Good Day!

This is a picture of a telecom engineer In London in the 1920s, installing a cable on a support wire 😟

PEG PROTECTION ENGINEERS GROUP

atis

The effects Ground Potential Rise (GPR) in a suburban environment

Created by the late Al Martin

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Story…

In 2011 the Japanese telecom NTT had a problem. About 0.05% of their ONT/HGW boxes were failing due to insulation breakdown. Now 0.05% doesn't sound like much, but with 15 million installed devices, that amounted to 7500 units per year. An investigation showed that the 0.05% failure rate corresponded to a 7.7 kV surge, so what could cause voltages of that amplitude?

So what's a suburban environment?

Well by suburban environment I mean one in which there are many structures, but not really close together, as they might be in an urban environment.

In this situation the interconnects might be a path for insulation breakdown. What follows explains why.

Start with a story…

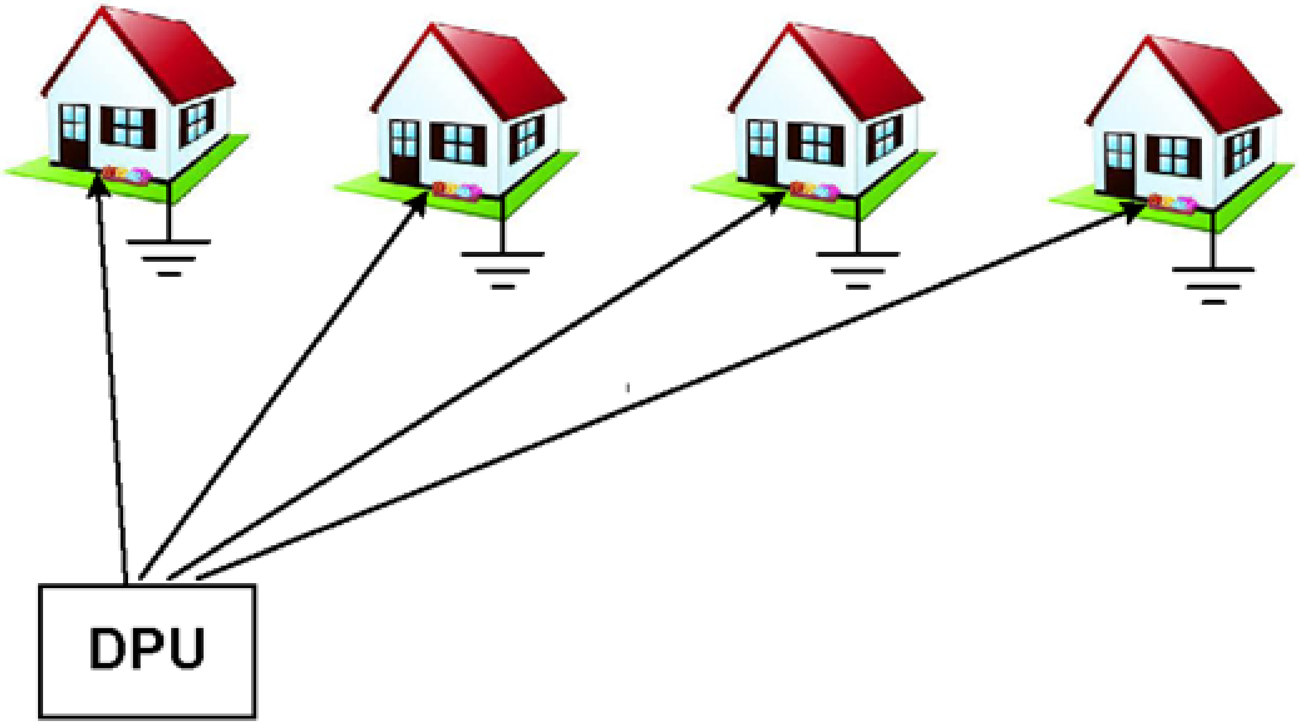
Story…

In 2011 the Japanese telecom NTT had a problem. About 0.05% of their ONT/HGW boxes were failing due to insulation breakdown. Now 0.05% doesn't sound like much, but with 15 million installed devices, that amounted to 7500 units per year. An investigation showed that the 0.05% failure rate corresponded to a 7.7 kV surge, so what could cause voltages of that amplitude?

Well a good candidate is GPR (Ground Potential Rise). Generally when we think about GPR we think about single structures with multiple grounds, as was the case in the NTT study. But what if the multiple grounds are not in a single structure but in multiple structures with a mutual connection, as might exist in a suburban environment?

For example, the next slide shows several structures all connected to a Distribution Point Unit (DPU), such as a fiber-to-the curb unit connected to the structures with a coax, a shielded twisted pair or an unshielded twisted pair.

Networked structures to distribution power point



Assuming no overvoltage protection, what we want to know is whether in this multiple structure environment, equipment failures could be caused by insulation breakdown due to GPR caused by lightning.

One way do that is to model the various possibilities, and see what results come out.

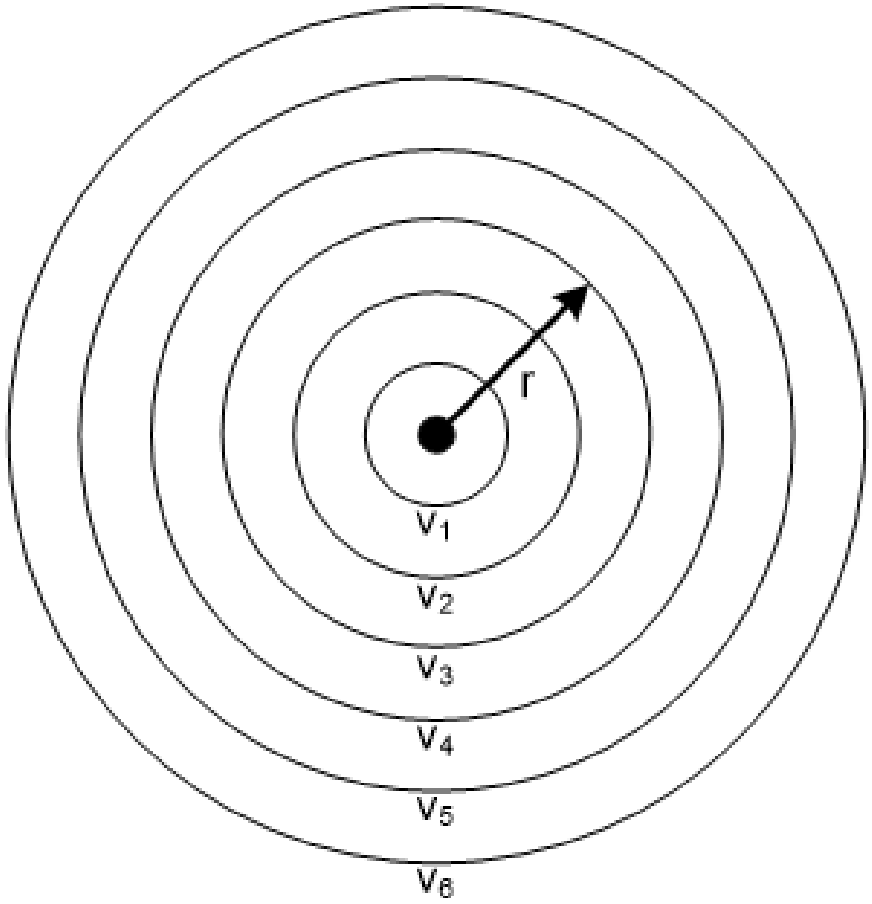
Let’s begin with a bit of a review…

Review

In a uniform earth a lightning strike creates a series of equipotential surfaces according to the relation,

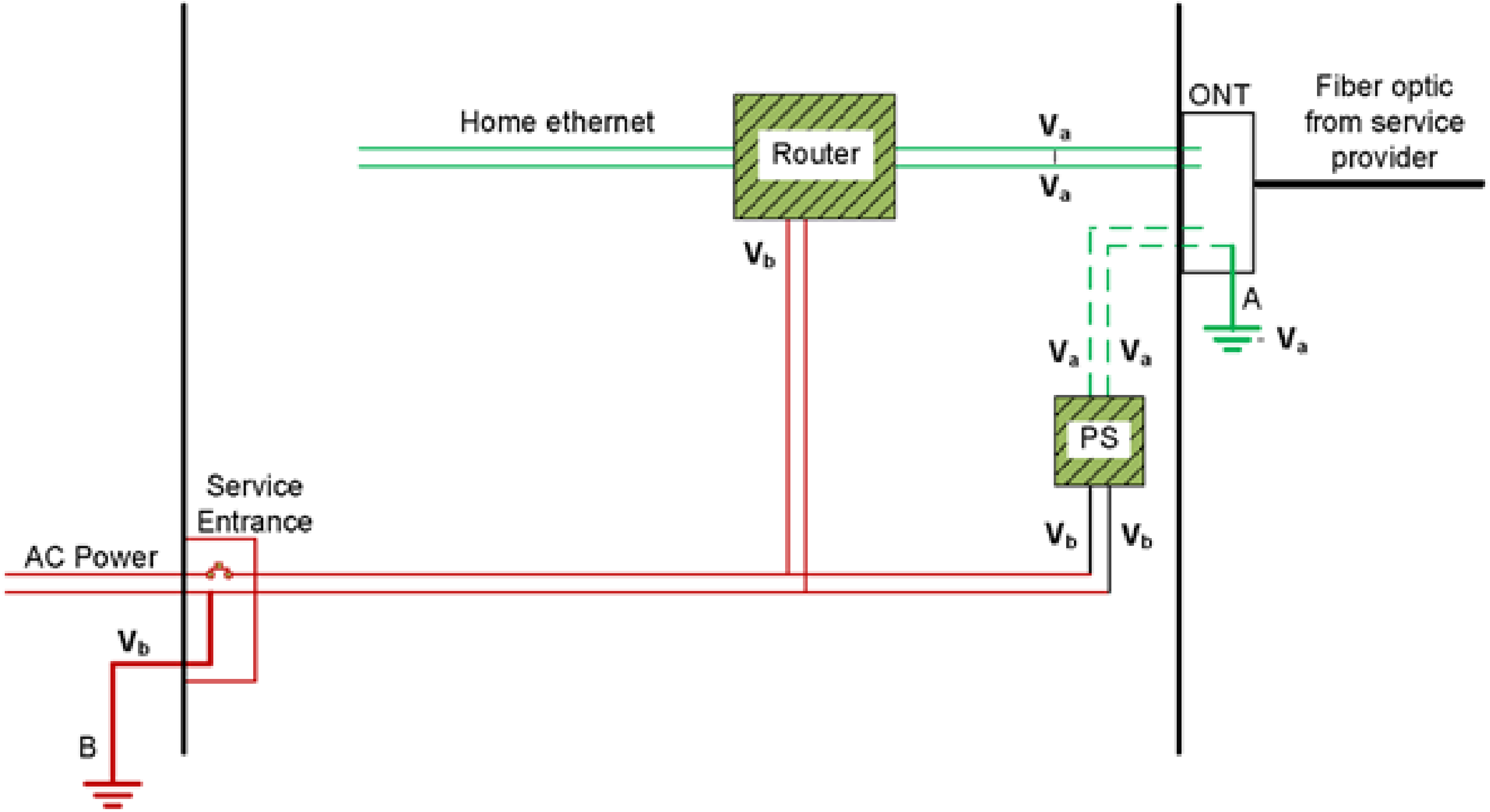
$$GPR = \frac{\rho I}{2\pi r}$$

Where ρ is the ground resistivity, I is the lightning current, and r is the distance from the lightning strike.

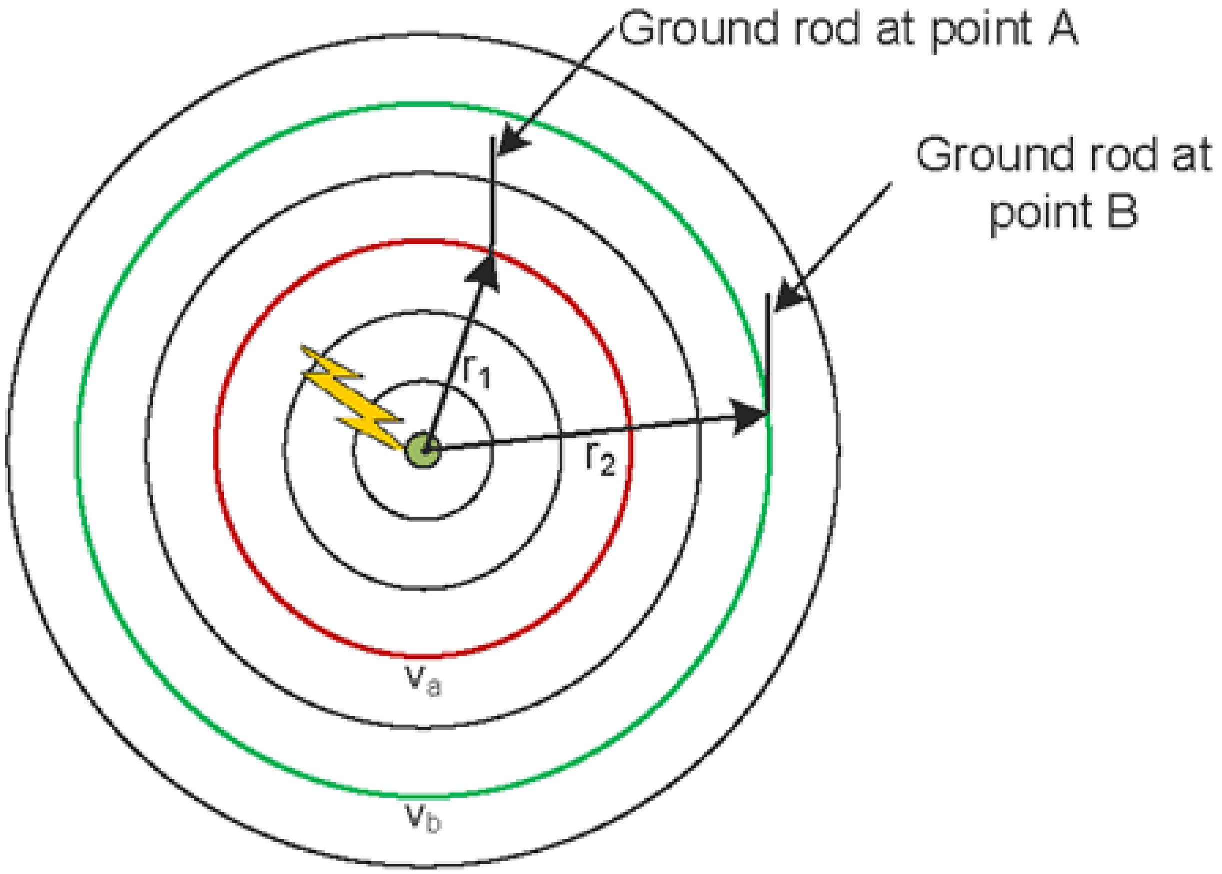


In the uniform earth case, GPR plots like this. The plot shows a series of equipotential surfaces of decreasing voltage ($V_1 > V_2 > V_3$, etc.)

In the classical GPR case, we have a structure with two or more separated grounds (one at point A and one at point B), and wired possibly like this:



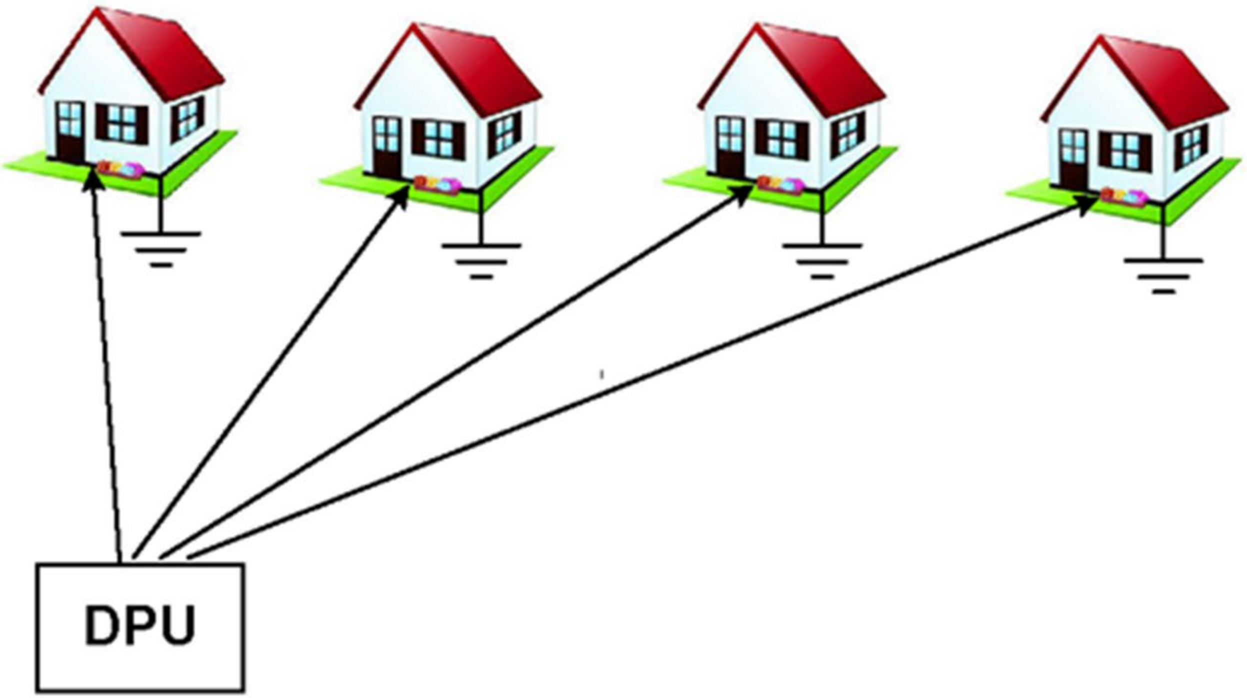
The grounding points A and B could be located on a set of lightning-induced equipotential surfaces like this



From the GPR analysis we know that the voltage at point A > the voltage at point B, so there is a potential difference between the ground rod at point A and the ground rod at point B. This means that equipment grounded at point A can be at a different voltage than equipment grounded at point B. If the voltage difference is big enough, insulation breakdown and possibly destructive current flow can occur.

So let's see how this applies to multiple structures in a suburban environment

Back to this picture:



Assuming that all the structures in the last slide are grounded, there are four cases to consider:

- Case 1: Where the DPU and the structures are grounded and connected by a coax or shielded-twisted pair
- Case 2 where the DPU and the structures are grounded and connected by an unshielded twisted pair;
- Case 3 where the DPU is not grounded, but is connected to the structures with a coax or shielded-twisted pair;
- Case 4 where the DPU is not grounded and the structures are connected to the DPU with unshielded twisted pairs.

The question is whether lightning-caused GPR can damage equipment in any or all of the four cases.

Case 1: The DPU and the structures are grounded and connected by a coax or shielded-twisted pair, as illustrated the in the next slide, when there is only one structure connected to the DPU

Rg_1 is the ground resistance between the lightning strike point and the nearest ground rod (r_1)

Rg_2 is the ground resistance between the farthest ground rod and infinity (r_2)

Zr_1 is the impedance of the nearest ground rod

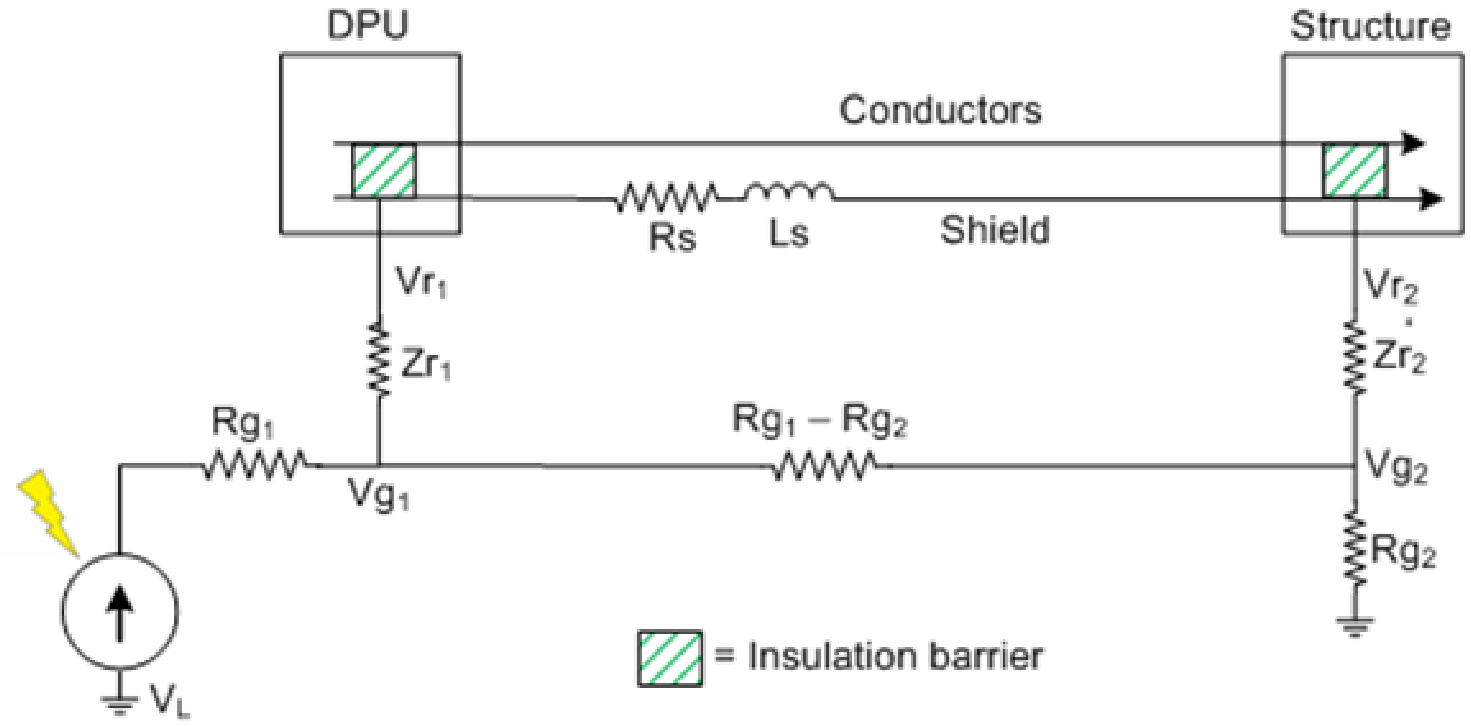
Zr_2 is the impedance of the farthest ground rod

R_S is the resistance of the shield

L_S is the inductance of the shield

Vr_1 is the voltage across the nearest ground rod

Vr_2 is the voltage across the farthest ground rod



There are a lot of variables here, one being the separation of the structures. Let's consider two cases: One where the DPU and the Structure are separated by 30 m, and one where the Structure and the DPU are separated by 300 m.

Some assumptions:

1. The lightning flash is 50 m from the DPU.
2. An RG6U coax is the connection between the DPU and the structure (except as noted),
3. A uniform ground of resistivity ρ of 400 ohm-m (about average, according to MIL-HDBK-419).
4. An 8 foot 5/8 inch diameter ground rod
5. No overvoltge protection is installed either at the DPU or at the structures

The ground rod impedance Zr for calculating peak voltage was given In the 2021 PEG meeting [2] as

$$Z_r = \frac{A\rho\left[arcsin\left(\frac{2s}{d}\right)\right]}{180\pi s}\left[ln\left(\frac{4s}{a}\right) - 1\right] \qquad (1)$$

Where s is the length of the ground rod and d is the distance from the lightning strike to the ground rod. From Grcev [3]:

$$A = \alpha s + \beta \qquad (2)$$

$$\alpha = 0.025 + exp[-0.82(\rho \cdot T_1)^{0.257}] \qquad (3)$$

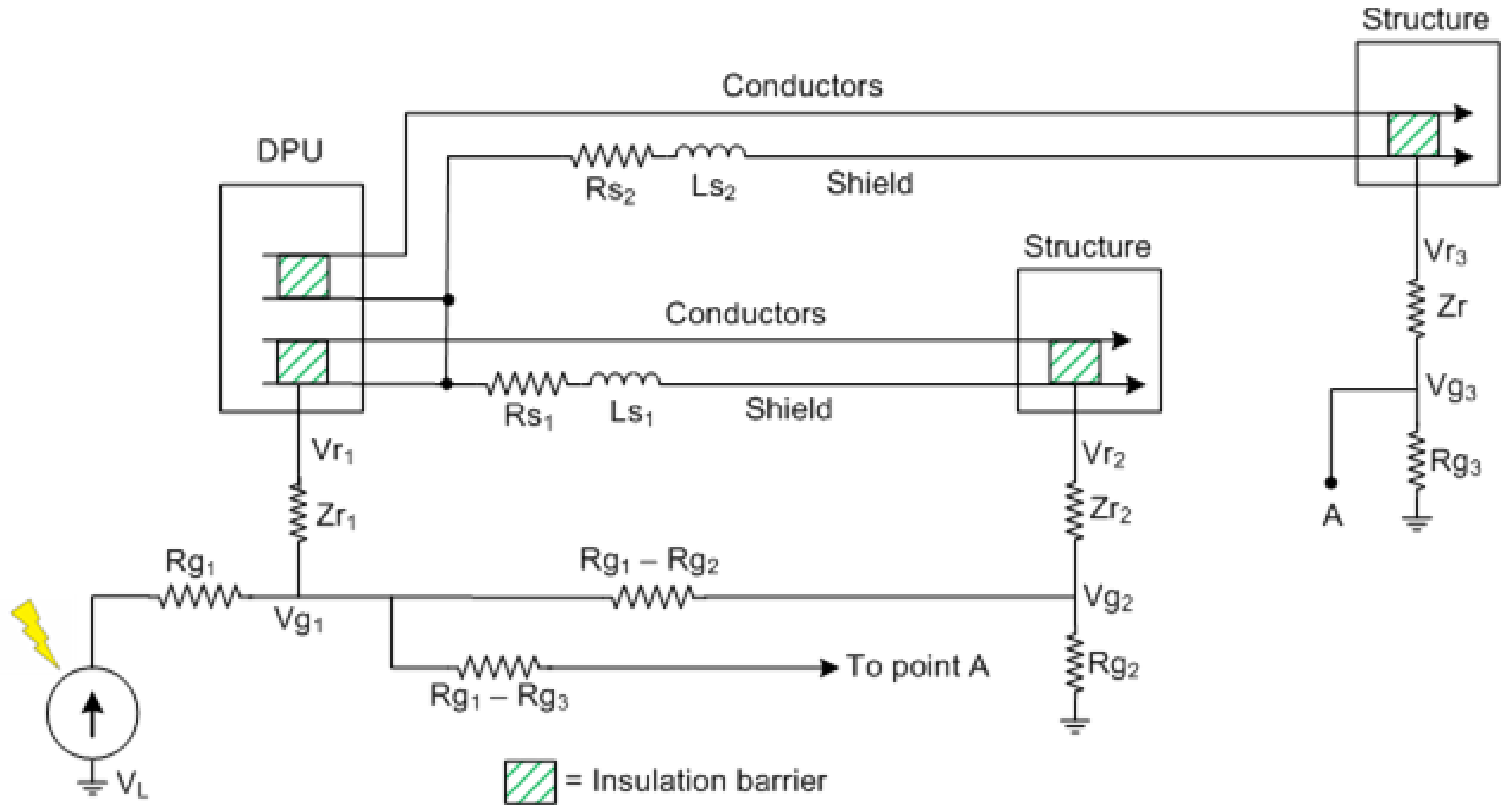
$$\beta = 0.17 + exp[-0.22(\rho \cdot T_1)^{0.555}] \qquad (4)$$

Assume a 4.5/75 median lightning surge from CIGRE TB549. Based on all the assumptions, the table at right shows the values for the elements in the figure for Case 1. The peak voltage difference $Vr_1 - Vr_2$ is between the DPU and the structure

For a median strike, TB549 table 3.5 shows a lightning current of 30 kA. So from this table, for 30 m separation between the DPU and the Structure, $Vr_1 - Vr_2$ = 17 kV; and for 300 m separation, $Vr_1 - Vr_2$ = 60 kV.

Element	30 m	300 m
Rs	0.25 ohms	2.5 ohms
Ls	53.4 µH	673 µH
Rg_1	2.52 ohms	
Rg_2	1.58 ohms	0.36 ohms
Zr1	2.5	
Zr2	1.56	0.36
$Rg_1 - Rg_2$	0.94 ohms	2.16 ohms
$Vr_1 - Vr_2$	0.56 kV/kA	2.0 kV/kA
I_{shield}	153 A/kA	108 A/kA
I_{ground}	890 A/kA	964 A/kA

Now suppose another structure is added with a connection to the DPU. Assume the connection is basically the same as that as previously shown. The result is shown here:



For simplicity, use the same assumptions as were made in the previous calculation. Take one connection to be 30 m, and the other to be 300 m. This table shows the values for the elements and the results of the calculation:

Element	30 m	300 m
Rs	0.25 ohms	2.5 ohms
Ls	53.4uH	673 uH
Rg_1	2.52 ohms	
Rg_2	1.58 ohms	0.36 ohms
Zr1	2.5	
Zr2	1.56	0.36
$Rg_1 - Rg_2$	0.94 ohms	2.16 ohms
$Vr_1 - Vr_2$	0.27 kV/kA	0.89 kV/kA
I_{shield}	68 A/kA	52 A/kA
I_{ground}	500 A/kA	493 A/kA

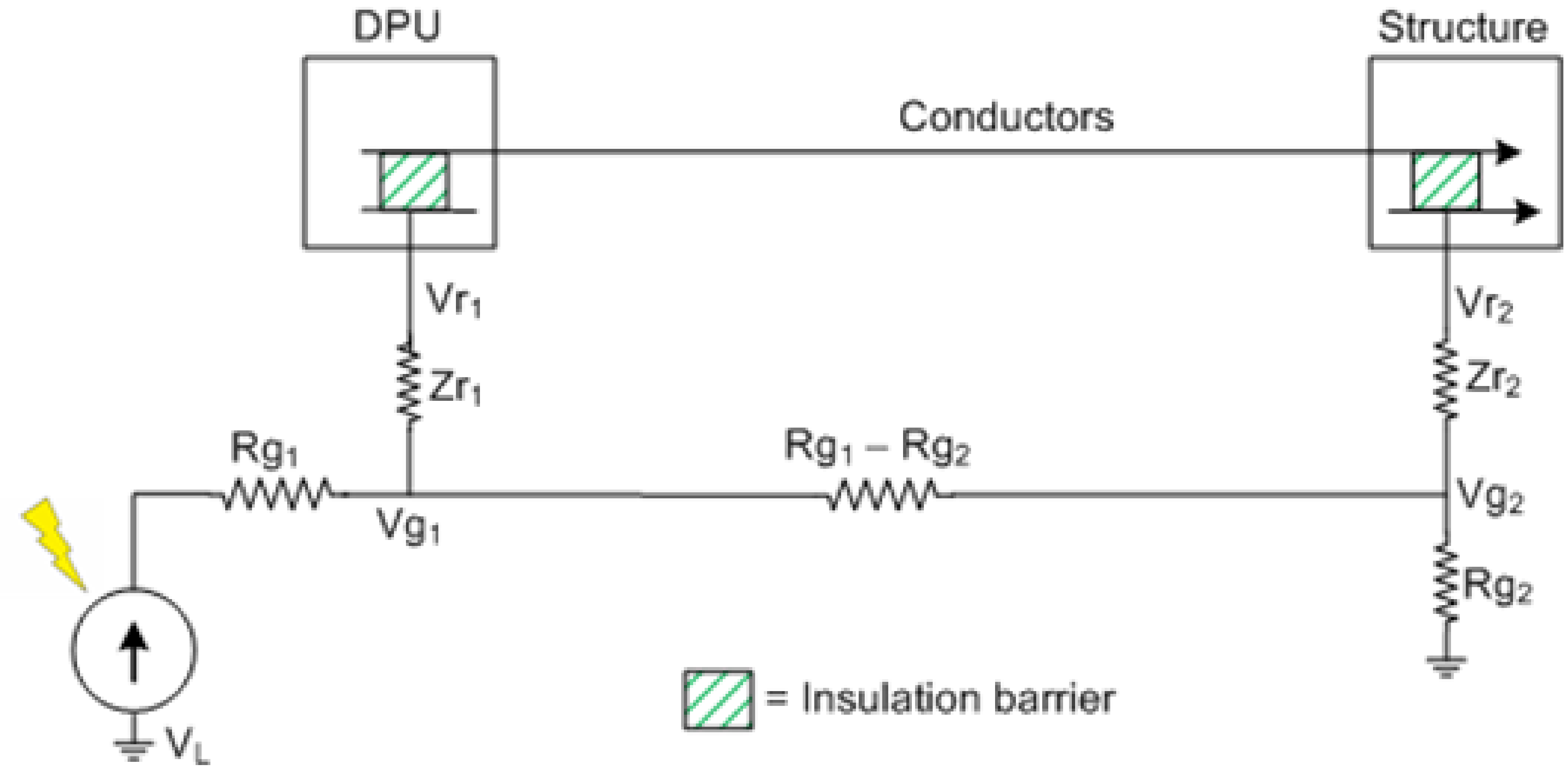
As before, calculate $Vr_1 - Vr_2$ using a 30 kA surge to get 8 kV for the 30 m connection, and 27 kV for the 300 m connection. These voltages are roughly half those associated with the single-wire calculation. The reason is that the surge current is divided between two ground paths of roughly the same impedance.

As the number of ground paths increases, the $Vr_1 - Vr_2$ differences diminishes approximately by the number of ground paths. The $Vr_1 - Vr_2$ differences also depend somewhat on the geometry of the additional structures. For example, for one 30 m connection and two 300 m connections, $Vr_1 - Vr_2$ = 5.1 kV for the 30 m connection, and 17 kV for the 300 m connections. For two 30 m connections and one 300 m connections, $Vr_1 - Vr_2$ = 4.8 kV for the 30 m connection, and 17 kV for the 300 m connection.

Case 2: The DPU unit and the structures are grounded and have an unshielded connection

This case is similar to that shown in figure for the single wire with a shield, except that the connecting cable either never had a shield (e.g. for a TWP), or it did have one, but the ground connection was interrupted due, for example, to corrosion or the shield being destroyed by a previous lightning strike

So Case 2 looks like this:



Using the previous assumptions, This table can be constructed for Case 2.

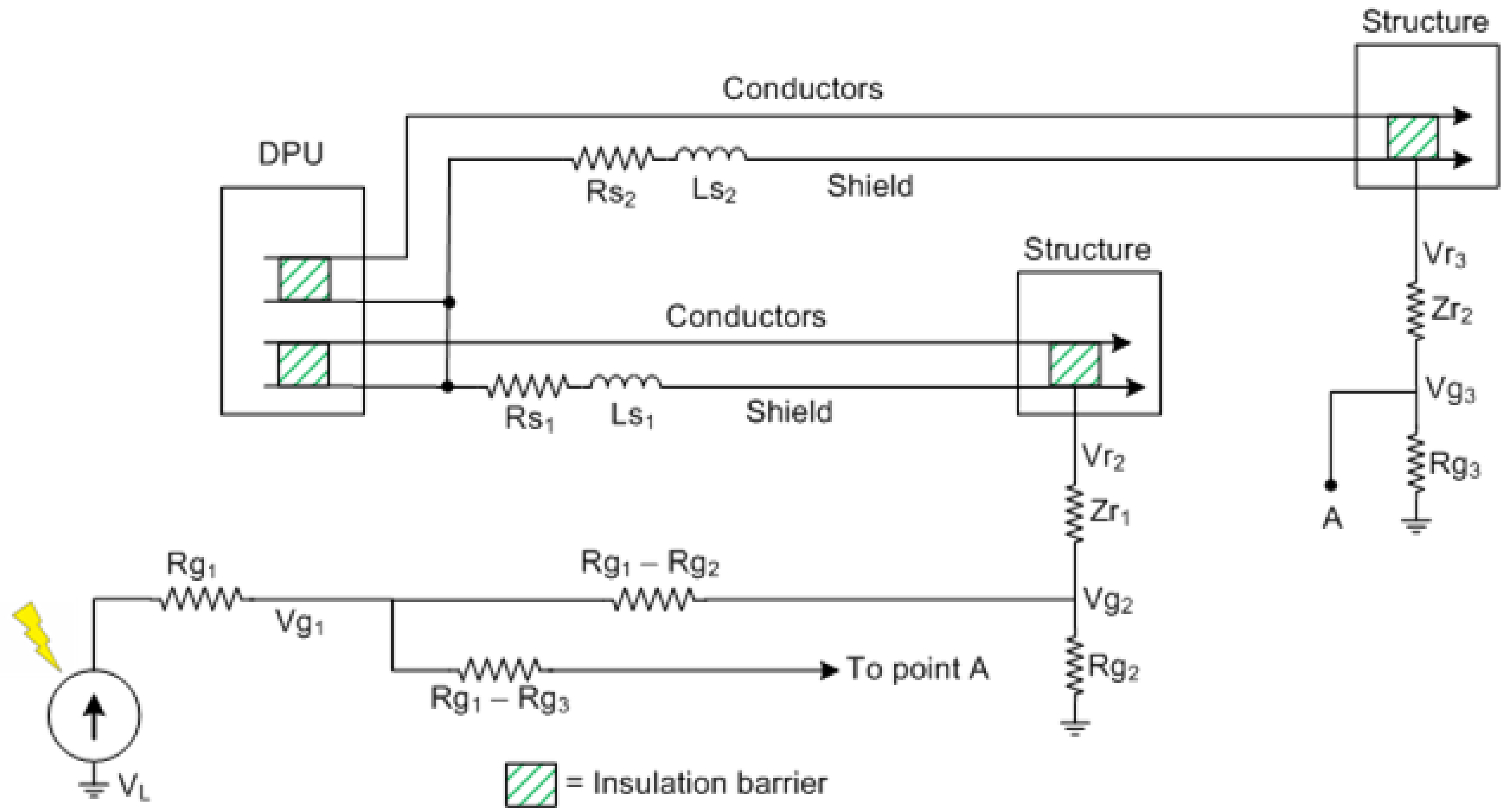
Element	30 m	300 m
Rg_1	0.25 ohms	
Rg_2	1.58 ohms	0.36 ohms
Zr1	2.5	
Zr2	1.56	0.36
$Rg_1 - Rg_2$	0.94 ohms	2.16 ohms
$Vr_1 - Vr_2$	0.94 kV/kA	2.16 kV/kA
I_{ground}	1000 A/kA	

For 30 m separation between the DPU and the Structure and a 30 kA lightning strike, $Vr_1 - Vr_2$ = 28 kV; and for 300 m separation, $Vr_1 - Vr_2$ = 65 kV.

If there are N equal connections from the DPU to a structure, $Vr_1 - Vr_2$ is the value in the table on the previous slide divided by N.

Case 3: The DPU is not grounded, but has a shielded connection to the structures

This case is similar to that shown in Case 1, except that there is no ground at the DPU.



Again using the previous assumptions, this table can be constructed for Case 3.

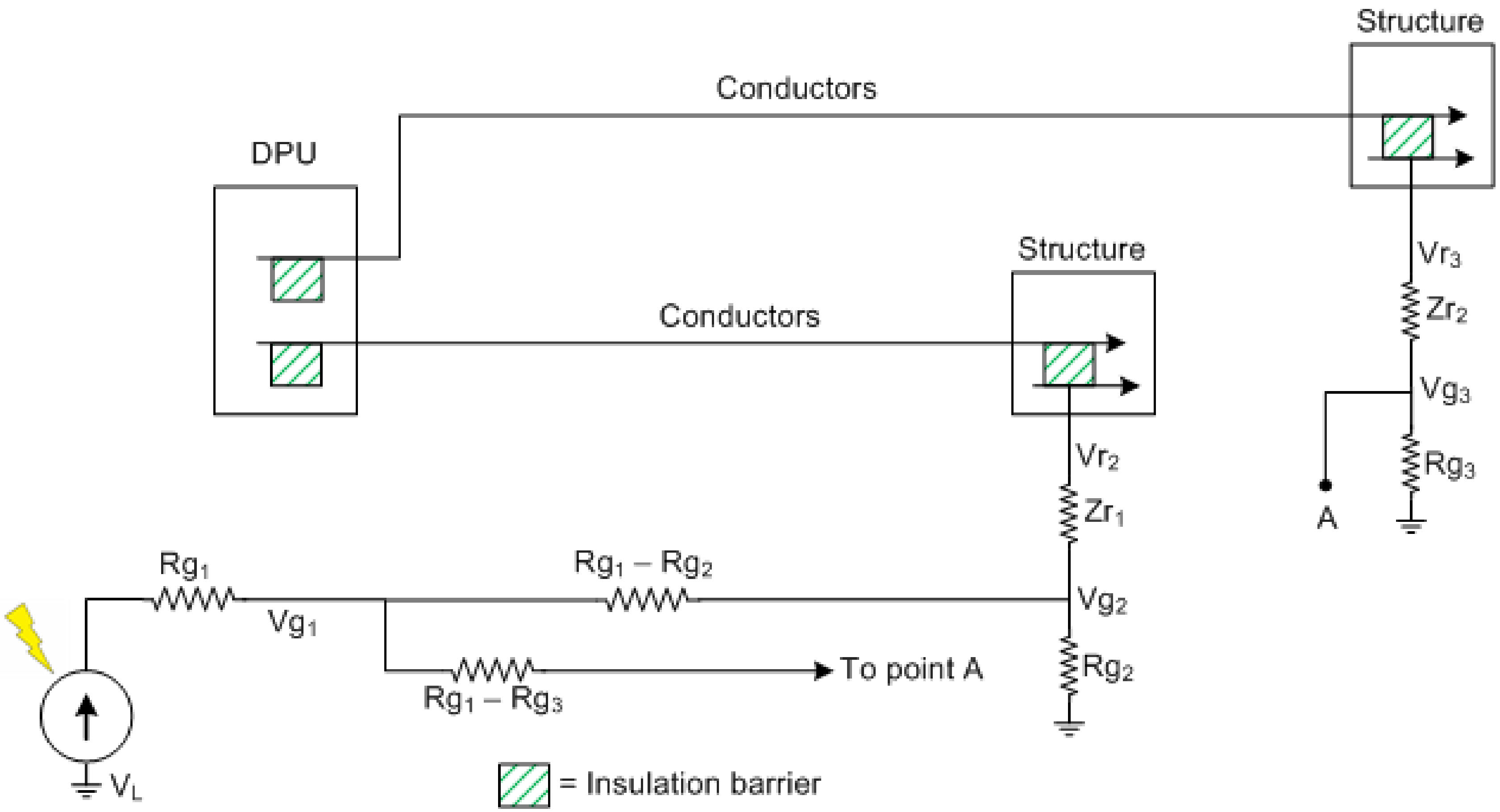
For a 30 kA lightning strike and either a 30 m separation between the DPU and the Structure or a 300 m separation, $Vr_1 - Vr_2$ = 17 kV. *In this case, $Vr_1 - Vr_2$ is the voltage difference between structures.*

If there are N equal connections from the DPU to a structure, $Vr_1 - Vr_2$ is the value in Table 4 divided by N.

Element	30 m	300 m
Rs	0.25 ohms	2.5 ohms
Ls	53.4uH	673 uH
Rg_1	0.25 ohms	
Rg_2	1.58 ohms	0.36 ohms
Zr1	2.5	
Zr2	1.56	0.36
$Rg_1 - Rg_2$	0.94 ohms	2.16 ohms
$Vr_1 - Vr_2$	0.58 kV/kA	
I_{shield}	35 A/kA	
I_{ground}	500 A/kA	493 A/kA

Case 4: The DPU is not grounded, and has an unshielded connection to structures

This case is similar to that shown for Case 1, except that the connecting cable either never had a shield (e.g. for a TWP), or it did have one, but the ground connection was interrupted due, for example, to corrosion or the shield being destroyed by a previous lightning strike


Structure
Conductors
DPU
Structure
Conductors
Vr3
Zr2
Vg3
Rg3
A
Vr2
Zr1
Rg1
Rg1 – Rg2
Vg1
Vg2
To point A
Rg2
Rg1 – Rg3
VL
= Insulation barrier

From the assumptions used in previous cases and a 30 kA lightning strike, for either a 30 m separation between the DPU and the Structure or a 300 m separation, $Vr_1 - Vr_2$ = 18 kV. Also In this case, $Vr_1 - Vr_2$ is the voltage difference between structures.

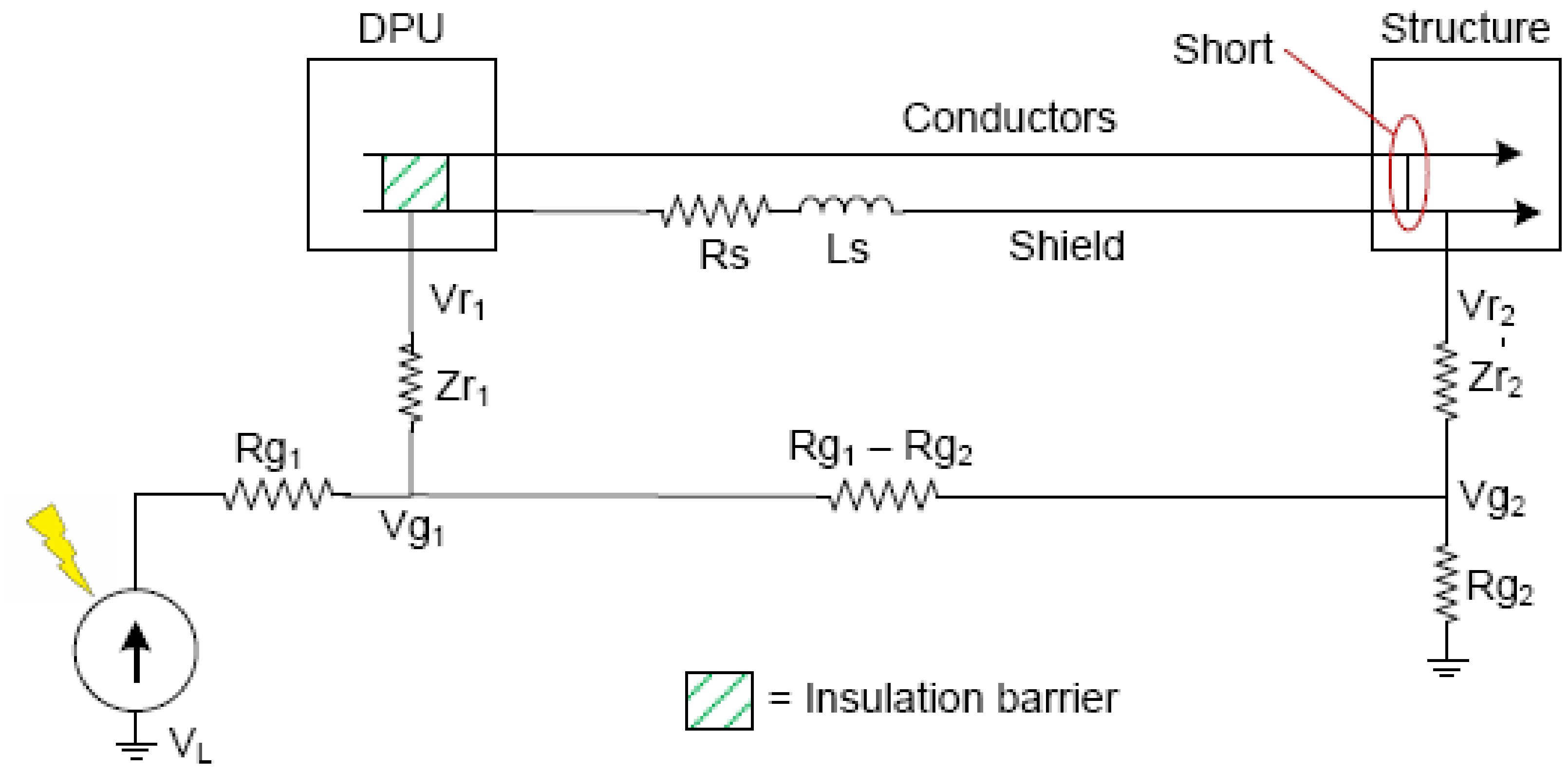
Values for the elements in Case 4 are shown is this table:

Element	30 m	300 m
Rg_1	0.25 ohms	
Rg_2	1.58 ohms	0.36 ohms
Zr1	2.5	
Zr2	1.56	0.36
$Rg_1 - Rg_2$	0.94 ohms	2.16 ohms
$Vr_1 - Vr_2$	0.61 kV/kA	
I_{ground}	497 A/kA	497 A/kA

Overvoltage protection installed at the structures, but not at the DPU

Now suppose overvoltage protection has been installed at the structures, but not at the DPU. Further, assume the overvoltage protection has been activated. That effectively shorts out the insulation barrier at the structure.

When that happens, the figure for Case 1 becomes that shown on the next slide


DPU
Short
Structure
Conductors
Rs
Ls
Shield
Vr1
Zr1
Rg1
Rg1 – Rg2
Vg1
Vr2
Zr2
Vg2
Rg2
VL
= Insulation barrier

The shorting of the insulation barrier as shown in the previous slide doesn't change the voltage calculations.

What does change is that in the previous case with no overvoltage protection at the structures, two insulation barriers have to be broken down to cause a system voltage withstand failure; whereas with overvoltage protection at the structures, only the insulation barrier at the DPU has to be broken down.

These observations were made for Case 1, but the same is true for Cases 2, 3 and 4.

Overvoltage protection installed at both the structures and the DPU

Assuming that the lightning surge activates both the protection at the structures and the DPU, no system voltage breakdown will happen. But now the $Vr_1 - Vr_2$ difference can drive a large current through the wires and shield (if present).

What happens in this case requires a different model, since other aspects of the system now need to be taken into account, and I^2t damage is now potentially the problem.

Results and discussion

Summarizing the results in the first four cases discussed, based on the assumptions made, the breakdown voltage $Vr_1 – Vr_2$ ranges from 17 kV to 65 kV for a single connection. The results are consistent with those reported by Pretorius' study of large electrode systems [4]. For N connections, the breakdown voltage is the single connection case divided by N. The results were for median values of the variables, and could be more or less depending on the assumptions made and the configuration of the connections.

So will breakdown happen? Like much in surge protection, the answer is "it depends"; and it depends first of all on what an acceptable failure rate is. The issue was cast this way by the NTT study of network equipment failure, where an 0.05% failure rate caused 7500 total failures, which was too much to be acceptable.

Considering the NTT results, mitigating failure due to insulation breakdown in equipment without overvoltage protection would likely require insulation barriers to exceed 7 kV; because if they are less the equipment failure rate would probably be unacceptable.

If there is no overvoltage protection installed at the structures or the DPU, then the two insulation barriers shown in Case 1 are in series, so both must break down for failure to occur. If we assume that an acceptable failure rate requires a single insulation barrier to withstand 7 kV, then a $Vr_1 - Vr_2$ of at least 14 kV needs to occur for failure to happen. Things that could diminish the ability of an insulation barrier to withstand 14 kV include the 2 kV rated capacitor in the ethernet Bob Smith termination, and inadequate creepages and clearances [6].

If overvoltage protection has been installed at the structures but not the DPU, then only the insulation barrier at the DPU has to break down for failure to occur. In this case a $Vr_1 - Vr_2$ of 7 kV or more could cause insulation breakdown failure.

Similarly, if the overvoltage protection is at the DPU but not the structures, then a $Vr_1 - Vr_2$ of 7 kV or more could cause insulation breakdown at the structures.

If overvoltage protection is installed at both the structures and the DPU, system voltage breakdown is not likely.

In this case the issue is I^2t damage due to GPR-driven current. Estimating that would require a new model based on the details of how the system was configured, and that's another project.

Mitigation

One way to mitigate overvoltage damage is to install overvoltage protection. However doing that might actually make the problem worse [7]. A better approach might be to increase the voltage withstand of insulation barriers, where possible by installing an appropriately-rated isolation transformer. This approach was done successfully by NTT [8].

Summary

We began by asking whether equipment without overvoltage protection in a multiple structure environment could fail due to insulation breakdown from GPR caused by lightning, when the multiple structures have a mutual connection, as might be the case in a suburban environment. To help answer the question, calculations were done, based on a model of structures in that environment without overvoltage protection.

The results of calculations were that insulation breakdown could happen, depending on the values chosen for the variables in the models (as discussed in Case 1), and the geometry of the connections. In this environment insulation barriers at both the DPU and the structures should withstand at least 7 – 8 kV to provide adequate voltage withstand.   A higher voltage withstand would likely be required in more extreme situations.

We then asked if system insulation breakdown would be a problem if overvoltage protection was installed at one end of the line, but not at the other.

Similar to the cases with overvoltage protection installed at both ends of the line, an insulation barrier at the unprotected equipment should withstand at least 7 – 8 kV to provide adequate voltage withstand.

Acknowledgement

Thanks to Joe Randolph for sharing data and information about the project that led to this presentation.

References

[1] Martin, A. R. (2011a). "A new TIA standard for equipment installations with two or more separate grounds" ATIS PEG Conference 2011 (This Document is available from the Alliance for Telecommunications Industry Solutions (ATIS) <www.atis.org>)

[2] Martin, A.R. (2021), "How grounds affect the peak voltage due to lightning", ATIS PEG Conference 2021 (This Document is available from the Alliance for Telecommunications Industry Solutions (ATIS) <www.atis.org>)

[3] L. Grcev, "Impulse Efficiency of Ground Rods," IEEE Transactions on Power Delivery vol. 24, no. 1 (January 2009), 441-451.

[4] Pretorius, P.H., "Was lightning ground potential rise overlooked in the design of large earth electrodes?", EE Publishers, March 26, 2018.

[5] Tominaga, Tetsuya, "Damage to equipment in Japan" ITU-T Study Group 05, Technical Session on Home Networks Geneva, 29/04/2011, https://www.itu.int/dms_pub/itu-t/oth/06/52/T06520000020001PPTE.ppt

[6] Ardley, Tim, "Protecting PoE PSE and Ethernet to the latest international OSP standards," The Alliance for Telecommunications Industries Solutions Protection Engineers Group, Monroe, LA, April, 2016.

[7] Wiese, Jim, "Evolving Ethernet Applications Have Resulted in Protection Challenges", The Alliance for Telecommunications Industries Solutions Protection Engineers Group, Littelton, CO, March, 2014.

[8] Okugawa, Yuichiro, Yasuhiro Honma, and Kazuhiro Takaya, "EMC Technology that Protects Network Equipment from Electromagnetic Problems" In NTT Technical Review, March 2014, Vol. 12, No. 3.