Lightning protection for electric utility and industrial applications

Lightning strokes generate high interference voltages in industrial plants and high-voltage substations. The characteristics of the transients, the amplitudes of the voltages and their number vary considerably from one network to another. A sound understanding of the phenomena involved and of the implications of certain industry practices are necessary to ensure the safe and reliable operation of the installed electrotechnical equipment.

In industrial plants, most overvoltages on low-voltage networks due to lightning strokes are caused by inductive or capacitive coupling to the lightning discharge and not by the strokes themselves. Typical overvoltages caused by lightning have the form 1.2/50 µs and may have an amplitude of several kilovolts **1**. A rise time of 1.2 µs may correspond to a maximum frequency of about 0.1 to 1 MHz.

Since 1 January 1996 practically all electrical and electronic components, apparatus, systems and installations have had to conform to the European Union's EMC Directive. This means that such products must be constructed in such a way as to ensure that they neither cause excessive emissions nor are unduly affected by electromagnetic disturbances.

Mandatory CE marking

The mandatory CE marking shows compliance with all relevant directives. These minimum requirements, however, do not guarantee that installations exposed to the atmospheric phenomena represented by the effects of lightning will be free from interference.

The overvoltages that could occur in installations as a result of atmospheric phenomena have to be calculated and verified before they occur in order to ensure the required level of electrical safety and electromagnetic compatibility [1].

Product, product family or generic standards based on the EN 61000-4-X series are used to verify compliance by electrical and electronic products. However, the general lack of product and product family standards means that the generic series EN 50081-X (emission) and 50082-X (immunity) are used widely to verify compliance. These generic standards relate to specific environments (eg, X = 2 for industry). Unlike the basic standards, they are not based on scientifically defined conditions, and are therefore greatly simplified. In practice, the EMC conditions for apparatus or systems never depend on the location (eg, industry) nor on the final product. Instead, they depend on the interference sources and installation conditions (eg, unshielded and/or shielded cables, segregation of cables, use of conduits, suppression of inductive loads, earthing and grounding systems, product shielding and filtering philosophy, etc). The generic standards totally lack any requirement of immunity against atmospheric phenomena such as lightning and are therefore an incomplete and insufficient political compromise.

It would be unfair not to mention that Sweden introduced already 25 years ago a standardized interference immunity test in the form of an impulse voltage test to verify immunity against lightning. This standardized test has been absolutely realistic and has given clear information and hence clear answers to both manufacturers and customers, which is not the case with the generic standards.

How lightning strikes

Observation of lightning discharges between a cloud and the earth shows that they start with a predischarge that moves step by step towards the earth. The predischarge leaving a charged cloud (usually negatively charged in its lower regions) starts with a velocity equal to about 15 % of the speed of light and travels about 50 meters as a first step. It then pauses for about 50 microseconds before making the next step, and this pattern is repeated until the discharge reaches the earth. As it moves towards the earth the predischarge usually divides into branches. On reaching a distance of only a few steps from the

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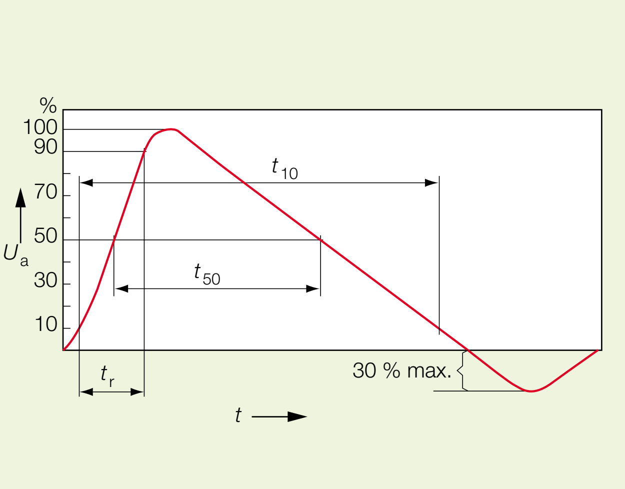
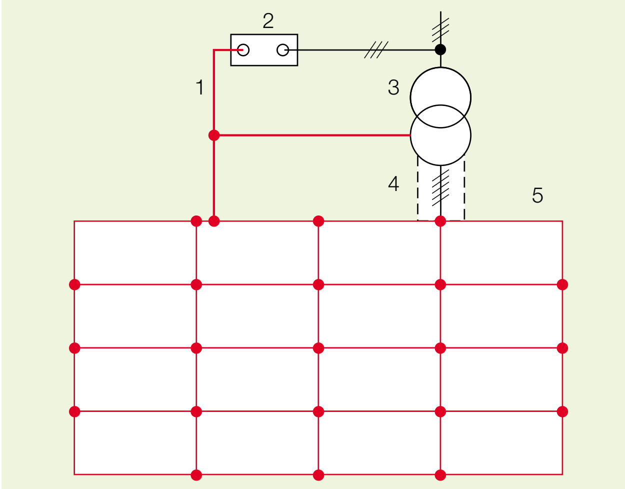


Characteristic curve of lightning transients **1**

U_a *Voltage amplitude*
t_r *Rise time*
t_{50} *Duration at 50 %*
t_{10} *Duration at 10 %*



Earthing system with lightning protection **2**

1 *Earth-line network*
2 *Lightning arresters*
3 *HV or MV transformer*
4 *Buried power distribution*
5 *Building's earth-line network*

earth, it is usually met by another predischarge rising from the earth.

The main discharge occurs when the incident predischarge reaches the earth or the predischarge from the clouds meets the one from the earth. The main discharge travels from the earth to the cloud at about 10% of the speed of light. It may carry currents as high as 200 to 300 kA. If a discharge current travelling from a cloud to the earth is defined as positive, then the major part of the lightning current due to the main discharge is negative.

The duration of the main discharge is between a few microseconds and several hundred. After the main discharge a smaller current may flow along the discharge track for a relatively long time (between 10 and 20 ms), after which a new predischarge occurs, but this one does not move step by step. It travels continuously towards the earth at a constant velocity equal to about 3% of the speed of light. When it reaches the earth, a fresh main discharge is generated. A lightning discharge generally consists of a number of main discharges. Multiple discharges are not usually more than three in number. The effects of lightning discharges are comparable to a current generator.

Cables within the confines of a substation

A substation has an earthing system consisting of a meshed network of copper conductors [3]. The control cables are located within this meshed network. Lightning protection above the meshed network is provided by conductors, known as top lines, linking the tops of the pylons. These top lines are connected to the meshed network via the pylons. Substation transformers are protected against atmospheric voltage surges by discharge arresters, which are also earthed to the meshed network.

When lightning strikes a power line connected to the substation, stray waves will propagate towards the substation. If the overvoltage is high enough, a flashover occurs in the discharge arrester and the current is diverted to the meshed earth line network.

If lightning strikes the substation's lightning protection, the lightning currents are diverted by the pylons to the meshed earth line network.

Measurements during lightning strokes hitting power lines have shown that the value of the lightning current diverted by the discharge arresters very seldom exceeds 5–10 kA.

During a direct hit on the lightning protection, the lightning current may reach a very high value.

Calculating the overvoltages (voltage surges) generated in control cables by a lightning stroke, whether it hits a power line or the lightning protection, is a very complicated matter for which there are no simple rules.

Experience shows that the precautionary installation arrangements used in substations have made faults due to lightning very uncommon. The fact that the risk is very small may be demonstrated by the following example.

Cables are rarely more than 200 m long, which means that they may be regarded as electrically short with respect to the lightning stroke frequency band. Wave form may therefore be disregarded. The voltage that will be generated between the conductor and the shield of the cable will be approximately equal to the product of the current propagating in the shield and the resistance of the shield.

When lightning strikes the substation's lightning protection, the lightning current divides according to Kirchhoff's law. One part of the current propagates down the pylons to the meshed earth line network, the control cables and shields, while the other part propagates via the lines linking the tops of the pylons. The following division may be assumed: half of the lightning current flows to the station's meshed earth line network and the cable shields, the other part flowing to the top lines running along the power lines. Assuming that the whole of the lightning current conducted to the earth line network passes through one pylon and that one control cable and two earth line conductors run from that pylon, the current in the shield will be ½ × ⅓ = 0.1666, ie, 16.6 % of the total lightning current.

In a cable with a metal shield having a resistance of 1 Ω/km, a lightning current of 60 kA will develop a voltage U as follows:

$$U = 0.2 \times 0.1666 \times 60 = 1.9992 \text{ kV}$$

For a station with a 'catchment area' of 0.1 km^2 and the lightning data given in chapter 22 of [1], such a voltage will occur about once in a hundred years. As the cables are designed for a voltage strength of at least 3 kV, the risk of damage to them is very low.

Power supplies for industry

Power supply systems in industry are assumed not to be exposed to the effects of lightning strokes. This is achieved by the primary transformer being protected by a surge arrester on the high-voltage side. Power is distributed to consumers at low voltage levels via underground cables in an integrated earth line system **2**.

There is risk of overvoltages and component damage, however, if the low-voltage distribution includes overhead lines or if the transformer (protected by surge arresters) is earthed outside the earth line system to which the electronics are earthed. In such cases, overvoltage protection must be provided for the electronics and be connected to the local earth. Such installations exist in many countries outside of Europe, so it is necessary to make sure that the interference immunity of the equipment is designed accordingly.

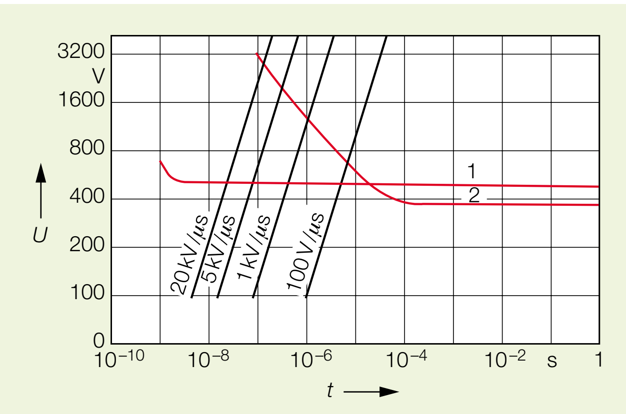
A TT network as defined in IEC 364 should never be used as the power supply for industrial electronics. The fact that different earthing points are used for the supply transformer and the electronics means that a hazard exists that could cause complete destruction of the electronics during atmospheric phenomena [3].

Lightning protection for industrial electronics

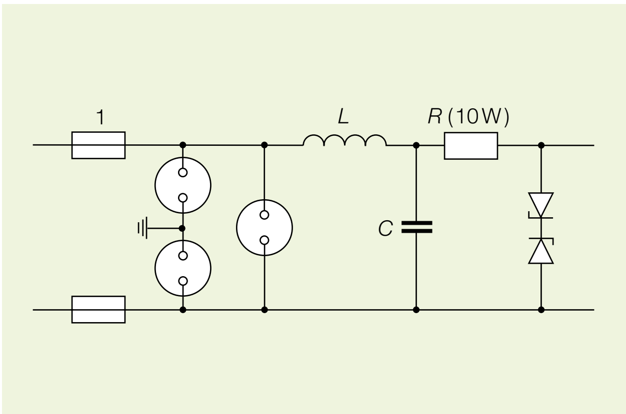
In industrial plants and power installations, properly interconnected earthing networks are usually installed together with the power distribution system. Such installations, which fulfil the above mentioned power supply conditions (electronics

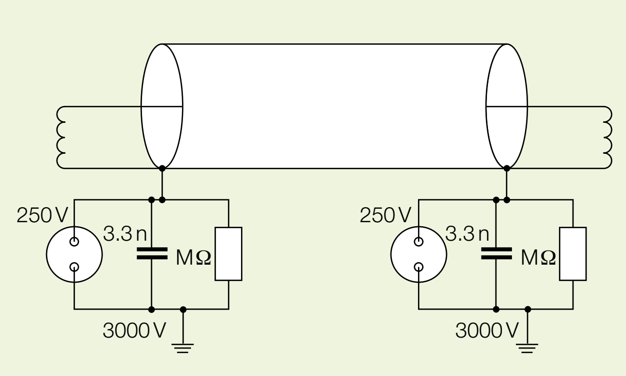
Gas discharge arrester: firing voltages U and firing times t as a function of the front rate of rise. Conventional gas discharge arresters fire relatively slowly and therefore allow a relatively high voltage peak to pass. A special gas discharge protection device called 'Spikeguard' fires so quickly that, in practice, no overvoltage spikes can pass the discharge tube. **3**

1 *New gas-type arrester, firing voltage 500 V*
2 *Conventional gas-type arrester, firing voltage 400 V*

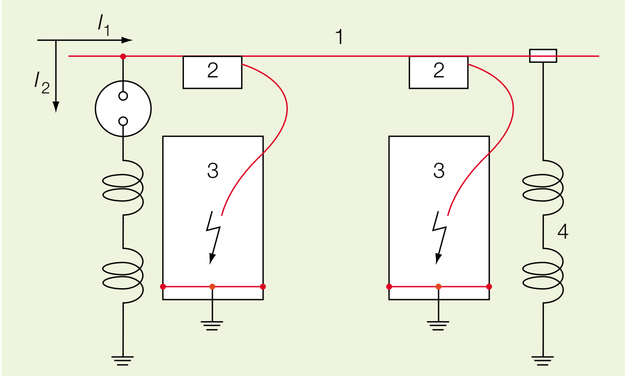


Lightning protection for telephone lines (Swedish National Power Authority and Swedish Telecommunications Authority). LC filters and Zener diodes have been added to the gas discharge tubes. References are made in the literature to adding high-voltage fuses 1 to the gas discharge protection devices. A sound, effective, inductance free short connection to system earth is essential. **4**





Lightning protection for coaxial cable 5



The problem of lightning strike protection for Ethernet communication 6

1 *Coaxial cable*
2 *Transceiver*
3 *Hazard in electronics*
4 *Earthing*

surge-tested to class 3 according to the basic standard EN 61000-4-5) require no supplementary lightning protection if no overhead cables are used outdoors. Large and extensive installations (waterworks, refineries, etc), however, may have inadequate earthing systems, with signal cables possibly routed above ground. Such cases require supplementary lightning protection, which is always necessary where cables leave the earthing system, even for distances as short as 10 meters.

Cables outside the earthing system always require lightning protection. Examples are the cables that run to transmitters outside the earthed area, eg those used in power station for water level measurement.

In contrast, cables which are outside the earthing network but are laid close to metal structures, such as brackets, rails, cranes, pipelines, etc, need no supplementary lightning protection, because such arrangements are similar to an earth line network.

Gas discharge arresters

Gas discharge arresters are mainly used for protection against lightning surges and are dimensioned to divert the lightning currents that normally occur, which experience has shown to be usually of the order of 5 to 30 kA. The energy involved is hundreds of watts.

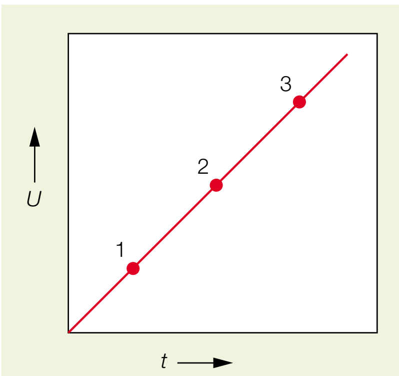
The diversion capacity of the various types is between 5 and 30 kA for 50 µs. DC firing voltages of between 100 V and 10 kV may be selected.

In the case of steep impulse fronts, however, the firing voltage is usually higher than the nominal firing voltage. 3 shows firing voltages and firing times for different front gradients. With steep impulses in steps, a normal gas discharge arrester with a firing voltage of a few hundred volts will allow spikes of a few kV and lasting a few microseconds to pass. This kind of arrester has therefore to be backed up by supplementary protection (eg, a Zener diode with resistor or inductor, varistor, RC filter) to remove the spikes, the energy content of which is in any case relatively low. 4 illustrates the complete lightning protection for telephone lines used by Sweden's national power authority Vattenfall and the country's telecommunications authority, Telia.

Dimension rule for cascade lightning-stroke protection 7

U *Nominal firing voltage*
t *Time*

1 *Primary protection (building)*
2 *Secondary protection (cabinet)*
3 *Tertiary protection (circuit board)*



New gas discharge arrester protection devices recently introduced have a very short firing time (0.2 ns) and can therefore be used without supplementary protection. The design of these 'Spikeguard' devices is such that they can be directly placed in coaxial cables. A normal gas discharge arrester has very small dimensions, being about 1 cm in diameter and 1 to 5 cm long.

After a gas discharge arrester has been activated, the voltage drop across it decreases sharply to a few volts. This voltage is called the 'glow potential' and lasts for as long as the current is higher than the 'extinction current'.

Table 1:
Summary of standard IEC 1000-4-5.

Level	Power supplies		Process I/O[4,5] LDB		Balanced[5] circuits		SDB, DB[1,5]	
	NMV[2]	CMV[3]	NMV	CMV	NMV	CMV	NMV	CMV
0	–	–	–	–	–	–	–	–
1	–	0.5 kV	–	0.5 kV		0.5 kV		
2	0.5 kV	1.0 kV	0.5 kV	1.0 kV	–	1.0 kV	–	0.5 kV
3	1.0 kV	2.0 kV	1.0 kV	2.0 kV	–	2.0 kV	–	–
4	2.0 kV	4.0 kV	2.0 kV	4.0 kV	–	4.0 kV	–	–
5	2.0 kV	4.0 kV	2.0 kV	4.0 kV	–	4.0 kV	–	–
X								

CMV Common Mode Voltage
NMV Normal Mode Voltage
DB Data buses
LDB Long-distance buses
SDB Short-distance buses

Class 0–4: 1.2/50 µs (8/20 µs for low-resistive circuits)
Class 5: As class 4 + 10/700 µs
Note 1: Limited distance, special configuration, special layout
Note 2: R = 2 ohms
Note 3: R = 12 ohms
Note 4: R = 42 ohms
Note 5: When shielded cables with the shield grounded at both ends are used, the impulse is injected into the shield only (CMV value R = 2 Ω). When shielded cables with the shield grounded at only one end are used, the cable shield is terminated by a 100-pF/m capacitor before the impulse is injected into the shield (CMV value R = 2 Ω).

The use of a conventional gas discharge arrester in power supplies is not allowed, because a few tens of mA are sufficient to prevent automatic recovery of such an arrester and it is in practice not feasible to shut the power supply circuit down manually. Supply lines for carrying voltages of more than 24 V to external transmitters have therefore to be protected by varistors or lightning arresters.

Lightning protection must always be situated directly at the cable entry to the cubicle, on the copper busbar or the sheet-metal housing. Simply mounting it on the wall with an earth line connection is usually ineffective and therefore dangerous, and is only suitable when it is used as supplementary protection (eg, where cables enter a building).

Signal lines that require gas discharge arresters must be fitted with one on each signal wire at each terminal equipment location and at the end of the shield of ungrounded cables. Where coaxial cables are used it is sufficient to fit the lightning protection to the screen **5**.

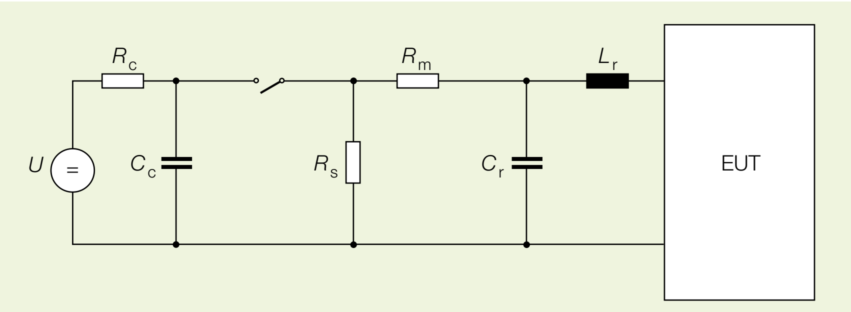
Ethernet communications must not be routed in such a way that cables might be exposed to overvoltages. The transceivers are sited at many locations in the field installation, thereby preventing any possibility of installing properly functioning inductance-free lightning protection **6**.

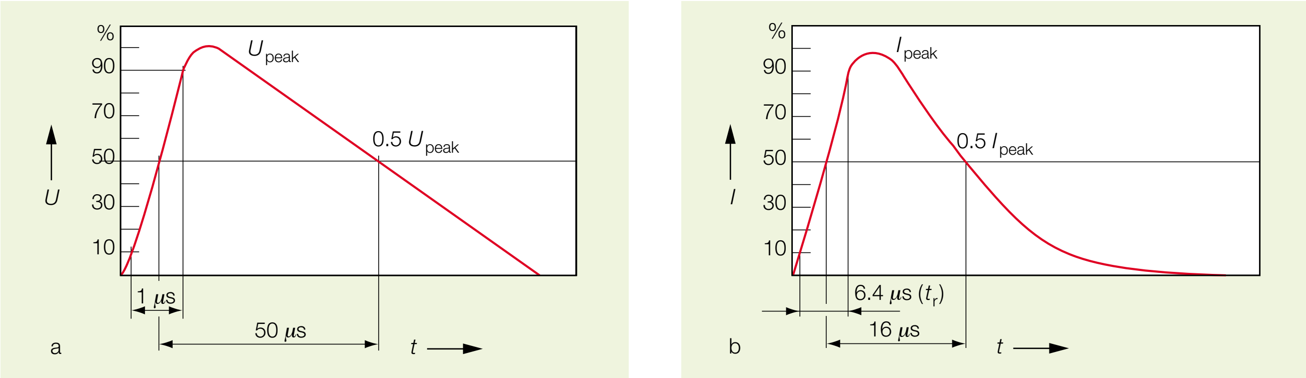
The inductance in the earth line may be many times greater than that in the rest of the field installation, which makes it very easy for a current due to lightning stroke to propagate through the electronics to

Hybrid surge generator used to verify immunity against atmospheric phenomena **8**

EUT Equipment under test

C_c *Energy storage capacitor*
C_r *Impedance matching capacitor*
L_r *Impedance matching inductor*
R_c *Charging resistor*
R_m *Impedance matching resistor*
R_s *Resistor forming pulse duration*
U *High-voltage source*





Waveforms of the voltage surge (a) and current surge (b) obtained with the hybrid surge generator **9**

t_r *Rise time*

the earth, in which case the equipment will be completely destroyed.

This means that a cable being run between buildings must always be buried 80 cm below ground level in steel conduit earthed at both ends. The parallel earth line connected at both ends must follow the configuration.

Finally, where cascade lightning protection is used, the nominal firing voltage has to be selected **7**.

Verification of immunity against atmospheric phenomena

EN 61000-4-5, with the so-called 'surge test', is the recently approved international standard for verifying immunity against atmospheric phenomena. This simulation method is based on the use of a 'hybrid surge generator' **8** which has a low output resistance and automatically switches over to voltage pulse for a front time of 1.2/50 µs (rise time 1/50 µs) or to current pulse for a front time of 8/20 µs (rise time 6.4/16 µs) **9**. The internal impedance of the test generator ranges from 2 to 42 Ω and its amplitude from 0.5 to 4 kV. The connection to the EUT is provided by the coupling network. A summary of the standard is given in *Table 1.*

Quite considerable opposition to this standard meant that it took some time to become adopted. It still has many shortcomings. It should be noted that, according to this standard, CMV (Common Mode Voltage) refers to coupling between a particular conductor and the earth, and NMV (Normal Mode Voltage) to coupling between one conductor and another [2].

Summary

Designing electronic systems to operate in industrial environments largely means mastering the art of manufacturing systems, apparatus and circuit boards that are protected against interference.

There are presumably no manufacturers who, in order to survive in this sector, do not try to ensure that the equipment they offer lives up to their claims. Nor can there be any doubt that every manufacturer tries his systems out in the development department and in the laboratory. But a question that arises is whether these procedures provide sufficient guarantee of trouble-free operation and satisfied customers. The answer will be in the affirmative when the sources of interference that apply in the particular industry (which of course include atmospheric phenomena) are taken into account and the manufacturer verifies this by means of an interference test.

Manufacturers need to be absolutely certain as to the standards that are to be applied. In ABB Industry and Drives, the internal company standard 'EMC Requirements and Policy' was created to meet this need. The two environments it recognizes are 'unprotected industrial' and 'high-voltage outdoor switchgear'. The underlying philosophy is that such a standard, besides having to meet all minimum legal requirements, also has to conform to other recognized needs for interference-free operational immunity, including immunity against atmospheric phenomena.

References

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