Water Tree Simulation on Underground Polymeric Cable Using Finite Element Method

Muhatifah Mohd Salleh[1], Mohd Hafiez Izzwan Saad[2], Yanuar Z. Arief[2], and Nor Asiah Muhamad[3]

[1]Institute of High Voltage & High Current, Faculty of Engineering,
Universiti Teknologi Malaysia (UTM), 81310 Johor Bahru, Malaysia.
[2]Department of Electrical and Electronic, Faculty of Engineering,
Universiti Malaysia Sarawak (UNIMAS), 94300 Kota Samarahan, Sarawak, Malaysia.
[3]School of Electrical and Electronic Engineering,
Universiti Sains Malaysia (USM), 14300 Nibong Tebal, Penang, Malaysia
ayzulardiansyah@unimas.my

***Abstract*—Most insulation failures in polymeric underground cables have been caused by the formation of water tree in the polyethylene insulation that leads to electrical tree. Electric field intensity is fundamental to water tree growth, hence studying and modeling water tree in a cross-linked polyethylene (XLPE) insulation is vital as insulation failure is frequently triggered by water tree. The aim of this study is to determine the electric field intensity and to identify the electric potential distribution in XLPE insulation used in the underground medium voltage cable which are affected by water tree. Finite Element Method is used to perform the simulation works. The Electrostatic numerical models of 11kV single core XLPE cable affected by the variations of water tree models and size of water tree are analyzed. The two types of water tree, vented tree and bow-tie tree are modeled in the simulation and the properties of the models were set by the experimental value found in the literature. The simulation results revealed that regardless of water tree type, size, length, shape, dimension or location, water tree contributes to higher electric field at the affected region and thus reduces the dielectric strength of cable insulation. Nevertheless, the relative permittivity, shape, length and location of water tree induce a significant variation of electric field intensity in the insulation. The electric field is found to be more intensified at the region where water tree is closer to the conductor. Therefore, electrical tree is more likely generated from the vented water tree initiated from the outer surface of the insulation that grows towards the conductor rather than the other types of water tree.**

***Index Terms*—Finite Element Method; Underground Polymeric Cable; Water Tree; XLPE insulation.**

I. INTRODUCTION

Underground cables have become more popular in recent years because they are less susceptible to environmental damage and have an advantage in densely populated area where land is aesthetically sensitive. In Medium Voltage underground cables, the most insulation failure in polymeric cables reported is due to formation of water tree in the polyethylene insulation that lead to electrical tree.

Water treeing have been being first described by Kitchin and Pratt in 1958 and the degradation of polyethylene due to water tree was first reported by Miyashita in 1969 [1]. Thus, studies on water tree have been continuously investigated for almost five decades and there is vast research about the water tree degradation [2].

Water treeing is a degradation phenomenon developing in dielectric insulation exposed to sufficient electric fields [3, 4] and relative humidity in the cable insulation exceeds a value of 70% [5]. Formation of a tree-like feature of voids and micro channels filled with water in the direction of electric field is result for the reduction of electrical breakdown strength in the cable insulation. This phenomenon has unfavorable effect to electric field distribution in cable insulation which reduces the dielectric breakdown potential of the cable and eventually causing catastrophic breakdown of the cable.

The water tree grows at a slow process and may take months or even years to grow and propagate. Water tree may propagate and breach the entire insulation and as they grow, the dielectric strength of the insulation getting lower that will cause electrical trees [6, 7]. The growth of water tree is first, the initiation of water tree, then the alone growth of water tree and finally, with the presence of water trees growth in the insulation, distribution of electric field is transformed which causes electrical stress in a cable insulation.

There is a vast research and report on the water treeing mechanism in the literature, but the simulation of water treeing in medium voltage underground cables has received little attention and was not widely reported. Electric field intensity is the fundamental of the water tree growth and it is difficult to observe or show the increase in the electric field. The effect of electric field intensity and electric potential due to water treeing in cable insulation can be observed through the simulation of electric field distribution based on a finite element method (FEM). Furthermore, the knowledge of transformation in electric field distribution across the insulation which causes dielectric breakdown can guide experimental effectively. The main objective of this study is to observe and simulate the electric field and electric potential distribution in the XLPE insulation used in medium voltage underground cable (11kV) affected by water tree using finite element method. Furthermore, it is also to observe the electric field distribution and compute the electric field stress exerted by water tree inside cable insulation with various water tree conditions and water tree models.

II. SIMULATION PROCEDURE

The simulation workflow of this study is illustrated as shown in Figure 1. Two-dimension models are used for the simulation of the electric field. Field lines are perpendicular to equipotential lines and directed from conductor to the outer sheath of the cable. Hence, 2D model is appropriate to study the electric field and electric potential distribution.

The models were developed in electrostatic regime where the Poisson equation is solved. After setting up the model environment, the next step is to draw the models. In this study, only three shapes are used, circle, ellipse and rectangle to draw the cable model and water tree model. Boolean operations such as union, difference, and intersection are used to form more complicated shapes to draw the water tree models.

A. Medium voltage underground cable modeling

Medium Voltage underground distribution cable of 11 kV is used for this study. The cable consists of stranded copper conductor and covered with an inner layer of semi-conductive polymer. The insulation of the cable is made of a cross-linked polyethylene (XLPE) and covered with an outer layer of semi conductive polymer. A set of copper wire screen are positioned on top of the outer layer of semi conductive polymer. The outer jacket for the cable is made of a polyvinyl chloride (PVC). The main function of conductor screen is to provide smooth interface between conductor and insulation and they are chemically bonded.

The presence of conductor screen is to prevent the sharp points that could intense the electric field concentration which results to high voltage stress between conductor and insulation. Semi-conductive material is used for the conductor screen so that the conductor and conductor screen are at the same potential when the voltage applied at the cable. The insulation screen provides the same purpose as the conductor screen. It is to ensure that the voltage outside the insulation is at ground potential. Hence, in this simulation, the conductor screen is set at the same potential as conductor at 11kV and insulation screen is at zero potential.

The modeling parameter of the cable is tabulated in Table 1 and two dimensional (2D) electrostatic model of 11kV single core XLPE power cable has been developed in this study as shown in Figure 2(a). The mesh is generated in the model cable so that the simulation software will compute the electric field and electric potential distribution across the insulation as shown in Figure 2(b).

To compute the electric field peak inside the insulation with the presence of water tree, the water tree model is considered in line with electric field in x-axis. It was in that way since the water tree propagates in the direction of the electric field. The location of water tree inside the cable insulation is shown in Figure 3.

B. Water tree modeling

Two types of water tree model are considered in this paper, individual water tree of ellipse shape and bouquet or branch structure of water tree consist of water filled voids connected with micro channels. The latter, water tree is modelled as water voids forming a string of pearls interconnected by narrow channel. The water trees properties and parameter are taken from the literature into the water tree models as tabulated in Table 2[8-10].

There are two types of vented water tree model found in the literature. Vented water tree can be modeled either as "bouquets" or branches of micro-cavities or individual vented water tree. "Bouquets" is defined as water voids forming a string of pearls interconnected by narrow channel.

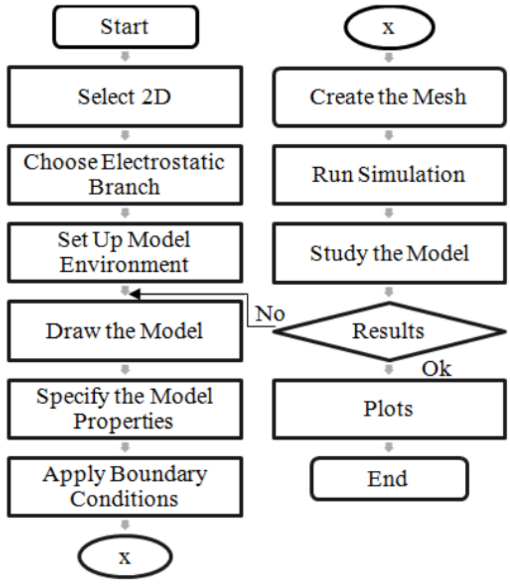
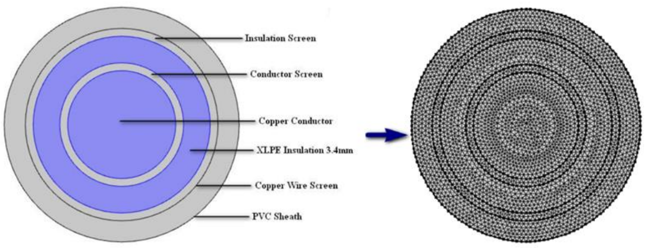


Figure 1: Flow chart of the simulation

Table 1
Physical properties and parameter of cable model

Cable components	Size (mm^2)	Material	Permittivity, ε_r	Conductivity, σ (S/m)
Conductor	Nominal area : 150	Stranded copper	1	6×10^{17}
Conductor screen	1.0	Semi conductive polymer	20	1×10^{-14}
Insulation	3.4	XLPE	2.3	1×10^{-15}
Insulation screen	Thickness: 1.0	semi conductive polymer	20	1×10^{-14}
Metallic screen	0.8	Copper wire	1	6×10^{17}
Outer sheath	1.9	PVC	2.9	1×10^{-15}
Overall diameter	30			



(a) 2D cable model (b) Meshing the cable model

Figure 2: Single core XLPE Model for water tree simulation

Table 2
Properties of water tree model

Water tree Model		Permittivity, ε_r	Conductivity, σ (S/m)
- Individual Ellipsoid		5	5×10^{-2}
- Relative permittivity:	Water voids	80	5.86×10^{-6}
	Channels	16	1×10^{-17}

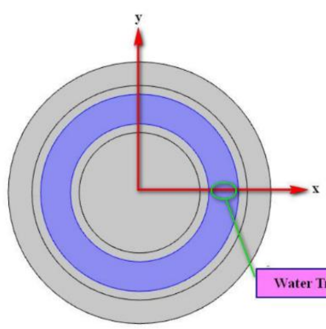


Figure 3: x-y axes in 2D domain inside cable insulation

The individual vented water tree model is illustrated as shown in Figure 4(a). Vented water is modeled as a shape of ellipsoid inside the cable insulation. The relative permittivity of a water tree is 5 instead of 80 for the water since the ellipsoid is not a water void, but representation of water tree which consists of water filled micro voids interconnected by channels. The size of the water tree is 0.3mm in major axis (0.6mm in length) and 0.1mm in minor axis (0.2mm in width).

The structure of bouquet water tree model is illustrated in Figure 4(b). The model is consisting of water tree main body with 12µm in major axis and 8µm in minor axis, water tree channels with 2µm in length and 0.2µm in width and ellipsoidal voids with 1.5µm in major axis and 0.5µm in minor axis. Bow-Tie water tree is modelled as an individual water tree. The model of bow-tie water tree is illustrated in Figure 4(c). The shape of the model is two ellipsoids group together in contact by their poles with a common major axis. The relative permittivity of the bow-tie water tree is 5.5.

The length of water tree models is based on insulation degradation condition state level as recommendation proposed in [11] and tabulated in Table 3. Therefore, three different lengths of water tree considered in this paper are based on thickness of 3.4 mm of XLPE insulation. The length of 0.3 mm water tree represents the mild degradation of the insulation, while 0.7 mm water tree length represents the moderate degradation and 1.5 mm water tree length represents the severe degradation in the cable insulation. The purpose of three different lengths of water tree considered in this paper is to study the effect of water tree length on the electric field distribution.

There are three geometric shapes of water tree model considered in this simulation to study the effect of water tree shape of the electric field distribution. The shapes of water tree in 3D model are cylindrical, spherical and elliptical located inside cable insulation. In 2D coordinates, these shapes became a circle for spherical, a rectangle for cylindrical and an ellipse for elliptical. The geometric shapes of vented water tree modeled on this study are shown in Figure 5.

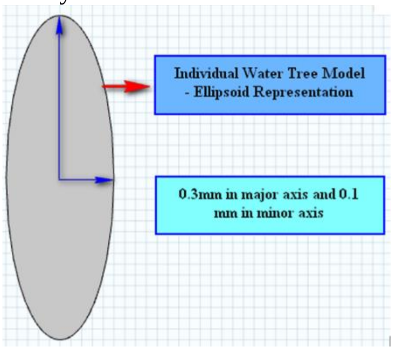
III. Results and Discussion

A. Individual water tree

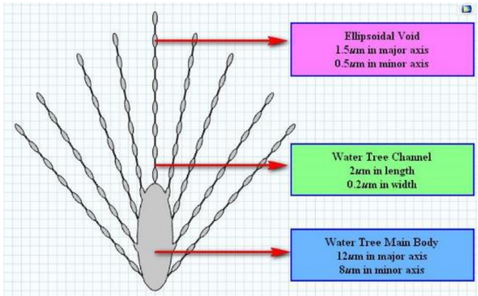
Simulation of a single ellipsoid model represents the vented water tree located in the middle of the insulation was performed in this study. The properties of this water tree are taken from the literature in [8]. This was done to understand the effect of single water tree on the electric field and electric potential distribution inside the cable insulation. Figure 6(a) shows a single ellipse of water tree in the middle of the XLPE insulation. This dimension of ellipse water tree was chosen about 20% of width across the insulation with the length of 0.6 mm and width of 0.2 mm and placed in the middle of the insulation material. Relative permittivity of water tree is 5 and electrical conductivity of the water tree is 5x10-2 S/m. Relative permittivity of XLPE is 2.3 and electrical conductivity of XLPE is 1x10-15 S/m.

The simulation results show that the ellipse water tree has distorted the electric potential inside the insulation as indicated by contour and surface plot as well as line graph as shown in Figure 6(b). However, the maximum potential remains at 11 kV and reduces at zero potential at ground conductor.

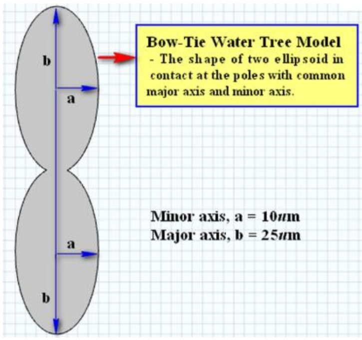
The line graph shows that electric field increases at the edges of the water tree especially close to the conductor and decreases inside the water tree region. With the presence of water tree, the peak value of the electric field computed is 5.6kV/mm, compared with healthy cable, which the computed peak value is 3.4kV/mm at the same location. The amplification of the electric field at the edges of water tree is almost 65%, significantly greater than the normal electric field in the healthy cable.



(a) Individual vented water tree



(b) Bouquet vented water tree

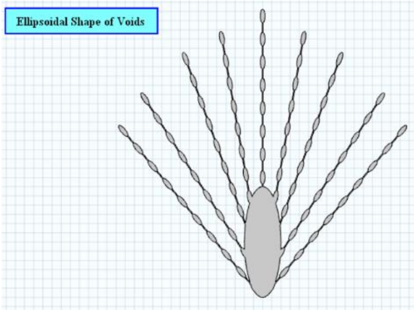


(c) Bow-tie water tree

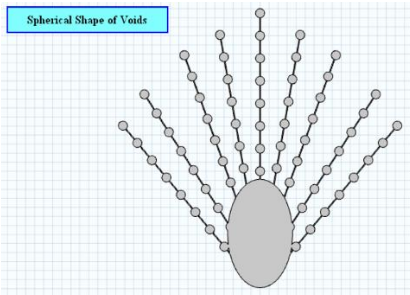
Figure 4: Type of water tree

Table 3
Definition of insulation degradation condition state level [11]

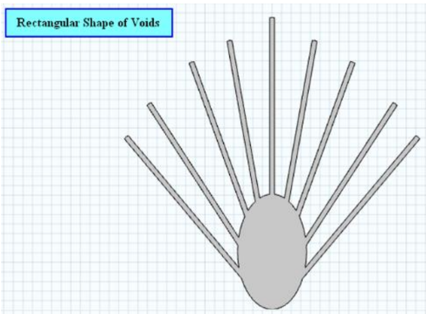
Insulation Degradation Condition State	Description	Length of Water Tree (Insulation thickness: 3.4mm)
No degradation	Insulation good as new	No water tree
Mild degradation	Small water tree Length of WT < 10% of insulation thickness	0. 3mm
Moderate degradation	Moderate water tree Length of WT 10% ~ 30% of insulation thickness	0.7 mm
Severe degradation	Severe water tree Length of WT > 30% of Insulation thickness	1.5 mm



(a) Ellipsoid shape braches



(b) Spherical shape branches



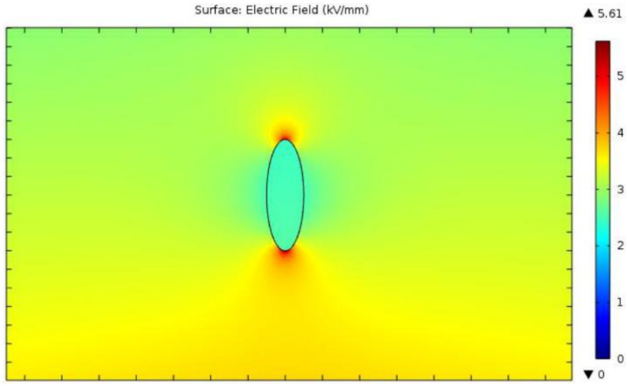
(c) Rectangular shape branches

Figure 5: Three different geometric of vented water tree model

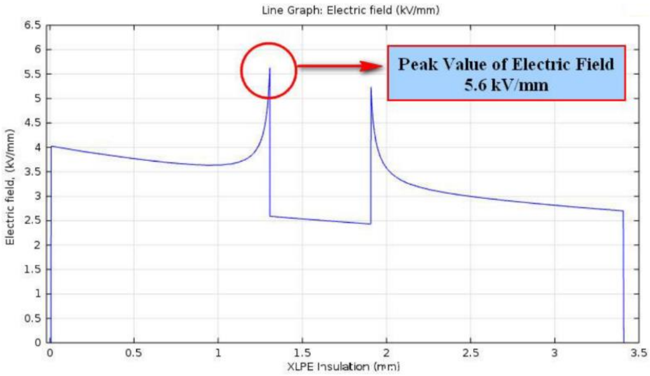
B. Different length of water tree

The simulation of three different lengths of water tree is performed to observe the electric field behavior with the growth of water tree size. The length is determined based on definition of insulation degradation condition state level (mild, moderate, severe) found in the literature. In this study, the thickness of the XLPE insulation is 3.4mm, therefore, the length of the water trees is 0.3mm, 0.7mm and 1.5mm. The water trees are located at the same distance, 0.5mm from the surface of the conductor as shown in Figure 7 (a). Electric field variations along radial line across the vented water tree of 1.5mm length is shown in Figure 7(b).

The increase of electric field at that region is almost 65%. For 0.7mm vented water tree, the computed electric field peak is 6.7kV/mm, amplification of 81% of electric field at the tip of the water tree. The longest vented water tree, 1.5mm shows the peak at 7.0kV/mm which indicates the highest electric field amplification at the tip of water tree at 90% with respect to the absence of water tree. The summary of electric field computation for three different lengths of vented water tree are summarized in Table 4.



(a) Surface plot for electric field distribution



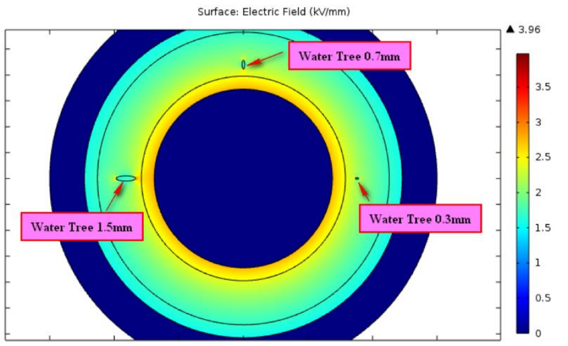
(b) Line graph for electric field distribution

Figure 6: Simulation result for single water tree

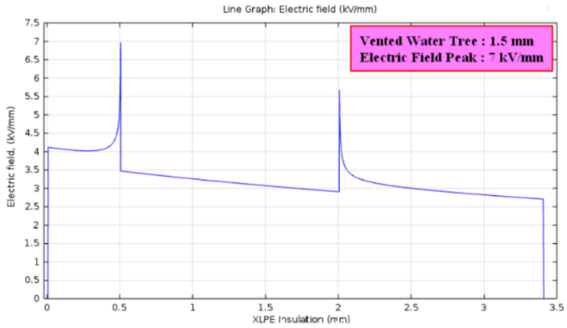
C. Different geometric shape and length of water tree

The simulation of different geometric shapes of water tree models is performed to study the electric field behavior in the cable insulation affected by different shapes of water tree. Three geometric shapes of water tree models are considered in this simulation, ellipsoidal, spherical and rectangular shapes for the water tree branches. The lengths of each three different models are 1.0mm. The computational domain of the water trees is displayed in Figure 8.

It is observed that the rectangular shape has the highest value of the electric field at the water tree tip followed by ellipsoid shape, while the spherical shape has the lowest value of the electric field at the water tree tip in comparison with rectangular and ellipsoidal shape. It proved that the sharp edge at the rectangle shape will have more concentration of electric field at the tip compared with smooth edge at circle shape. The electric field distribution at the tip of water tree in different geometric shapes is summarized in Table 5.



(a) Computational domain of electric field and electric potential inside cable insulation

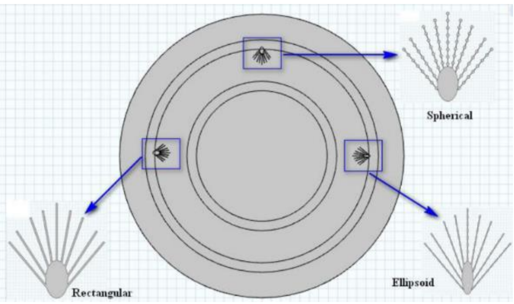


(b) Variation of electric field inside cable insulation across the lengths of water tree of 1.5mm

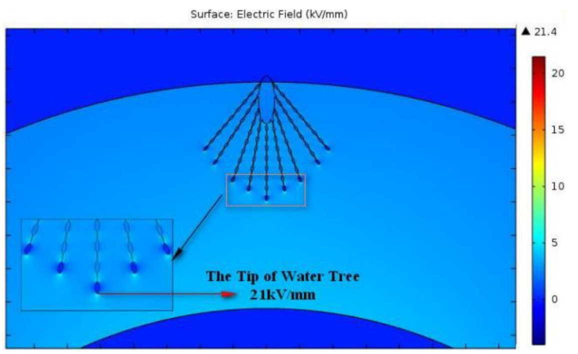
Figure 7: Simulation for different length of water tree

Table 4
Summary of electric field simulation for different length of vented water tree

No.	Length of WT (mm)	Distance from conductor (mm)	Electric field peak (kV/mm)	Field Amplification (%)
1.	No water tree	0.5	3.7	-
2.	0.3	0.5	6.1	64.9
3.	0.7	0.5	6.7	81.1
4.	1.5	0.5	7.0	89.2



(a) Computational domain of different shape of water tree



(b) Electric field distribution of ellipsoidal shape of vented water tree

Figure 8: Simulation for different geometric shape of water tree

Table 5
Summary of electric field distribution at the tip of water tree shapes

No.	Geometric shape of water tree	Electric field at the tip of water tree(kV/mm)
1.	Ellipsoidal	21
2.	Spherical	13
3.	Rectangular	29

IV. Conclusion

From the simulation results, it is found that the electric field is higher where water tree in the cable insulation models. The electric field intensity is higher when the size of water tree is bigger. The presence of 1.5mm length of vented water tree inside cable insulation showed a remarkable peak at 89.2% amplification of electric field at that region, 0.7mm vented water tree gave electric field amplification of 81.1% and 0.3mm vented water tree showed 64.9% increase in electric field, respectively. It is observed that the electric field intensity is one of the factors influenced the development of the water tree growth. The electric field distribution and peak value of electric field is also influenced by the relative permittivity of the water tree, the geometric shape or model of water tree, the size of water tree and position or location of the water tree, respectively. Electric field near water tree is a function of the edge sharpness of water tree. It was shown in the simulation results of three geometric shapes of water tree where the rectangular model with sharp edges gave the highest peak of electric field stress at 29kV/mm compared to ellipsoidal model (21kV/mm) and spherical model (13kV/mm). It also found that the closer water tree to the conductor, higher the electric field near the water tree. The electric field between two water trees is higher when the water trees are growing toward each other.

Meanwhile, for the electric potential distribution inside the cable insulation, the simulation results showed that the voltage remains at maximum value of 11kV and reduce to zero potential at ground sheath for all the cases of the simulation. However, the electric potential distributions were distorted due to the presence of water tree and the magnitude of the distortion is influenced by the shape and size of water trees. With a finite element method software, the computation of electric field inside the cable insulation is easily computed and the electric field and electric potential inside the cable insulation can be estimated and observed.

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