Análisis del diseño actual del apantallamiento ante rayos de líneas aéreas de alta tensión de Transelec

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Analysis of lightning shielding design of high voltage overhead lines for Transelec

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RESUMEN

Transelec es la principal empresa de transmisión de energía eléctrica en Chile, con casi 10.000 kilómetros de líneas y cerca de 60 subestaciones de 500 kV y 220 kV a lo largo del Sistema Interconectado Central (SIC) y el Sistema Interconectado del Norte Grande (SING). Debido a la diversidad geográfica y climática del territorio abarcado por las líneas de transmisión de Transelec, éstas están expuestas a frecuentes fallas y salidas de operación debido a impactos por rayos, lo cual ha afectado la operación de los sistemas interconectados. Preocupada por esta problemática, la empresa quiso analizar del estado actual del diseño del apantallamiento por rayos de sus líneas aéreas de transmisión. Desafortunadamente, Chile no cuenta con información de la actividad de rayos en su territorio, por lo tanto fue necesario calcular la densidad de rayos a tierra (DDT) con base en la información de la red WWLLN (Word Wide Lightning Location Network). Del total de líneas, se eligieron cinco líneas con alta tasa de falla y ubicadas en zonas de alta densidad de descargas a tierra. El apantallamiento contra rayos fue analizado basados en el método electrogeométrico teniendo en cuenta las irregularidades del terreno y la catenaria de los conductores. A partir del análisis, se concluyó cuál o cuáles tramos de la línea presentan las probabilidades más altas de falla del apantallamiento. Finalmente, los resultados fueron comparados con los reportes de falla de las líneas de transmisión con el fin de establecer una relación entre las fallas y la actividad eléctrica atmosférica de las zonas bajo estudio.

PALABRAS CLAVE: apantallamiento contra rayos, modelo electrogeométrico, protección contra rayos.

ABSTRACT

Transelec is the leading power transmission company in Chile, with nearly 10,000 kilometers of power transmission lines and nearly sixty 500 kV and 220 kV substations in the Central Interconnected System (SIC) power grid and the Great North Interconnected System (SING) power grid. Due to the geographic and climatic diversity of the territory covered by the transmission lines owned by Transelec, these are exposed to frequent faults and outages produced by lightning strikes affecting the operation of the whole interconnected system. Worried about the issue, Transelec wanted to analyze the current state of lightning shielding of their overhead lines. Unfortunately, Chile does not have information about lightning activity over its territory, therefore calculation of the ground flash density GFD was carried out based on Word Wide Lightning Location Network (WWLLN) database. Five overhead lines were analyzed based on failures reports and based on GFD maps, taking into account overhead lines with high outage rates and high GFD. Lightning shielding was analyzed based on electrogeometric method taking into account landform and catenary. From the analysis, it was concluded which section or sections show the highest likelihood of shielding failure for every overhead line. To sum up, results were compared with failures reports in order to stablish a relationship between them and lightning activity in those areas.

KEYWORDS: Lightning shielding, electrogeometric method, lightning protection

1. INTRODUCTION

Lightning is one of the most wonderful natural phenomenon that has accompanied the human being through the ages, but at the same time is one of the causes of power system failure. When a lightning occurs, there is a transfer of charge between the cloud and the ground that releases an enormous amount of energy, which is precisely what makes lightning a destructive force for structures if they are not adequately protected. Therefore, the necessary measures to avoid threats to life and damage to property must be taken. This is why protective measures are taken in electrical power systems to avoid damages that could jeopardize service reliability and generate costly equipment replacements.

Lightning affects electrical systems at transmission and distribution levels when strikes the substations and overhead lines. If a lightning strikes an overhead line, the overvoltage generated can cause damage to different equipment of the power system. The severity of the overvoltage depends on the operating voltage of the system; For example, in transmission overhead lines with a nominal voltage of less than 300 kV, lightning overvoltages are the most detrimental and define the selection of insulation, while above this level the switching overvoltages are usually the most important.

Lightning overvoltages are the most common cause of outage of overhead lines. When a lightning strikes an overhead line, the overvoltage generated can cause flashover in the insulators, which could produce a fault because the associated overcurrent is discharged to the ground through the tower. During the design stage of an electrical overhead line, the level of insulation and the lightning protection system are defined so that during the annual operation an acceptable rate of service interruption is not exceeded [1][2].

Overhead lines and other elements of the power system can be protected in two ways: installing one or more shield wires above the phase conductors and connecting them to earth at each tower, and, installing surge arresters that reduce excessive voltages [3]. The main function of the shield wire is to intercept most of the lightning on the line, accepting that only a very small percentage of discharges can reach some of the phase conductors. However, when a lightning strikes the shield wire, there may also be flashover caused by overvoltages present between the tower and the phase conductor; that phenomenon is called backflashover and depends on the impedance values of the tower and its grounding. On the other hand, lightning can strike the earth near the overhead line; this near impact can raise the potential of the phase conductors due to the electromagnetic coupling between them, what is known as induced voltage; this overvoltage could cause flashover in the insulator string as in the first case above described [3].

The efficiency of the protection with shield wires depends on the position of these with respect to the phase conductors. This efficiency is affected by several factors such as the frequency of occurrence of the lightning, the magnitude of the current and the angle of inclination, among others. It should be noted that there is no infallible method to determine the impact site of a lightning strike on an overhead line, but there are methods to position the shield wires and methods to evaluate the performance of the overhead lines against this natural phenomenon.

This work presents the lightning shielding study of some overhead lines of the Chilean electrical system based on information of World Wide Lightning Location Network (WWLLN), due to the fact that Chile does not have its own system of detection and location of lightning. Additionally, it is presented the compilation of reports of more than 60 outage of overhead transmission lines owned by Transelec due to lightning in the last 5 years.

2. LIGHTNING LOCATION SYSTEMS

Lightning phenomena (intra-cloud and cloud to ground) emit electromagnetic waves over a wide range of frequencies, very low frequency VLF (3-30 kHz), low frequency LF (30-300 kHz) and very high frequency VHF (30-300 MHz) [4]. The methods used for the detection of atmospheric discharges are based mainly on the use of VLF, LF and VHF emissions to determine the magnitude and location of the electromagnetic source, considering that different methods have different degrees of accuracy. The most used techniques for this purpose are direction finder (DF) and time of arrival (TOA) [5].

The DF technology has two parts: the sensor and the position analyzer. This system can operate with one station or with multiple stations. In a multi-station system, the analyzer receives data from three or more sensors with distances between 100 and 200 km. The bandwidth of the antenna system is approximately 1-400 kHz [6]. TOA system locates impact points by measuring the differences between arrival times of a return stroke on three or more sensors and finds the location by means of the intersection of hyperbolas on a spherical surface. The separation between stations varies between 10 and 400 km. Each station consists of an omnidirectional antenna (stroke antenna) and a synchronization antenna (GPS antenna) [6].

2.1. Lightning Imaging Sensor

The United States Aeronautics and Space Agency (NASA) that detects lightning from a satellite between the tropics 35 ° north latitude and 35 ° south latitude use the image-based measurement system. The system used is called LIS (Lighting Imaging Sensor), which was developed by a group of scientific research at the Global Center for Hydrology and Climatology (GHCC) and the NASA Marshall Space Flight Center. The system is based on an electronic device of optical elements "imager" which is able to detect and locate lightning during the day and night under the detection of variations of illumination around the globe captured by the satellite. The sensor is part of the Observatory of the Meteorological Measurement of Precipitation in the Tropics (TRMM) and is located 350 km above the surface of the earth [7], [8], [9].

2.2. Word Wide Lightning Location Network

The World Wide Lightning Location Network WWLLN receivers detect the VLF radiation (3–30 kHz) from a lightning stroke and use the time of group arrival (TOGA) to locate the position of the lightning. The WWLLN had 20 stations at the beginning of 2004 and reached more than 70 stations today. The stations consist of a 1.5 m whip antenna, a Global Positioning System (GPS) receiver, a VLF receiver, and a processing computer with Internet connection [10]. Residual minimization methods are used in the TOGA data at the processing stations to create high quality data from lightning locations. The lightning location accuracy of the network is ~5 km [10]. The detection efficiency depends heavily on maximum current values, with values greater than 10% for currents greater than 35 kA and values lower than 2% for currents between 0 and 10 kA. The efficiency can be greatly improved by increasing the number of stations [11].

The lightning data used in this study came from this network due to Chile does not have a lightning detection network. The University of Valparaiso provided the information for the years 2012 and 2013.

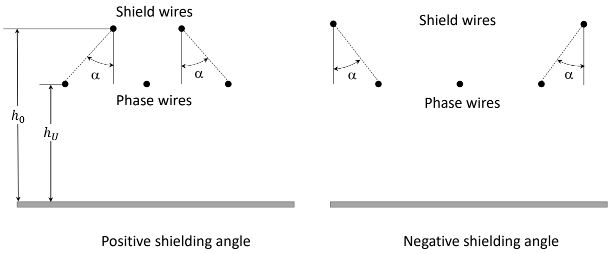
3. LIGHTNING SHIELDING

As it was informed before, lightning is one of the main causes of outage of electric systems. According to international statistics, lightning produces 65% of failures on overhead lines [13]. The rate of failure can be reduced by means of a correct shielding design of overhead line as long as the backflashover does not take place.

The shielding of overhead lines has to take into account electrical parameters of lightning such as keraunic level or ground flash density (GFD), amplitude of lightning current and angle of incidence. In addition, shielding has to consider the geometry of overhead line, wire height, and ground slope. Based on these parameters, the shielding failure flashover rate (SFFOR) is calculated [3].

3.1. Shielding models

To determine the location of shield wire respect to phase conductors, the shielding angle - the angle between the vertical and the line joining the shield wire and the phase wire- has to be determined. The shielding angle can be positive or negative, based on the location of shield wires respect to the phase wires. It is positive if the shield wires are inside the external phases, but is negative it they are outside of them (see Figure 1) [3].



Positive shielding angle

Negative shielding angle

Figure 1. Positive and negative shielding angles

To determine the shielding angle there are classic methods and modern methods. The classic methods are based on geometrical considerations; at the same time, they are divided in methods based on shielding angles and based on arcs. The methods based on shielding angles define protection areas at conical shape delimitated by the line defined by a specific angle. The shielding angles commonly used are 30° and 45°, however, the second one has a higher failure rate that the first one. The methods based on arcs use arcs instead of straight lines, the radius of the arc is the high of shield wire (Schwaiger criterion) or twice this high (Langrehr criterion) [3].

Modern methods are based on experimental and theoretical models of lightning, consequently the location of shield wire considers the rate of failure of the overhead line. Its location takes into account the likelihood of failure of the shielding. The lightning current and the shielding angle determine the probability of lightning strikes on the shield wire, on the phase wire or on the ground. In order to determine where the lightning strikes, the maximum current of shielding failure is computed, this current is the maximum value over that the shielding failure does not take place (lightning strikes the shield wire or ground). Moreover, there is another current to be determined, the critical current; this is the minimum value to produce flashover on the insulation strings [3].

3.2. Attachment models

The attachment models are divided in Electrogeometric models (EGM) and Generic models. The EGM was used in this study to analyze the performance of the overhead lines because it gives a clear and accurate idea of what happens when a discharge occurs on the transmission line [3]. The striking distance between the lightning and the conductors is determined by:

$$S(I) = AI_1^B \tag{1}$$

where S is the striking distance, I_1 is the current of the first return stroke and the coefficients A and B are empirical constants that depend on the magnitude of the current and the striking point [3]. Additionally, the critical distance to ground is calculated by:

$$S(I) = AI_1^B = \gamma S_g I_1 \tag{2}$$

where γ indicates the selectivity of the leader (channel of ionized air) respect to the wire and the ground. It is considered that *Sg* represents the attractive effect of the ground and can be significantly different to *S*, consequently each model has a different value of γ. In this study a value of γ = 1 will be considered, according to Anderson's model [14]. Based on above expression is possible to draw Figure 2 where a wire of length L [km] is located at a height h over the ground. In that figure the striking distance to ground and wire are depicted. From that, the distance R_{EGM} could be computed. See [3] for more detail.

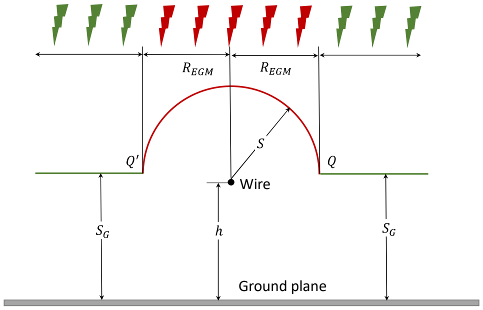


Figure 2. Striking distance of a wire over the ground

If a shield wire (O) and phase wire (U) are installed over the ground surface at a height h_O and h_U respectively, the striking distances are depicted in Figure 3 [1], [2]. If the downward leader reaches the Q'Q'' arc, the strike will be on the shield wire, however if the downward leader reaches the Q'Q arc (exposed arc), there will be shielding failure and the strike will be on the phase wire. The downward leaders that do not reach some point of the arcs mentioned above will finish on the ground.

Considering vertical lightning, the probabilities that the attachment will be on the shielding wire and phase wire are given by Po and Pu, respectively.

$$P_0 = \frac{W_0}{W_0+W_U} \tag{3}$$

$$P_U = \frac{W_U}{W_0+W_U} \tag{4}$$

where W_0 and W_U are the exposed widths of the shield wire and the phase wire, respectively.

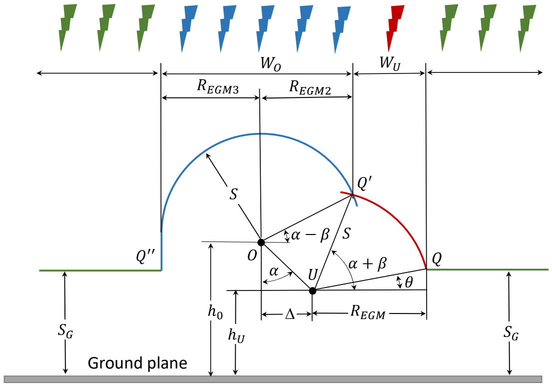


Figure 3. Striking distance of a shield wire and phase wire over the ground

If the ground is not considered entirely flat and the inclination is considered, then the exposed widths are modified according to the Figure 4.

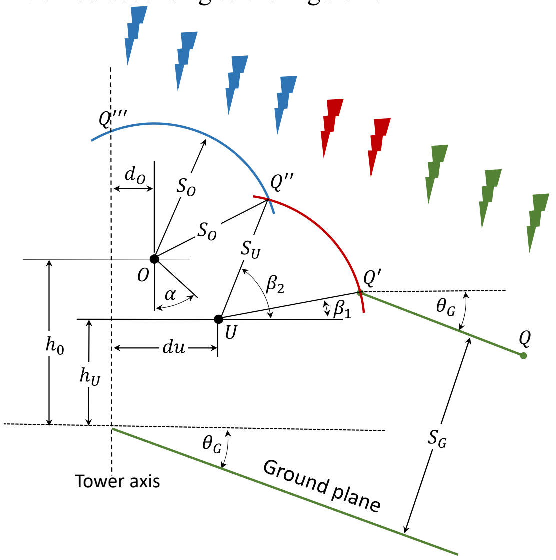


Figure 4. Striking distance of a shield wire and phase wire over the ground with lateral slope.

3.3. Shielding failure outage

The SFFOR is defined as the total number of annual shielding failure outages in a distance of L kilometers along the transmission line. The SFFOR is calculated considering the attractive width, W_U, and the probability density of the prospective lightning current $f_1(I)dI$, as follows [3], [12]:

$$SFFOR = \frac{2GFD}{1000} L \int_{I_{crit}}^{I_{max}} W_U \cdot f_1(I) \cdot dl \tag{5}$$

where *GFD* is the annual ground lightning flash density, and I_{crit} is the minimum lightning stroke current causing flashover.

4. LIGHTNING PARAMETERS FOR CHILE

Chile is divided into 15 territorial regions. For each of them the *GFD* was calculated for the years 2012 and 2013. For this, areas of 5x5 km^2 were used, the total amount of lightning was counting for each area during a year, this value was divided by the area. The results for the two years analyzed were similar. Unfortunately, keraunic levels maps for Chile are outdated and there is no analysis of another detection network such as LIS to determine the efficiency of the WWLLN in Chile. Therefore, *GFD* values can be much higher than those obtained, but without knowing the efficiency of the network, better values cannot be estimated.

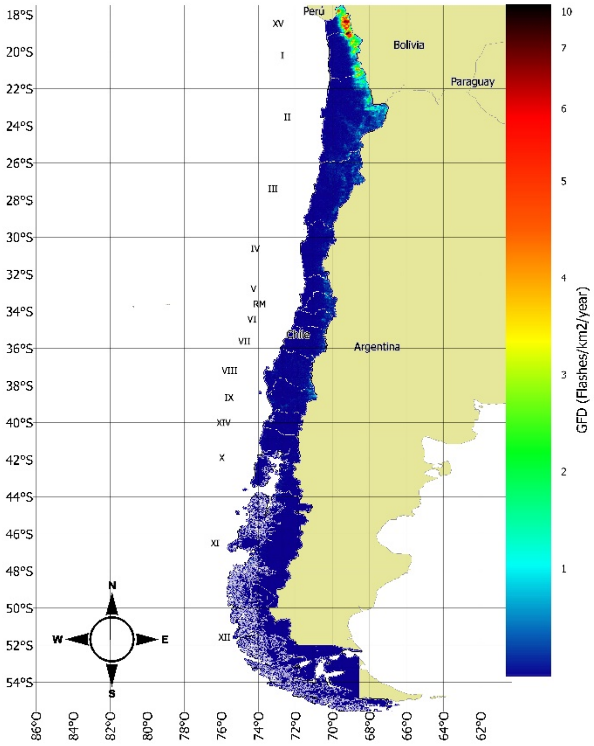


Figure 5 presets GFD for 2013. The higher value is 10 flashes/km^2/year, which takes place in the Andes Mountain between Chile and Bolivia.

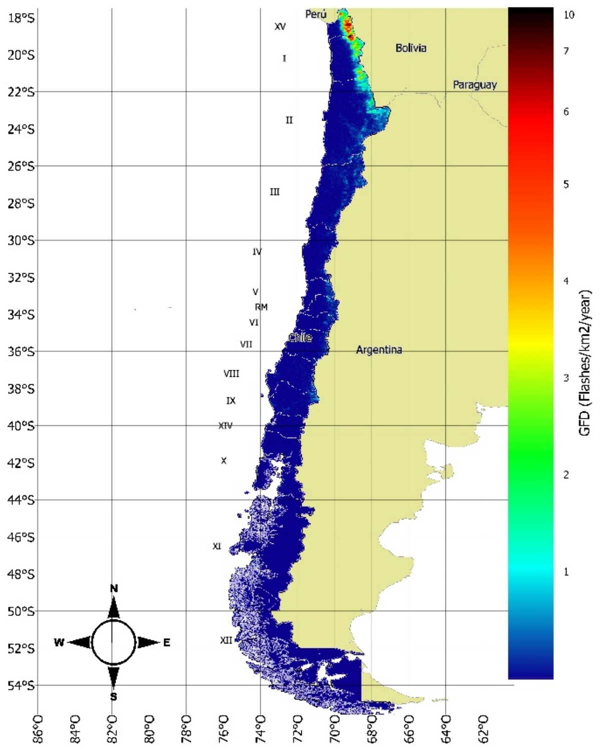


Figure 5. Ground Flash density for Chile for 2013.

5. OVERHEAD LINES UNDER STUDY

Based on Transelec´s databases, five overhead lines were selected for this study. The overhead lines to be analyzed were chosen according to the number of faults reported, length of the line and topography. Table 1 presents the list of the overhead lines selected for the analysis. Information of CFO is not available. The type and number of insulators of each string is included.

Table 1. Overhead lines under study

Overhead Line	Region	Voltage (kV)	Distance (Km)	Insulator (Un)
Tinguiririca – Rancagua – Alto Jahuel	VI	154	184	10*
Sauzal – Rancagua	VI	154	13	10*
Canutillar – Puerto Montt	X	220	60	14*+
Valdivia – Puerto Montt	X - XIV	220	215	12*
Antuco – Charrúa	VIII	220	67	14*

* Insulator B&S 10”x5 ¾”, + insulator type F12 / 146

6. RESULTS

The analysis was developed based on this characteristic:

- The slopes of the ground along the overhead line were considered
- The EGM was applied to perform the analysis with the parameters A = 10, B = 0.65 and γ= 1.

- For the calculation of the probabilities, only the shield wire and the upper phase were considered. This is because it is the most critical phase.
- For all cases, the GFD value was 1.5 flashes/km^2/year. See regions VI, VIII, X and XIV in Figure 5.
- For each of the overhead lines the analysis was done separately for each type of structure.

6.1. Shielding Failure

Taking into account that there is no information about lightning current for Chile, it was not possible to compute the SFFOR for the overhead lines under study, but the maximum current from which there is no shielding failure was computed considering the above described. Table 2 shows these current values for each overhead line. There are minimum and maximum values of lightning current taking into account that every overhead line has different structure types. Each overhead line has up to 15 different structure types, so the analysis was differentiated for each one.

Table 2. Lightning currents to analyze shielding failure

Overhead Line	Imin (kA)	Imax (kA)
Tinguiririca – Rancagua – Alto Jahuel	10	>100
Sauzal – Rancagua	8	30
Canutillar – Puerto Montt	11	25
Valdivia – Puerto Montt	12	21
Antuco – Charrúa	11	58

In order to clarify the results, Figure 6 shows results for Antuco-Charrúa overhead line. It can be seen that the 2A40ER structure does not present shielding failure for currents higher than 11 kA, whereas the 2V038 structure does not present faults for currents greater than 58 kA.

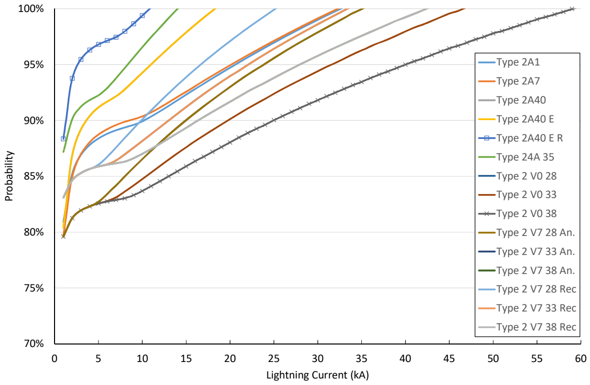


Figure 6. Probability of impact to the shield wire for Antuco – Charrúa overhead line.

6.2. Backflashover

An analysis was made for the overhead line with the highest number of reported faults; this is Canutillar-Puerto Montt, where the type 22DD1 structure was modeled (see Figure 7). Overhead line, structure and grounding were modelled in ATP/EMTP program in order to determine the lightning current from which backflashover can appear over the insulator string.

Figure 7. Type 22DD1 structure

Overhead line was modelled by means of a Jmarti model presents in ATP/EMTP, tower was modelled by means of a multiconductor model according to [15] and the grounding was modelled by means of a resistance of 15 Ω according to information supplied by Transelec. The voltage withstand capability of the insulator is calculated using [16]:

$$V_0 = 0.9(400 + \frac{710}{t^{0.75}})d \qquad (6)$$

where:

V_0 = flashover voltage, kV

t = time elapsed after lightning stroke, µs

d = length of gap between arc horn, m

Taking into account these assumption and parameters, it was found that for currents equal to or greater than 35 kA there would be backflashover in the insulator string. This value must be analyzed together with the current values obtained in the previous numeral, because although some overhead lines are properly shielded the faults can be presented due to backflashovers.

7. CONCLUSIONS

Based on previous analysis and definitions the conclusions are:

- The results presented in this work are very important for the local engineering since there are no previous works that show values of GFD for the Chilean territory. These values were obtained based on the

WWLLN network of the University of Washington State.

- Another important contribution of this work is the analysis of the transmission lines of the main transport company in Chile. It was analyzed the current state of the shielding against lightning for overhead lines with the highest fault rates. The results showed that in some of the overhead lines some of their structures have very high current values for which the shield wires completely shield the phase wires. In short, the shielding failure may occur at medium currents.
- For a particular type of structure in the overhead line that presents the highest failure rate, the current value for which backflashover appears in the insulator string was computed. The critical value for lightning current was 35 kA.
- Finally, it can be stated that the results presented in this study are the starting point for future works because it is necessary to calculate the efficiency of the WWLLN network in Chile and it is necessary to obtain the typical values of lightning current for Chile and thus obtaining better results.

8. ACKNOWLEDGMENT

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