LE3 or NE3 will operate first if they are having different *Up* values (or due to the randomness of operation of the SPDs even if they have similar *Up* values). If LE3 operates before NE3 the current will flow across the load that could damage it.

If lightning incidence L4 occurs, we have a similar scenario as the earth potential rise at B may trigger the operation of LE3 or NE3 depending on their *Up* values and randomness of operation. Thus, if LE3 starts before NE3 the current will flow across the load.

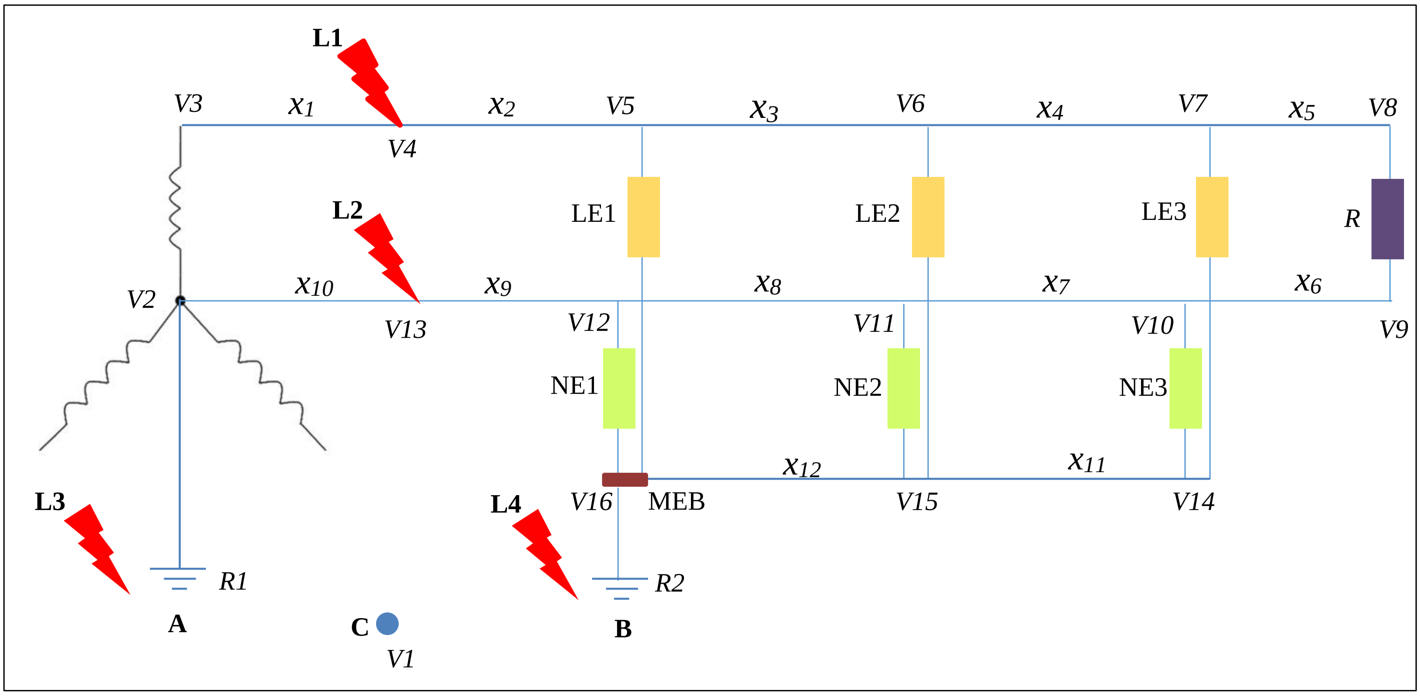

Figure 7. The (3LN + N)E configuration of SPD connection in TT wiring system

III. DISCUSSION

This paper delineates few important aspects of the selection and installation of SPDs in a low voltage wiring system that have been overlooked in the literature.

In the event of a lightning direct strike it is highly unlikely that the attachment process takes place with all four wires injecting equal current to each line. The most preferable attachment point in such case is the neutral wire as the streamer development through the transformer winding may be much slower than that across the neutral connection.

If the attachment process occurs at the neutral wire (L2), the total current will flow into the substation earth at the beginning raising the potential at the point of attachment in the neutral wire. The total lightning current may be much higher than the 12.5 kA peak value that we have considered in this study, thus, both EPR at A (*V2*) and *v(t)* will take proportionately higher values.

As this potential *V13* appear all over the neutral and line wires, one may expect arcing at the consumer's facility or across the transformer winding, in the absence of SPDs. However, the voltage across the transformer winding, *(V2-V13)*, which is equal to [v(t) × x_{10}] is lower than the voltage across the neutral and earth at the consumer's facility; which is equal to [$i(t) \times R1 + v(t) \times x_{10}$]. Most often the insulation level across a transformer winding is higher than the same between neutral and earth of consumer electrical goods, thus the arcing in the latter case is much more probable than that in the former case.

If the lightning hits a line by chance, then the initial current is most likely to flow entirely through the load. Now in the absence of SPDs arcing across transformer winding or across line/neutral to earth at consumer end is somewhat equally probable as the R1 does not come into play in either case. However, in this case too it should be noted that the total current in a lightning strike may significantly be higher than the 12.5 kA peak value that we have considered in this study.

It is also of interest to investigate the division of lightning current proposed in IEC 61643-12 [3]. In the event of lightning strike occurs at the external lightning protection system of the structure. This scenario is depicted in Figure 7. As per our earlier analysis, first, the total current will flow into the consumer's earth, where the EPR at B (potential at MEB, V_B) will rise depending on both *I* and *R2*. When V_B exceeds the *Up* value of NE, it starts operating driving a part of the current into the substation earthing giving rise to an EPR at A (V_A). The division of current between the two earthing systems depends on the ratio of *R1* and *R2*. Most often V_B will be large enough to operate the three Line-to-neutral SPDs. Thus, the potential across the winding will be ($V_B - V_A$). This potential difference which is equal to the *v(t)* × (wire length from main panel to neutral point), will be too low to drive a non-negligible current through the windings or to cause internal insulation breakdown. Thus, it is highly unlikely that any current flow through the Line to neutral SPDs. This scenario remains the same for (3L+N)E configuration as well. Thus, it is reasonable to assume that in all cases the NE SPD will be subjected to driving the total current in the event of transient EPR at the MEB due to any reason.

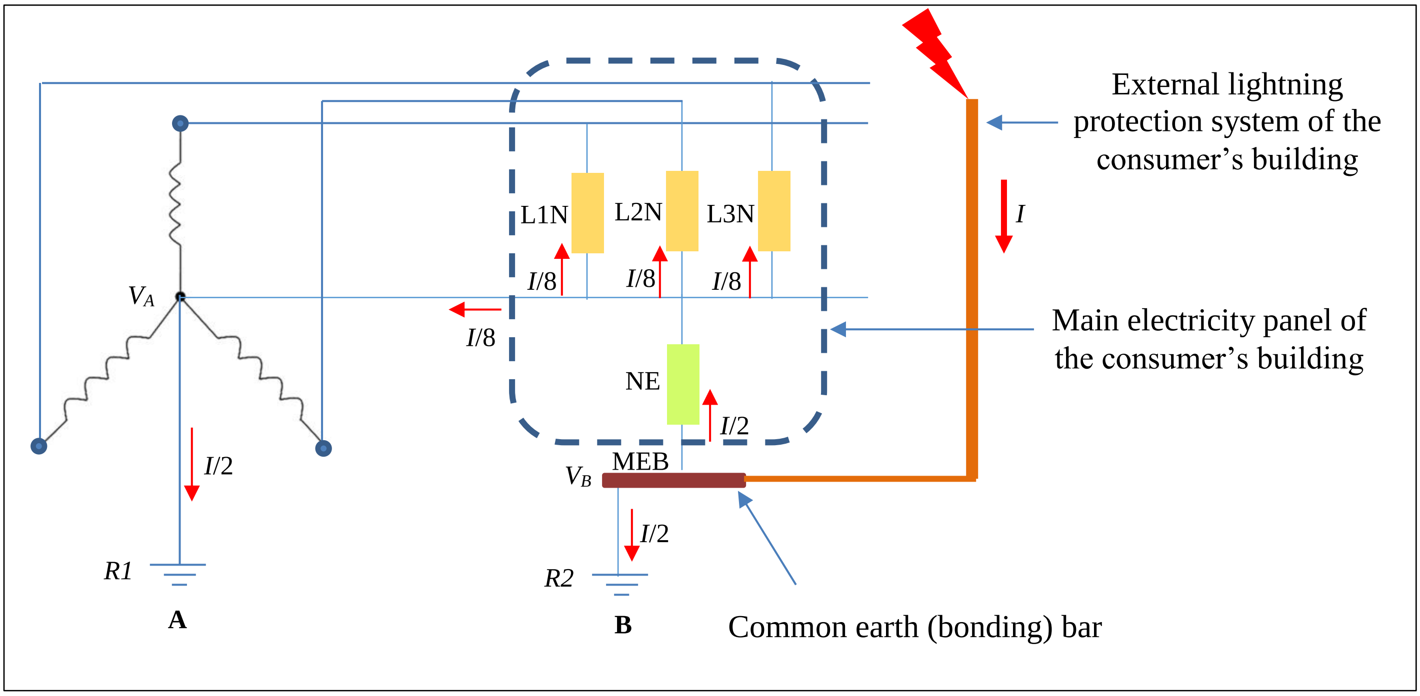

Figure 7. Current division among the consumer's earth and substation earth as per IEC 61643-12 [3].

IV. Conclussions

It is shown that there are many selection and installation concerns should be taken into account in a TT wiring system of a LV network to ensure the protection of the load. There are some specific outcomes of this study that should be highlighted as below

- In a TT wiring system, the 3LN + NE configuration has distinct advantageous over (3L+N)E configuration. In the latter case, it is not that feasible to assure the protection of the load, as the SPD operation depends on various site-specific parameters.
- It is not always possible to ensure that SPDS will operate in the ascending order of their Up values. The operation strongly depends on the inter SPD wire lengths.
- The substation earth plays a significant role in the safety of equipment at a consumer facility, where there is no surge protection. In the event of large substation earth resistance, arcing may occur at consumer's power panels or equipment if lightning strikes to line, neutral or in the vicinity of substation earth. The situation may be worse in such cases if the consumer's earth resistance is very low.
- High substation earth resistance, also results SPDs at consumer end being stressed excessively, reducing their life-time.
- An EPR at MEB of the consumer's end will drive a large current through the NE SPD irrespective of the configuration of connection. The current that flows in this case depends on *R1* and *R2*.

Acknowledgment

Authors would like to thank ESKOM Power Plant Institute (EPPEI)-HVAC, School of Electrical and Information Engineering, University of Witwatersrand, South Africa and School of Electrical Engineering and Computer Science, KTH, Royal Institute of Technology, Stockholm, Sweden for the facilities and funding rendered for this study.

References

[1] C. Gomes and M. Z. A. Ab. Kadir Lightning Protection: Getting it Wrong, IEEE Technology and Society Magazine (selected as the cover page article), Summer-2011, Volume 30, Issue 2, pp 12-21, 2011.

[2] IEC 61643-11- Low-voltage surge protective devices - Part 11: Surge protective devices connected to low-voltage power systems - Requirements and test methods, 2011.

[3] IEC 61643-12, Low-voltage surge protective devices - Part 12: Surge protective devices connected to low-voltage power distribution systems - Selection and application principles, 2008

[4] IEC 61643-21, CSV Consolidated version - Low voltage surge pr.otective devices - Part 21: Surge protective devices connected to telecommunications and signalling networks - Performance requirements and testing methods, 2000.

[5] IEC 61643-22, Low-voltage surge protective devices - Part 22: Surge protective devices connected to telecommunications and signalling networks - Selection and application principles, 2015.

[6] IEC 61643-311, Low-voltage surge protective devices – Part 1: Surge protective devices connected to low-voltage power distribution systems – Requirements and tests, 2005.

[7] IEC 62305-4, Protection against lightning – Part 4: Electrical and electronic systems within structures, 2010.

[8] V. Milardic, I. Uglesic, and I. Pavic, Selection of Surge Protective Devices for Low-Voltage Systems Connected to Overhead Line, IEEE Transactions on Power Delivery 25(3):1530 – 1537, 2010.

[9] C. Gomes, On the selection and installation of surge protection devices in a TT wiring system for equipment and human safety, Safety Science, Vol. 49, 861–870, 2011.

[10] Z. Mohammed, H. Hizam, and C. Gomes, Analysis of Lightning Transient Effects on Hybrid Renewable Energy Sources, 34th International Conference on Lightning Protection (ICLP), Rzeszow, Poland, September, 2018

[11] Z. Mohammed, H. Hizam, C. Gomes, Lightning Strike Impacts on Hybrid Photovoltaic-Wind Systems, Indonesian Journal of Electrical Engineering and Computer Science, Vol 8, No 1,115-121, December 2017

[12] M. A. Dehcheshmeh, S. H. Hosseinian, M. H. Bigharaz, K. Mohseni, Analysis of lightning transient in 2 × 25 kV AC autotransformer traction system, International Journal of Power and Energy Conversion 9(1):89, 2018 DOI: 10.1504/IJPEC.2018.088268

[13] B. Richter, Overvoltage protection concept for DC railway systems, Journal of Electrostatics, Volume 65, Issues 5–6, May 2007, Pages 356-362

[14] Gomes, C. and, Ab. Kadir, Z.A.A., Protection of naval systems against electromagnetic effects due to lightning, Progress in Electromagnetics Research, 113, 2011, 333-349.