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ASSESSMENT OF THE LIGHTNING TRANSIENT COUPLING TO CONTROL CABLES INTERCONNECTING STRUCTURES IN LARGE INDUSTRIAL FACILITIES AND POWER PLANTS

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Abstract: Large industrial facilities and power plants often require a huge number of information and control cables between the different structures. These I&C-cables can be routed in reinforced concrete cable ducts or in isolated buried cable runs.

KTA 2206 is the German lightning protection standard for nuclear power plants. During the last several years considerable effort has been made to revise this standard. Despite the well established principles and design guidelines for the construction of the lightning protection system, this standard puts special emphasis on the coupling of transient overvoltages to I&C-cables.

Keywords: Lightning, current distribution, electromagnetic coupling, overvoltages.

1. INTRODUCTION

The KTA 2206 standard [1] mainly considers information and control cables (I&C-cables) installed between individual structures (buildings) of nuclear power plants. These I&C-cables are highly subject to dangerous overvoltages due to the large extensions of several 10 m to a few 100 m. There are two common installation practices in large plants in Germany:

If a large number of cables is to interconnect structures, these cables usually are routed in large reinforced concrete cable ducts having a cross section of 2 m x 2 m, or more.

If only some I&C-cables are to be installed between two locations of a plant, it is common practice to install these cables in isolated buried cable runs. Such a cable run consists of a small diameter (typ. 100 mm) plastic conduit containing a set of I&C-cables. Commonly, the I&C-cables used in isolated cable runs are equipped with an additional shield, e.g. 16 mm^2 Cu, to be capable of safely carrying substantial parts of a lightning current.

The overvoltages coupled to I&C-cables are determined by two main factors:

- the share and the distribution of the lightning current along the reinforcement of a duct or along the outer shield of an I&C-cable
- the transfer mode between the reinforcement or the shield and the control wires inside an I&C-cable.

Principal intention during the revision of the KTA 2206 standard was to specify methods for the assessment of overvoltages not requiring the application of complex electromagnetic computer codes. On the other hand, the simple rule-of-thumb for the current share ("50% - rule") described in IEC 61312-1 [3], or the method in IEC 61024-1 [2], were considered not sufficiently to fit the requirements represented by the diversity of systems and installations connecting the various structures in a large power plant.

Several programs were conducted in order to develop easy-to-apply methods for the assessment of overvoltage coupling to I&C-cables. The validity of those simplified methods of the new KTA 2206 standard was verified by comparison with more sophisticated computer codes. The comparison was performed at an example model of an existing power plant. The power plant model comprised the earth termination impedance of the buildings and all interconnecting installations (e.g. pipes, cables, cable ducts and runs, and earthing wires).

2. LIGHTNING CURRENT DEFINITIONS

Coupling to I&C-cables may be a function of a) the current peak value in case of resistive transfer or b) the current steepness in case of inductive transfer. The highest current peak values occur in positive first strokes, while negative subsequent strokes involve the highest current steepness. Current waveforms for positive and negative first strokes and for negative subsequent strokes are defined in the IEC 61024 and IEC 61312 [2, 3]. For the large industrial facilities or power plants considered here, the current peak values of protection level I were chosen.

Table 1: Lightning current parameters

Lightning type	i_{max} (kA)	T_1 (µs)	T_2 (µs)	i_{max}/T_1 (kA/µs)
Positive first stroke	200	10	350	20
Negative first stroke	100	1,0	200	100
Negative subsequent stroke	50	25	100	200

Although not having the highest current peak values and steepness, negative first strokes should not be generally omitted: Measurements and theoretical studies [6, 7] at a large reinforced concrete cable duct showed that the highest coupling to I&C-cables inside the duct indeed occurs for a current front time in the 1 µs range, representing negative first strokes. A severe negative first stroke may be defined by a peak current of 100 kA and a 1.0/200 µs waveform [4]. The current waveforms used in this study are summarized in table 1.

3. LIGHTNING CURRENT DISTRIBUTION

The distribution of a lightning current to the individual structures of a large facility is a complex problem. The simplified assessment methods for common structures, described in IEC [2, 3], seemed not sufficient to address the diversity of systems and installations of large facilities. The geometrical dimensions of the systems to be considered for the calculation of the current distribution are so different that it is no more possible to lump them all together, as done for instance by the "50%" rule-of-thumb in [3]. The dimensions range from centimeter (e.g. 50 mm^2 earth conductor) up to meter (e.g. large cooling water tubes).

The current distribution further depends on the earthing condition of the system: If a buried system is in contact to the surrounding soil, the penetration depth of the soil limits the high frequency coupling effects to a short distance (e.g. a few 10 m) from the current entry point into the system [6]. Also the low frequency coupling will be reduced, because the current along the system decreases due to current flow to earth [5]. In case of systems, which are not in contact to soil, the system's inductance in conjunction with the earth resistance of the structure, where the system is leading to, form a (L/R) low pass filter. This filter may significantly slow down the current rise and attenuate the current amplitude.

4. TRANSFER MODE

For the calculation of the voltages actually coupled to the wires of I&C-cables the transfer impedance between the system outer shield and the inside I&C-cable wires has to be known. Often, lightning electromagnetic coupling is dominated by either an inductive (~ di/dt) or a resistive (~ i) transfer mode.

For large cable ducts it is shown in [7] that the inductive coupling is dominant. Experimentally determined values for the transfer impedance of cable ducts built to common construction practice in Germany are given there.

In case of the isolated buried cable runs, I&C-cables with an additional "squirrel cage" shield of for instance 16 mm^2 Cu are used. For these I&C-cables plots of the transfer impedance as a function of frequency are available from the manufacturer. Typically, the transfer impedance is constant up to a few 10 kHz, increasing then with frequency. As shown in section 6, for the systems not in contact to soil a low pass filter behaviour becomes effective. Isolated cable runs mostly are used for connections to smaller, remote buildings, the length then being in the 100 m range. With the resulting high system inductance the current rise is slowed down so much (clearly below 10 kHz), that the resistive coupling mode dominates.

5. APPROACH OF THE NEW KTA 2206 LIGHTNING PROTECTION STANDARD

The current waveforms and peak values considered in KTA 2206 [1] are identical to those given in table 1. For the assessment of the lightning transient coupling to I&C-cables in a large plant the most crucial point of strike has to be found. This may require several calculations for different points of strike, but usually the worst case is a strike to the smaller one of the structures interconnected by the cable duct/cable run considered: The smaller structure usually has the higher earthing resistance and the number of lines connected to it is lower. Both facts act to increase the share of the lightning current to the interconnecting system.

The new KTA 2206 lightning protection standard distinguishes between two scenarios for the lightning current distribution: The first method for the inductive coupling in case of cable ducts uses weighting factors based on the current sharing for higher frequencies. The second method for resistive coupling in case of isolated cable runs uses weighting factors based on the low frequency current sharing.

The variety of the geometrical dimensions of the systems is taken into account by specifying weighting factors for typical systems and installations used in large plants.

5.1 I&C-cables in reinforced concrete cable ducts

5.1.1 Current distribution

The calculation of the current distribution has to be performed for all three lightning current waveforms. One-third of the total lightning current I_B is assumed to flow to the earth termination system of the structure considered. The remaining current I_{ab} (eq.1) is distributed to all electrically conductive lines in contact with soil entering the structure. Isolated cable runs are not considered here, because their self inductance blocks remarkable current flow during the fast rise time portion of the lightning current.

$$I_{ab} = 2/3 \cdot I_B \qquad (1)$$

Table 2 gives the weighting factors p_K for the currents along the various lines connected to the structure considered. For cable ducts the inductive coupling during the fast di/dt portion of a strike dominates. During the fast rise the current share is mainly a function of the line's inductances. The inductance of a line, and with it the ratio of the weighting factors, is related to the outer dimensions via the natural logarithm ($L_L \sim \ln[1/r_{eq}]$, see eq. 8).

Table 2: Weighting factors p_K for lines in contact with soil in case of inductive transfer mode

External line	Weighting factor p_K
Cable duct (approx. 2 m x 2 m)	**3**
3- or 4-fold cable duct (each approx. 2 m x 2 m)	**6**
Line in contact with soil: D < 0,1 m (e.g. earthing wire)	**1**
Line in contact with soil: 0,1 m < D < 1 m (e.g. water pipe)	**2**
Line in contact with soil: D > 1 m (e.g. water pipe)	**3**

With the values of table 2, the part I_K of the lightning current along the cable duct considered is given by:

$$I_K = \frac{p_{KK}}{\sum_{v=1}^{n} p_{Kv}} \cdot I_{ab} \qquad (2)$$

p_{KK}: weighting factor of the cable duct considered

$\sum p_{Kv}$: sum of weighting factors of all lines in contact with soil entering the structure

n: number of all lines in contact with soil.

5.1.2 Effective length of the cable duct

As demonstrated in section 6.2, the current steepness decreases exponentially along a line in contact with soil. Therefore, coupling to the I&C-cables inside occurs mainly around the entrance to a cable duct, eventually reaching the maximum after a given distance. The coupled voltage can be approached by assuming a constant current over a so-called fictitious length of the cable duct. The parts of the cable duct beyond this fictitious length do not contribute any further to the coupled voltage, i.e. the current here is assumed zero. Of course, if the real length of a cable duct is shorter than the fictitious length, the real length has to be taken. The fictitious length l_f equates to the penetration depth (eq. 9) in soil [6]:

$$l_f = K \cdot \sqrt{\rho_e}, \qquad \rho_e \text{ in } \Omega m \qquad (3)$$

The factor K depends on the lightning current waveform. The values of K in table 3 are based on the equivalent frequencies for the waveforms given in table 6.

5.1.3 Induced voltage

The induced voltage U_L coupled to I&C-cables inside cable ducts can be calculated by:

$$U_L = Z'_M \cdot I_K \cdot l \qquad (4)$$

Z'_M: coupling impedance per unit length (table 3)

I_K: current along the cable duct

l: effective length of the cable duct.

Table 3: Lightning type factor K and coupling impedance Z_M' for large reinforced concrete cable ducts

Lightning type	Positive first stroke	Negative first stroke	Negative subsequent stroke
K in $(\Omega/m)^{-1/2}$	3	1	0.5
Z'_M (V/(kA*m))	0.08	0.30	0.50

The values of table 3 [7] are valid for reinforced concrete cable ducts conform to the design criteria given in [1]. For 3- or 4-fold cable ducts the current I_K along the multiple cable duct is split equally to the sections.

For mechanical reasons, longer cable ducts require expansion joints. At these expansion joints the reinforcement is interrupted. The current I_K along the cable duct is forced through some connecting wires (jumpers) bridging the joint. At these discontinuities of the shield, the coupling to the inside I&C-cables is remarkably increased. This effect can be taken into account by a fictitious extension l_{DF} of the length of the cable duct. Of course, only expansion joints located within the fictitious length l_f of the cable duct are to be considered. Table 4 gives the values for the fictitious increment l_{DF} depending on the number of jumpers and the lightning type, characterized by its front time T_1.

With that the effective length l of the cable duct, necessary to calculate the coupled longitudinal voltage U_L, is given by:

$$l = l_f + \sum_{v=1}^{N} l_{DFv} \qquad (5)$$

l_{DFv}: fictitious extension for one expansion joint

N: number of expansion joints located within the fictitious length l_f

Table 4: Fictitious increment l_{DF} of a cable duct

	Fictitious increment l_{DF} (m) per expansion joint for			
T_1 (µs)	16 jumpers	8 jumpers	4 jumpers	2 jumpers
10	5	10	20	30
1.0	10	20	35	55
0.25	15	30	50	70

5.2 I&C-cables in isolated cable runs

5.2.1 Current distribution

Here the calculation has to be performed for the slow 10/350 µs waveform only. Again it is assumed, that 1/3 of the lightning current I_B flows through the earth termination system of the structure considered and that the remaining current I_{ab} is distributed to all electrically conductive lines connected to the structure (eq. 1).

Table 5 gives the weighting factors p_E for the currents along the different lines. Table 5 is similar to table 2: For long isolated cable runs the resistive coupling dominates. Therefore, the ratio of the weighting factors has to be a function of the line's earthing resistances. Like the inductance in section 5.1.1, the earthing resistance of a line is related to its outer dimensions via the natural logarithm ($R_{L/E} = 1/G_{L/E} \sim \ln [1/r_{eq}]$, see eq. 8). However, for a low frequency current distribution buried cable runs have to be taken into account, too.

With the values of table 5, the part I_E of the lightning current along the cable run considered can be determined using eq.6. In case of a cable run with more than one I&C-cable, first the current I_E for the entire cable run is calculated. The current I_E then is assumed to split equally to the individual I&C-cable shields.

$$I_E = \frac{p_{EE}}{\sum\limits_{v=1}^{n} p_{Ev}} \cdot I_{ab}\,; \qquad I_{KS} = \frac{1}{q} \cdot I_E \qquad (6)$$

p_{EE}: weighting factor of the cable run considered
$\sum p_{Ev}$: sum of weighting factors of all lines
n: number of all lines
q: number of I&C-cables in the cable run

Table 5: Weighting factors p_E in case of resistive transfer mode along buried cable runs

External line	Weighting factor p_E
Single I&C-cable	1
Buried cable run (2 – 10 I&C-cables)	2
Buried cable run (> 10 I&C-cables)	3
Cable duct (approx. 2 m x 2 m)	3
3- or 4-fold cable duct	6
Line in contact with soil: D < 0,1 m	1
Line in contact with soil: 0,1 m < D < 1 m	2
Line in contact with soil: D > 1 m	3

5.2.2 Induced voltage

The longitudinal voltage U_L coupled to I&C-cables routed in isolated cable runs can be calculated by:

$$U_L = Z'_M \cdot I_{KS} \cdot l_E \qquad (7)$$

Z'_M: coupling impedance per unit length of the I&C-cable
I_{KS}: part of the lightning current along the cable's shield
l_E: real length of the cable.

Due to the slow rise of the current I_{KS} along the shield of the I&C-cable, usually the DC-resistance per unit length may be used as the coupling impedance Z'_M.

6. NUMERICAL CODE ANALYSIS

To prove the validity of the KTA-approach shown in section 5, the lightning current distribution has been determined for an existing large power plant using two more sophisticated methods. The one method already has been described in [6]. The other verification method described here used PSpice [8] analysis software. The interconnecting systems were simulated as lossy transmission lines. In the following model and methods used are demonstrated for an example power plant (figures 1 and 2).

6.1 Model description

The principal configuration of the example power plant is shown in figure 1. It consists of the following major structures:

- Structure 1: Central complex consisting of turbine, switchgear, and control building with foundation earth electrodes and a common ring earth electrode
- Structure 2: Utility system building with foundation earth electrode
- Structure 3: Pump building with a foundation earth electrode at the riverside
- Structure 4: Small remote building containing measuring equipment with a ring earth electrode in a distance of about 200 m to the central complex.

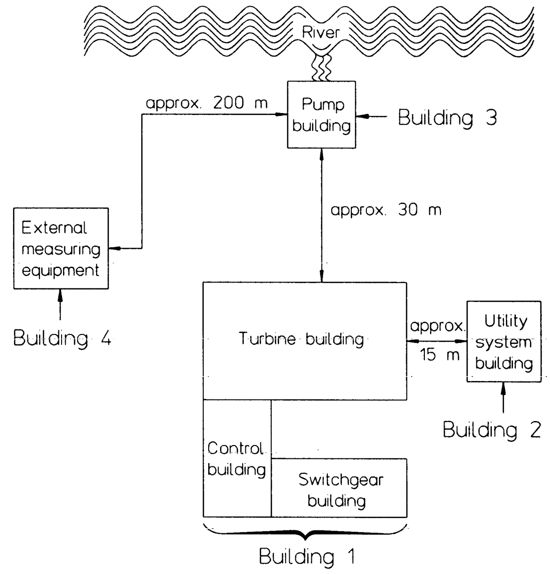


Figure 1: Configuration of the example power plant

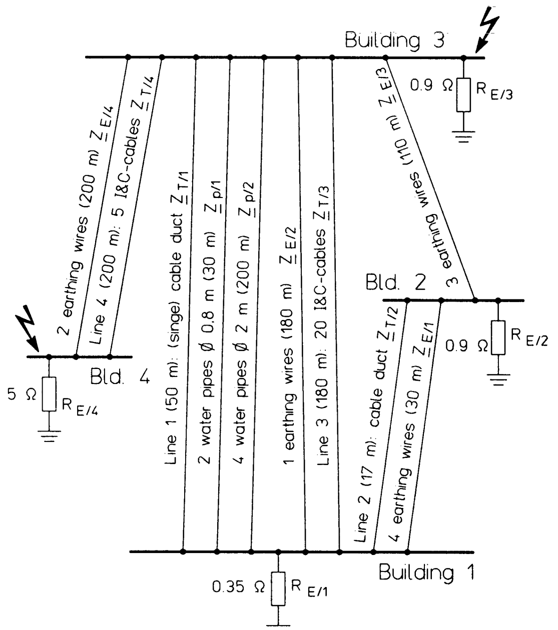
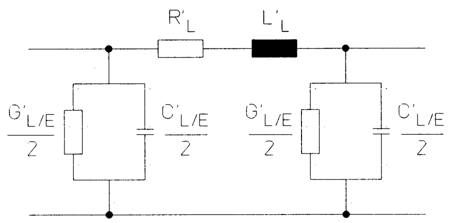


Figure 2: Interconnecting systems and lines



R'_L : resistance per unit length
L'_L : self inductance per unit length
$G'_{L/E}$: earth conductance per unit length
$C'_{L/E}$: earth capacitance per unit length

Figure 3: Differential element of the transmission line formed by a buried system

The lines interconnecting the structures of figure 1 are given in figure 2.Typically, the lines are dug in at a depth ranging from some 10 cm to a few meters. The burying depth, thus, is much lower than the penetration depth δ in soil. The elements of the equivalent circuit of a line then can be calculated using the formulae of a half-cylinder (eqs. 8) having an outer radius δ and an inner radius r_{eq} [6]. The radius r_{eq} is either the radius of the line itself or, in case of non-circular lines, an equivalent radius determined from equal perimeters:

$$R'_L = \frac{\rho}{A}; \qquad L'_L = \frac{\mu_0}{\pi}\cdot\ln\left[\frac{\delta}{r_{eq}}\right]$$

$$G'_{L/E} = \frac{\pi}{\rho_e}\cdot\frac{1}{\ln\left[\frac{\delta}{r_{eq}}\right]} \qquad C'_{L/E} = \frac{\pi\cdot\varepsilon_0\cdot\varepsilon_r}{\ln\left[\frac{\delta}{r_{eq}}\right]} \qquad (8)$$

ρ: resistivity of the line's material
A: cross-section of the line's conductive material
δ: penetration depth in the surrounding soil
r_{eq} equivalent radius of the line
ε_r dielectric constant (worst-case assumption: $\varepsilon_r = 1$)

The penetration depth δ in soil as a function of frequency is:

$$\delta = \sqrt{\frac{\rho_e}{\pi\cdot\mu_0\cdot f_{eq}}} \qquad (9)$$

with f_{eq} being the equivalent frequency of the impressed lightning current waveform. For the rise time portion up to the current peak the values of table 6 can be used.

Table 6: Equivalent frequencies f_{eq} and penetration depths δ for the different current waveforms (ρ_e = 100 Ωm)

Current waveform	f_{eq} (kHz)	δ (m)
10/350 µs	25	32
1/200 µs	250	10
0.25/ 100 µs	1000	5.0

In case of the isolated cable runs, where a set of cables is running in a small diameter (typ. 100 mm) plastic tube, these cables were treated as one common system having an effective radius r_{eq} equal to the tube radius. For the determination of the voltages coupled to an individual cable, it was then assumed that the current equally distributes to the all the cables in the plastic tube.

6.2 Results

Using eqs. 8, 9 and table 6, the elements of the equivalent circuit in figure 3 for all interconnecting lines of the power plant model were calculated. The transient current distribution to the individual structures and lines was determined for different points of strikes using numerical code analysis. A basic description on the use of PSpice analysis software [8] for the numerical calculation of transient lightning current distributions is given in [9]. This analysis also allowed to establish the distribution of the current steepness along a cable duct. Following, example results are given for a cable duct in contact with soil (line 1 of fig. 2) and an isolated cable run (line 4 of fig. 2). A value of ρ_e = 100 Ωm was assumed for the soil. The results corroborate the approach given in [6].

Figure 4 illustrates the distribution of the maximum current steepness along the cable duct "line1" in case of a negative first stroke (100 kA, 1/200 µs) to the pump building (structure 3). For this calculation the 50 m long cable duct was split up into 10 segments. The current steepness exponentially decays with distance from the cable duct entry point: di/dt ~ exp(-l/δ). The value δ ≈ 10 m corresponds well to the penetration depth δ given in table 6. As the transfer mode for a cable duct is dominantly inductive [7], the bulk of the coupling to the I&C-cables inside occurs along the first 10 m ... 20 m of the duct. The distribution of the current steepness along the cable duct is governed by the low pass filter effect of the cable duct inductance and its earthing conductance. The higher frequency components of the current are filtered out by the low pass characteristic given by $L'_L\cdot G'_{L/E} = \mu/\rho_e$.

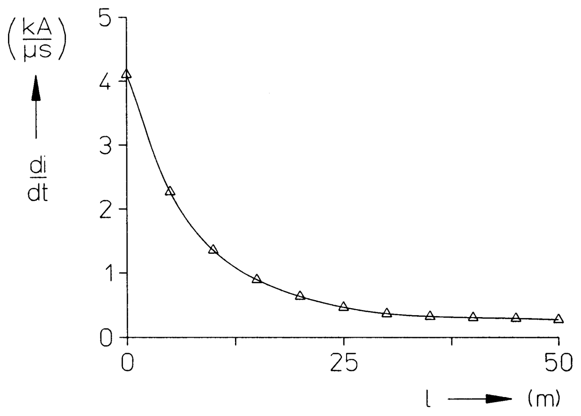


Figure 4: di/dt - distribution along cable duct "line 1"

The waveshape of the current along the isolated cable run "line 4" (see figure 2) is shown in figure 5 in comparison to the incident lightning current of 200 kA, 10/350 µs striking building 4. The current rise is drastically reduced:

The peak value is not reached before 250 µs, corresponding to an equivalent frequency of about 1 kHz. For most I&C-cables the transfer impedance at such low frequencies is equal to the DC-resistance of the shield. Therefore, it seems justified to use the DC-value for Z'_M in eq. 7.

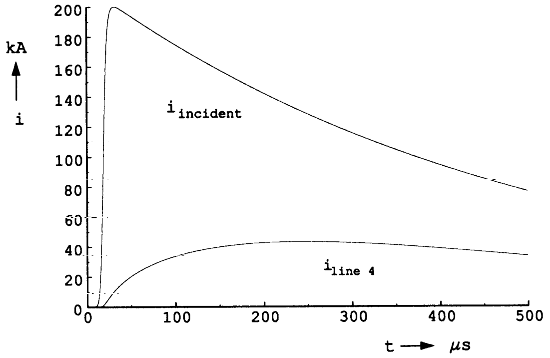


Figure 5: Incident current and current along cable run "line 4"

Table 7: Comparison of the different methods

Line	Strike to Structure	Coupled Voltage (V)		
		IEC	KTA	Transmission Line Model
1	3	12	72	76
4	4	560	2600	1500

In table 7 the peak coupled voltages for the two systems, "line 1" and "line 4" (see figure 2), are given using different methods to assess the current share. The table compares the IEC 50% rule-of-thumb [3], the new KTA approach [1], and the lossy transmission line computation shown in section 6.1. In case of the cable duct "line 1" effective length and expansion joints were considered in the same way for columns "IEC" and "KTA". The approach of the new KTA standard is within reasonable limits to the more sophisticated lossy transmission line modeling. With a tendency to overestimate, the KTA-values are on the safe side, while the IEC 50% rule-of-thumb clearly underestimates the coupled voltages.

7. CONCLUSION

For the determination of voltages coupled to information and control cables the revised KTA 2206 standard specifies two different procedures for the calculation of the current distribution in a large facility, one for inductive coupling based on the current sharing for higher frequencies and one for resistive coupling based on the current sharing for low frequencies. The variety of geometrical dimensions of systems are taken into account by specifying weighting factors for typical installations. For systems in contact to the surrounding soil, the penetration depth into soil is taken into account: Inductive coupling is limited to a short distance (e.g. a few 10 m) from the current entry point into a system.

Comparison of the new KTA approach with a more sophisticated model using PSpice computation with lossy transmission lines shows reasonable agreement with a tendency to overestimate. The KTA approach thus is on the safe side.

8. REFERENCES

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