STUDY OF CURRENT DISTRIBUTION IN WOODEN SUPPORTING STRUCTURES USING FINITE ELEMENT METHOD

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Abstract: The power distribution and transmission networks in many countries use wood for fabricating service poles for the overhead power lines. A main disadvantage of using these wooden poles is the formation of pole top fires. In this paper, a wooden pole used in an 11kV distribution system is modelled and the current distributions of the wooden supporting structures are studied using Finite Element Analysis. The three dimensional model takes into consideration both the resistive and capacitive properties and closely resembles the actual pole. The current distributions are used to understand the heat generation at the metal / wood interfaces of the structure at different weather conditions. Our analysis show that the voltage and current distributions of the utility pole changes significantly with the change of moisture content, and the current density distribution can be very high at wet conditions. We could see from the thermal analysis, that due to this high current distribution, the temperature of the metal / wood interface could rise over 100 ^{0}C, making an aged wooden pole vulnerable to fire.

1 INTRODUCTION

Electricity has become a necessity in the 21st century with industries as well as households demanding an efficient, faultless and uninterrupted power supply. Having proper infrastructure in the transmission and distribution networks is paramount in achieving this objective. Inability to provide this infrastructure not only affects the reliability of the supply, but also may cause atrocious disasters which would affect the wellbeing of mankind. The reliability and the safety of power are the two main motivation factors behind our work.

In many countries, wood is the most popular fabrication medium for utility poles in power distribution and transmission networks. Its low initial cost, environmental impacts and electrical and mechanical properties makes wood advantageous over most other materials such as concrete, steel, and fibreglass reinforced composite poles. In Australia, there are more than 5 million wooden poles used in energy networks, and in the state of Victoria the number exceeds 0.8 million, which is 74% of the total number of utility poles used in the state [1].

Even though wooden poles have many advantages over its alternatives in terms of the above discussed qualities, it has a major disadvantage, which is the formation of pole top fires [2]. This affects the reliability of the system through interruptions. The fires may also lead to catastrophes such as bush fires, which have become a main concern in Victoria and other parts of Australia in the past decade [3]. In the recent years, the annual wood pole failures in some parts of Australia have gone well above industry standards, with the Western Australian network having between 1.88 to 4.34 failures per year, per 10,000, in comparison with the industry target of 1 per year, per 10,000 [4].

There are two types of burning that can occur in wood, which are pocket burning and tree burning. Pocket burning extends into the body of wood and may damage the wooden members. This requires replacement of the poles. On the other hand, tree burning forms carbon paths in the surface, and even though these occur more frequently, it doesn't damage the wood and requires no replacement [5]. Finding a solution to this problem started with research on the physical properties of wood [6, 7] and reliability assessments of the pole. These works included studying the effect of humidity levels on fire formation in wood and the use of preservatives to reduce the risk of fire. However, the research focus shifted to an electrical engineering view point gradually.

In this perspective, the main causes of wood pole fires are deemed to be dry band arcing [5] and leakage current of high voltage (HV) insulators [8]. Dry band arcing occurs if a small portion of the pole is dry, which is a common occurrence after a light shower on a windy day. The resistance of wood becomes very low when wet because of the increased moisture content inside wood [8, 9], which makes a series connection with the dry parts having a very high resistance. The concentration of the voltage drop across the dry area leads to electric breakdown and forms carbonized paths along the wooden pole. It is shown in previous experiments that when a small current flows through the wooden pole, these carbonized paths ignite the wood which leads to pole top fires [10]. The other major cause is the leakage current of HV insulators which flow through the pole causing the structure to heat up due to its resistance variations [6]. Ultimately, this generated heat may cause fire.

Experiments also show that fire is more prone to occur at the metal and wood interfaces of the structure. Some work has already been carried out to study the effect of the current flows in generating heat at these interfaces. [9] studied the leakage current in the wooden pole, and [11] studied the current induced at the king bolt (the bolt inserted to attach the supporting cross arm to the pole). In [9], the structure was assumed to be purely resistive, and in [11], the model of the pole was considered axisymmetrical. A novel approach which our work takes is studying the behaviour of these interfaces under an electromagnetic environment with a goal of uncovering the most critical reasoning for pole top fires. Unlike previous work, this paper simultaneously takes into consideration the resistive and capacitive properties as well as the three dimensional geometry of the wooden pole, making the model almost similar to the actual scenario.

In this paper, the current distribution of the structure at various weather conditions is studied in an electromagnetic environment. In order to calculate the current distribution, we calculate the potential gradients of the three dimensional structure of the wooden pole using the Finite Element Method (FEM). These results are then used to obtain the heat generation and the temperature rise at the metal / wood interface. From the results obtained from the above calculations, we show that there can be a considerable temperature increase at the metal / wood junction, which some times can reach 100 ^{0}C, even with a small amount of current flowing through the metal bolt.

The structure of the paper is as follows. The system model and the problem formulation is given in section 2. Section 3 summarizes some important and fundamental results from FEM which are useful in the analysis. We present the results in section 4, and Section 5 concludes the paper.

2 SYSTEM MODEL AND PROBLEM FORMULATION

In this study, a chromate copper arsenate (CCA) treated red pine pole is modelled and analysed at different weather conditions. The wooden pole is cylindrical with a height of 10 meters and has a constant diameter from top to bottom as illustrated in Figure 1. The stainless steel king bolt which has a radius of 15mm is inserted across the diameter of the pole 0.5 meters from the top. This bolt is used to fix the cross arm at the top of the pole. The wooden structure consists of two types of wood, namely heartwood and sapwood, which have different electrical properties due to their different moisture contents. The moisture gradient of heartwood is considered 5% higher than that of sapwood at dry weather conditions since it is the interior of the pole and not directly exposed to sun light (refer Figure 1). The resistivity of sapwood and heartwood are calculated as

$$\rho = 10^{(-0.25(MC\%)+9.12)}(\Omega m), \tag{1}$$

where *MC* is the moisture content of wood [8]. The permittivity of wood at different moisture contents are given in [12].

Three types of weather conditions are considered in this study. The moisture contents of sapwood and heartwood for each of these conditions are given in Table 1. An 11kV supply is modelled by an Aluminium conductor which is placed on the top of an 11kV insulator. The metal / wood contact may not be perfect due to manufacturing methods, thus air or other gasses can be present at these cavities. A thin air layer is inserted around several parts of the bolt to model these cavities. We analyze the electric field, voltage and the current distributions of the area where the bolt is inserted using FEM.

In the next section, we will briefly summarize sum important theoretical aspects of FEM, which will be useful in obtaining the results.

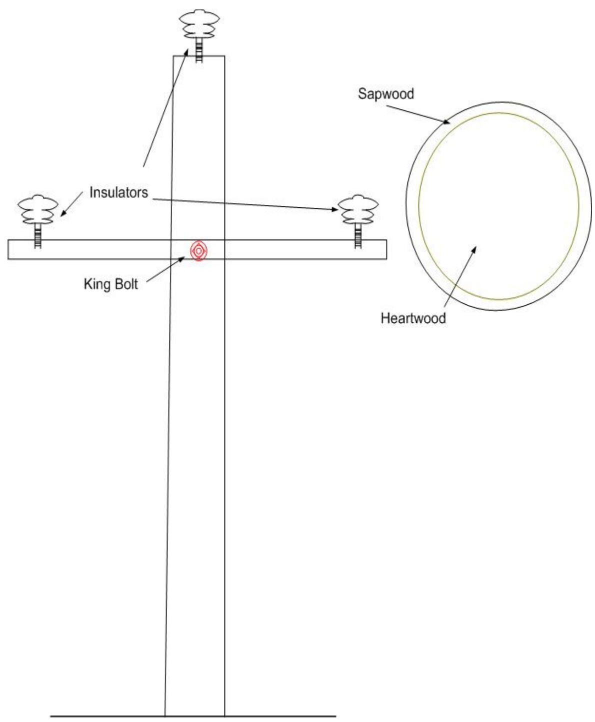

Figure 1: The model of the utility pole

Table 1: Moisture Gradient of sapwood and heartwood at different weather conditions.

Weather Condition	Moisture Content (%)	
	Heartwood	Sapwood
Dry	11	11
Slightly wet	14	14
Moderately wet	18	22

3 FINITE ELEMENT ANALYSIS

Finite element analysis is used to solve the Maxwell's equations in order to understand the electric fields around the wooden pole structure. The area under discussion is divided into tetrahedral elements as shown in Figure 2. The electric field, voltage distribution and current density are calculated for each of these elements.

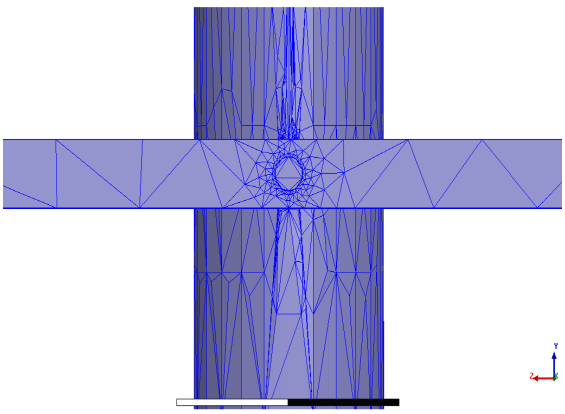

Figure 2: Finite Element Mesh created for analysing the structure

Electric Field calculations: The utility pole discussed in this study has both conductive and dielectric properties. The field equation for a region where materials hold both conductive and dielectric properties is given in [13] as

$$div\left[\sigma.grad(\phi)+\frac{\partial}{\partial t}\{\varepsilon.grad(\phi)\}\right]=0, \quad (2)$$

where Φ is the potential, σ is the conductivity and ε is the permittivity of the elements. Once the electric potential is obtained by solving the above equation for the problem region, Maxwell's equations are then used to calculate the electric field strength *E* as follows:

$$E=-grad(\phi) \quad (3)$$

Current density calculations: The current density

$$J_i=(\sigma+j\omega\varepsilon).E_i, \quad (4)$$

where σ+jωε is the complex conductivity of the element. The subscript *i* is used to represent the i^{th} element.

Thermal Analysis: The rate of heat generation in a current carrying resistive element is calculated using the fundamental equation

$$P=I^2R, \quad (5)$$

where *I* is the current flow and *R* is the resistance of the object.

4 RESULTS AND DISCUSSION

4.1 Electric Field

Electric field distribution of the metal, wood and air interfaces at dry weather with no moisture present at the insulator is shown in Figure 3. The current conduction from the conductor to ground is almost zero because of the high resistance of the whole structure. Here, the insulator is considered as a perfect insulator with no surface pollution. It can be clearly seen that the electric field distribution in the concerned area is in the range of 0 - 2kV/mm, and the highest gradient occurs at the interface of wood and air. This high electric field is present due to the vastly different electrical properties of wood, air and metal. Metal would be at a very low potential due to its conducting nature. The wooden surface which is highly resistive at this point with the additional connecting resistance of air will be at a very high potential. Hence, the electric field of air between wood and metal will be very high.

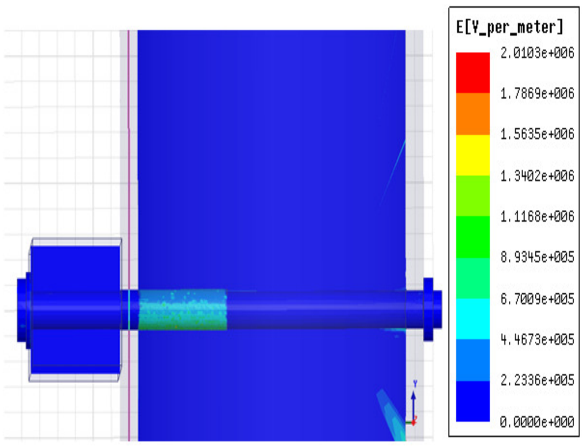

Figure 3: Electric field around the metal / wood interface at dry weather

To get a clear idea of the voltage distribution, the voltages along the marked lines in Figure 4 are plotted in Figure 5. Line AB, which is 5m long, starts at heartwood and then goes through the wood, metal and air interfaces along the pole length. Line CD, starts at the top of the pole and goes down through sapwood along its length. The change in voltage due to the complex conductivity of different materials can be seen in Figure 5. Along line AB, the voltage is high at the beginning because of the low resistivity of heartwood, and then gradually decreases along its length. It again increases near the air layer because of the change in electric properties as discussed above, and then becomes almost zero at the bolt because of its high conductivity. Along CD, the voltage is mostly zero due to the high resistance of sapwood. However, this gradually increases up to 25V when it comes close to the air layer.

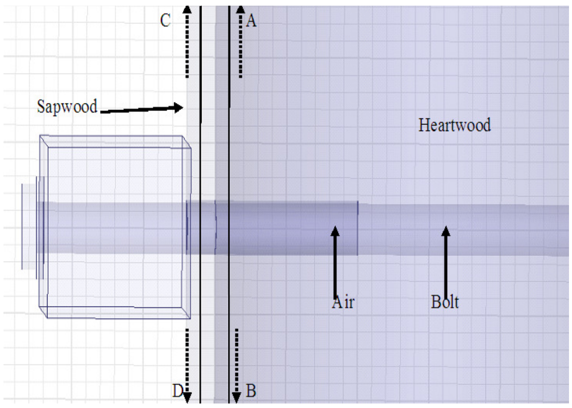

Figure 4: Geometry lines used for the voltage plot

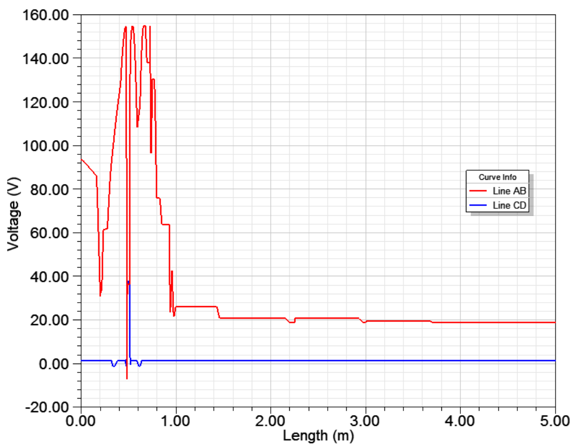

Figure 5: Voltage Distribution along the length of the pole

With the understanding With the understanding of the field characteristics at dry weather conditions, our analysis next focuses on the behaviour of the electric field at slightly wet weather conditions. This scenario can occur at the presence of light showers, causing the moisture content of wood to increase by 11 – 16%. This increased moisture content changes the properties of sapwood and heartwood, making them more conductive, hence changing the electrical properties of the whole structure. Even though the distribution patterns are the same as dry weather conditions, the magnitude of the electric field around the metal wood interface diminishes slightly. This happens due to the change in electrical properties of the wooden members. The change in complex conductivity of the wood surrounding the bolt reduces the diversity of the electrical properties. This reduces the potential gradient, resulting in a lower electric field.

Our next test case is for moderately wet weather conditions. Due to the high moisture content (22% –27%) the conductivity of wood increases, resulting in a higher leakage current flow in the system. Since the rain cannot penetrate through sapwood to the heartwood instantly during rain, the heartwood part was modelled to have a moisture content of 20%. Normally at this type of weather, a water trail forms from the conductor to the pole, creating a direct conducting path from the top to bottom. This makes the voltage at the top of the wooden pole very high, thus allowing a high leakage from top to the ground. Figure 6 shows that at extremely wet weather conditions, the electric field of air captivated between the bolt and the pole is very high, and in the range of 2-3 kV/mm.

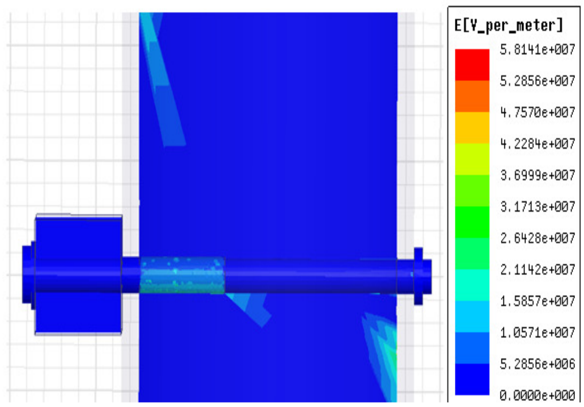

Figure 6: Electric field around the metal / wood interface at wet weather

4.2 Current Distribution

Figure 7 presents the current density distribution of a cross section at the metal / wood interface for dry weather conditions. The current flow through the bolt is around 10μA, which is negligible when it comes to pole fire studies. A zero current density can be observed at some parts of the bolt. These are the parts which are surrounded by the trapped air. There is no conducting path from the bolt to the ground because of the very high resistance of air. The current flow through heartwood is also very low, allowing only a very small heat generation.

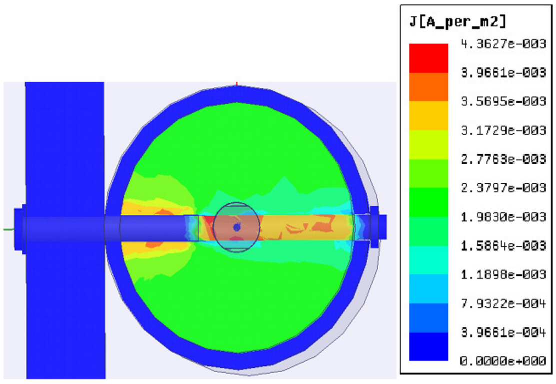

Figure 7: Current density around the metal / wood interface at dry weather

The next step was analysing the current distribution at slightly wet weather conditions. The current density distribution around the metal bolt for this scenario is shown in Figure 8. The maximum current flow through the bolt in this case is around 1mA, which also may not generate much heat when flowing through highly resistive wooden parts. The current density of both Sapwood and heartwood have increased at wet weather conditions, but still, the current magnitude is very low and does not contribute to the heating of the wooden parts.

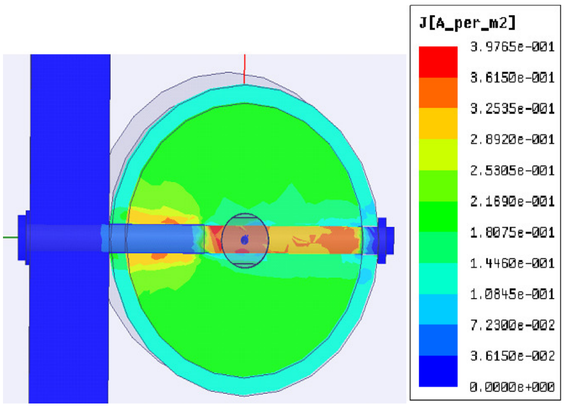

Figure 8: Current density around the metal / wood interface at slightly wet weather

Figure 9 shows the current distribution at moderately wet weather conditions, where a water trail is present around the insulator from the conductor to the pole. This allows a high current to pass through the pole. The current density of heartwood and the bolt are very high in this case, and the maximum current that flows through the bolt is 60mA. This can increase the temperature of the structure depending on their specific heat constants. Coupling the results obtained here in a thermal analyser shows that the temperature of the structure may increase up to 100 ^{0}C, and the maximum temperature rise occurs in heartwood, where the metal bolt is inserted. This is quite a considerable increase.

Since the current flow through the structure varies depending on the electric properties of the wood, our analysis also focused on studying the effect of the current flow through the bolt. We considered this important since the fires normally start at this metal / wood interface, and we chose the moderately wet weather conditions. To study this phenomenon, we turned off the 11kV supply and injected a current to the metal bolt. Turning off the supply makes sure that there is no conducting path between the supply and the wood, and the only current through the pole is the one which was injected at the bolt. Then, we observed the temperature rise at the metal / wood junction. Figure 10 shows the temperature rise for currents between 5mA – 60mA, with a step size of 5mA.

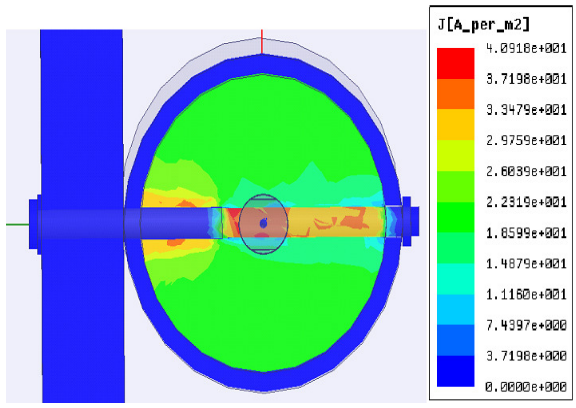

Figure 9: Current density around the metal / wood interface at dry weather

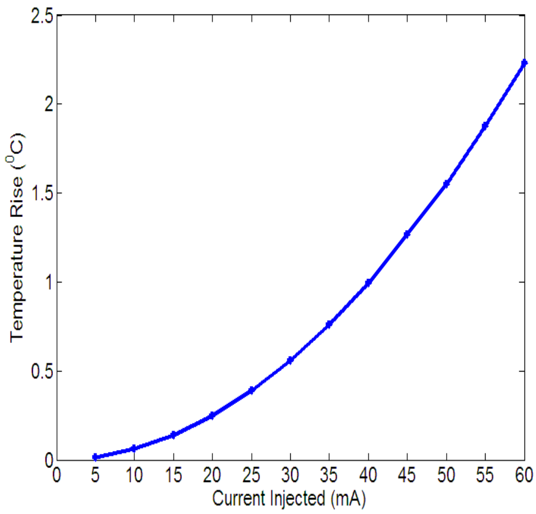

Figure 10: Temperature variation at the metal / wood junction with the injected current

These results show that even without any influence of the supply, the current flow through the bolt can increase the temperature of surrounding wooden particles considerably.

Figure 11 shows the maximum heat generation at each of these simulation steps. From these results, we can see intuitively that when the influence of the supply is also present in an aged structure, where many dry band arcs has occurred and many carbon paths are present at the metal / wood junction, this heat can be sufficient to ignite the wood.

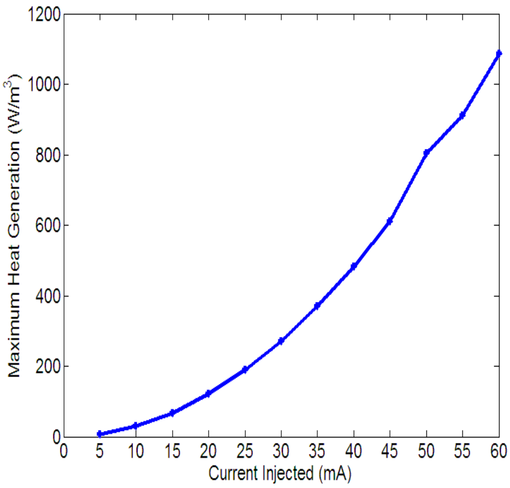

Figure 11: Heat generation at the metal / wood junction with the injected current

5 CONCLUSION

In this paper, the behaviour of a wooden utility pole under an electromagnetic environment is studied using Finite Element Analysis. The actual three dimensional geometry of the structure is modelled under an 11kV distribution line in order to calculate the electric field and the current distribution of the wooden pole. The analysis was done at three different weather conditions. We could see that the voltage and current distribution of the utility pole changes significantly with the moisture content of the environment. At wet weather conditions, the current density distribution around the metal / wood interface is very high due to the conducting nature of the structure. We could see from the thermal analysis that the temperature of the metal / wood interface could raise over 100 ^{0}C due to this high current distribution. We further show that even without any influence of the 11kV supply, a current flow through the bolt can increase the temperature of surrounding wooden particles considerably. This generated heat can damage an aged wooden structure where dry band arcs have carbonized the wooden surface of the metal / wood interface.

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