FEA Simulation Studies of Accelerated Aging of Power Cables in Water Tanks

Xufei Ge
Institute of Energy and Environment
Dept. of Electronic & Electrical Engineering
University of Strathclyde
Glasgow, UK
xufei.ge@strath.ac.uk

Martin Given
Institute of Energy and Environment
Dept. of Electronic & Electrical Engineering
University of Strathclyde
Glasgow, UK
m.given@strath.ac.uk

Brian G Stewart
Institute of Energy and Environment
Dept. of Electronic & Electrical Engineering
University of Strathclyde
Glasgow, UK
brian.stewart.100@strath.ac.uk

***Abstract*—IEEE Standard 1407 provides guidance on accelerated insulation aging experiments on multiple medium voltage (MV) power cables using water-filled tanks. An applied cable current increases the temperature within the water tank and thus provides the accelerated aging conditions for the cables. Understanding the precise nature of the temperature distribution within the water tank and within the cable insulation is important to quantify and calculate the effective aging of the cables. This paper presents initial finite element analysis (FEA) simulation studies that evaluate the temperature distribution within a water filled tank and across submerged power cables when multiple cables are supplied with current. Two scenarios are evaluated and compared, namely the temperature profiles of cables when the water in the tank is treated (a) as a solid material, and (b) as a fluid with natural convection. The importance of applying effective water circulation mechanisms are also highlighted.**

Keywords—FEA, cable insulation, accelerated aging, temperature distribution

I. INTRODUCTION

Insulation materials used in extruded power cable are known to progressively degrade with time as a result of the synergistic action of moisture and thermal and electrical stress. The degradation may be very serious so that the cable may fail in service even at normal working stresses. [1]

In order to investigate the mechanisms of thermal and moisture-induced degradation, several laboratories have accomplished cable accelerated aging experiments in water-filled tanks. [2] However, the aging conditions between different arrangements make a direct comparison of the data between laboratories perhaps uncertain. To assist in this area, IEEE Standard 1407 provides a guide for accelerated aging tests on extruded medium-voltage (MV) cables using water-filled tanks. [3]

As thermal aging appreciably impacts the electrical and physical characteristics of the insulation material, [4] temperature is therefore an essential factor in the cable aging process. The temperature monitoring method recommended in IEEE Standard 1407 uses a dummy cable loop to collect temperature information, where several thermocouples(T/C) are placed on the conductor of the cable as shown in Fig. 1. The dummy cable used for temperature monitoring is imposed with approximately the same heating conditions as the active cables.

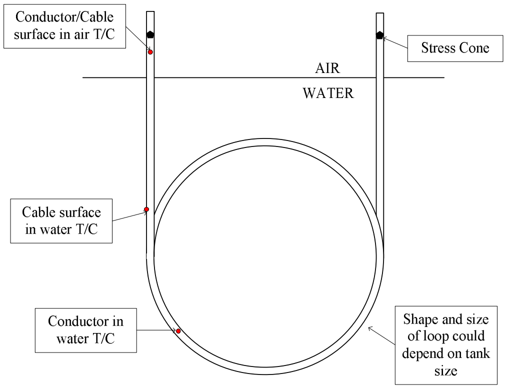

Fig. 1. Dummy cable used for temperature measurement as outlined in IEEE Standard 1407

It is usually supposed that the temperature is evenly distribution across the water tank, then the temperature of the dummy loop is the same for all other cables. However, if there is no circulation system and no temperature control system in the water tank, the temperature distribution of the cable specimens submerged in the tank will be impacted by several factors. These factors include water tank size, shape and material, the number of cables in the tank, the volume of water and whether the tank is thermally insulated etc. This means that the temperature profiles may vary at different positions in the water tank and even be different across each cable length.

Finite element analysis (FEA) methods have become an important tool in many engineering disciplines to simulate and evaluate a variety of engineering scenarios and solutions. ANSYS is a commonly used application and analysis FEA tool with an extensive library of elements that support thermal, fluid and structure simulations. [5] ANSYS workbench is utilized in this work to simulate and evaluate the thermal distribution and profiles of tank-type accelerated aging of power cables.

Two scenarios are initially evaluated and compared, namely the temperature profiles of cables when the water in the tank is treated (a) as a solid material, and (b) as a fluid with natural convection. This initial study is evaluated without considering any water circulation in the system.

II. SIMULATION SETUP

A. Geometry Model Construction

In order to evaluate the synergistic effect between various materials under stresses, the cables used in experiments, at a minimum, must constitute a conductor, conductor shield, insulation, insulation shield and metallic shield. In the models developed in ANSYS, the thin shield parts including semiconductors are omitted as their small physical thickness has minimal impact on the thermal conductivity properties of the cable. The constructed cable models are composed of a conductor and insulation as shown in Fig.2. The cables are designed on typical 11kV power cable parameters. The overall diameter of each cable is 20mm, the conductor is solid copper with a diameter of 8mm, and the thermal conductivity of conductor is 386.7$\mathrm{Wm^{-1}K^{-1}}$. The insulation material is XLPE with 6mm thickness around the conductor, the specific heat value of XLPE is defined as 4000$\mathrm{Jkg^{-1}K^{-1}}$, thermal conductivity is 0.29$\mathrm{Wm^{-1}K^{-1}}$ and density is 941$\mathrm{kgm^{-3}}$.

The cables are assumed to be mounted into the water-filled tank after being looped as per the standard. Three types of tank layout are recommended in IEEE Standard 1407 with the shape of tank being rectangular or cylindrical. In this simulation, the rectangular type water tank is utilized with the physical layout and components of the water tank specified in Fig. 3 and table 1. The tank walls are constituted by two layers, namely the inner tank surface which contact with water and tank insulation which used for heat preservation. A surface covering is place on the tank top to presume water in the tank does not evaporate, and to maintain thermal boundary stability of the temperature of water as well.

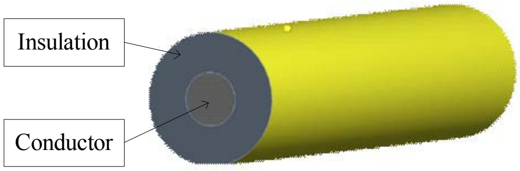

Fig. 2. Local structure of cable model

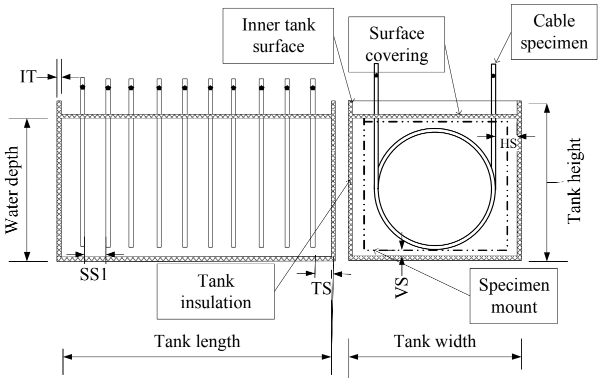

Fig. 3. Tank layout according to IEEE Standard 1407

The simplified simulation tank structure with 10 cables is shown in Fig. 4. The tank is designed as an enclosed domain, filled with water and its walls are steel boundaries but with neglectable thickness. In addition, the cable specimens are not in contact with the tank walls or tank bottom to follow IEEE Standard 1407. The details related to the tank dimensions are setup are shown in Table 1. Each of the 10 cable specimens are placed into the water tank, with a presumed bend radius of 350mm.

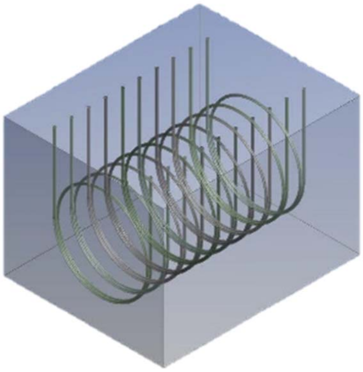

Fig. 4. Overall simulation model

TABLE 1 Tank dimensions according to IEEE Standard 1407

Length (mm)	875
Width (mm)	800
Height (mm)	910
Side spacing (HS) (mm)	50
End spacing (TS) (mm)	75
Bottom spacing (VS) (mm)	50
Specimen spacing 1 (SS1) (mm)	75
Water depth (mm)	800
Tank material	stainless steel
Specimen bend radius(mm)	350

B. Simulation Setup

1) Water treated as solid material

The first simulation using steady-state thermal analysis tool which is for the case of treating water as a solid material. As such the water in the tank only has thermal and density properties with no natural fluid convection.

IEEE Standard 1407 stipulates a method to increase the conductor temperature to accelerate the aging process of the cables. A current transformer is utilized to induce current into each cable conductors to generate heat due to joule loss. The advantage of this heating method is its similarity to cable heating in actual field use.

A power density is applied to the conductors of each cable in the simulation to model the heat generated by current flowing in the cable. In order to reach a steady state maximum temperature around 90^0C, which is specified maximum temperature in Standard 1407, a power density of 2×10^5 W/m^3 is applied on each cable conductors.

The tank walls were given a convection property to simulate heat dissipation from steel walls to the surrounding air environment. The ambient temperature was set to 27^0C, and the convection coefficient was set as $5 Wm^{-2}K^{-1}$ which for air natural convection. It is supposed that the tank in a stagnant air and convection coefficient are fixed with temperature.

2) Water treated as fluid

The second simulation used the Fluid Flow tool where water is treated as a fluid with natural convection properties. This scenario result will more closely resemble the reality of the cable temperature profiles with no assisted convection method.

The pressure-based solver is used in the simulation and absolute characteristic is defined for the velocity formulation, because there is only natural water convection exist in the water tank domain. Turning on energy function model in model set up stage, then going to cell zone conditions and boundary conditions set up, the conductor domains are treated as a source term with one energy source with a constant power density of $2x10^5$ W/m^3. The thermal conditions of the insulator walls and conductor walls are thermally coupled, while the thermal properties of the tank walls are set as heat convection to ambient air, with a heat transfer coefficient of $5 W/m^{-2}K^{-1}$ with again the ambient air temperature set to 27^0C.

C. Description of Simulation

In the simulations, the geometry models are meshed into 1.9 million and 9.8 million small elements in the Solid Simulation and Fluid Simulation respectively. Calculations are made for each single element and combining the individual results provides the result of the temperature distribution.

Calculations run until the thermal steady condition is achieved in which case the internal heat generation rate and external wall heat dissipation rate reach a balance point.

III. SIMULATION RESULTS

1) Solid Simulation Results

The final steady state temperature distributions of the 10 cables are shown as left side of Fig. 5. The maximum temperature of the cable loops is 91^0C, occurring in the middle cables. The minimum temperature within cable loops is 58^0C, the location of the minimum temperature occurs on the cables near to the tank walls. It is obvious that cables closer to the middle of the tank have a higher temperature. The reason for such a temperature variation is the cables near to the tank walls will have priority to dissipate heat into ambient air, with the cable in the middle of the tank accumulating more heat.

The temperature ranges of each cable loop in the Solid Simulation results are collected as right side of Fig. 5, where cables in the tank are numbered from 1 to 10, 1 and 10 representing the loop surfaces closest to the tank walls. The blue line in Fig. 5 represents the maximum temperature within each cable loop and the orange line the minimum temperature within each cable loop. The temperature range of each cable loop varies by approximately is 15^0C.

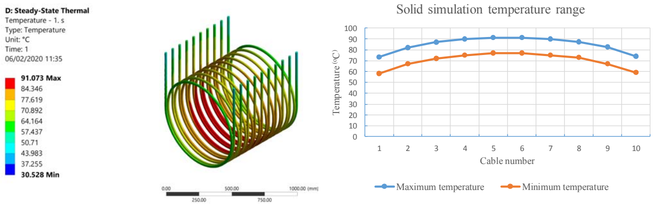

Fig 5. Solid Simulation result and maximum and minimum temperatures within each of the 10 cables for the Solid Simulation

2) Fluid Simulation Results

In the steady state condition for the Fluid Simulations, the temperature distributions of the 10 cables are shown in Fig. 6. The maximum temperature of the central cable loops is 86^0C, and the minimum temperature of the cable loops is 62^0C. Again, the locations of the minimum temperatures are on the cables closest to tank walls. The central cables have a lower temperature compared to the same cables in the Solid Simulation, but the cables near to tank walls have a higher temperature than the equivalent cables in the Solid Simulation. It can be seen from the results that the natural convection property of the water makes temperature across the cables more uniform.

Fig. 7 shows the maximum and minimum temperature ranges of each cable from the Fluid Simulation results as a function of cable number. The blue curve represents the maximum temperature of each cable and the orange curve the minimum temperature of each cable. In the Fluid Simulation the temperature range difference between each cable loop is only about 7^0C.

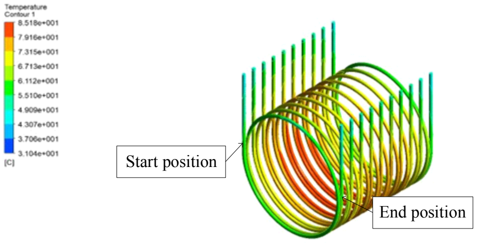

Fig. 6 Fluid Simulation result (start and end position identified for later temperature comparisons)

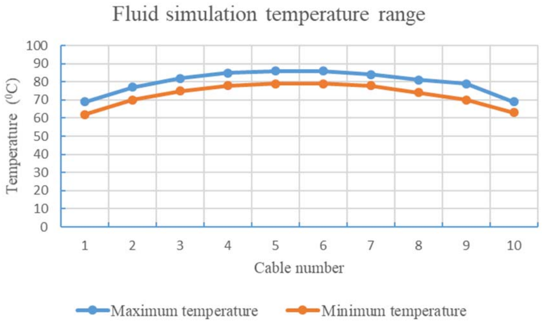

Fig. 7 Maximum and minimum temperatures within each of the 10 cables for the Fluid Simulation

IV. Discussion

The water natural convection in the Fluid Simulation makes the temperature difference between cables and across every single cable smaller. The main cause of this is water's natural convection which can distribute heat produced by cable conductors throughout the water tank, making the water temperature more uniform. However, there exists temperature differences in the Fluid Simulation results because natural water convection is slow and weak.

Fig. 8 shows the temperature distribution across cable lengths in Fluid and Solid Simulation. To compare central and outer cables, cable 1 and cable 6 have been chosen for comparison. The start and end reference positions used for temperature measurement locations in the simulations are shown in Fig. 6. All cables loops are spiraled with 1.5 turns and of bend radius 350 mm. As such every cable has an overlapped section in the lower half of the loop.

Both cable 6 and cable 1 in the solid simulation have a higher temperature than those from the fluid simulation with an increase of around 5^0C to 10^0C. Due to the looped nature of the cables, the looped sections folded back on each other near to the tank bottom will experience the maximum temperatures due to the close proximity of the fold back loop. In contrast, the top sections of the cable loops where the cable is exposed more to the surrounding fluid or solid simulation material and will this will experience a reduced temperature profile.

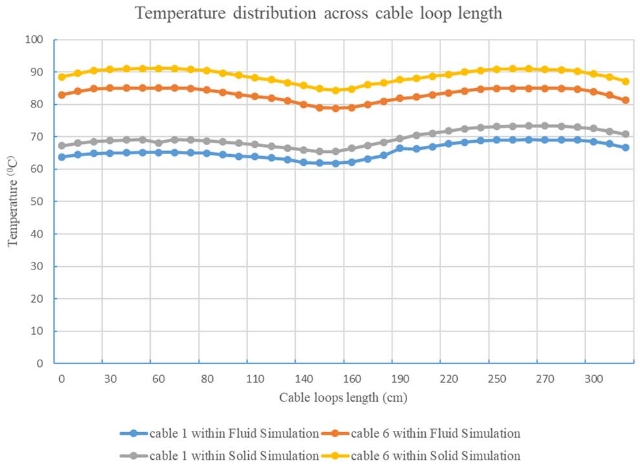

Fig. 8 Temperature distribution in single cable loops

There are several cable lifetime models shown that the cable insulation service lifetime has a proportional relationship with its working temperature.[6] Therefore, the temperature difference of cables in the tank will vary each cable's aging rate. The mechanisms of moisture-induced cable insulation degradation and accurate prediction of cable lifetime and its temperature dependence cannot be adequately investigated unless these temperature difference conditions are considered or controlled.

Appling a water circulation system into the water tank is a reasonable solution for aging temperature uneven distributions. However, IEEE Standard 1407 does not provide details regarding water pumps or fans which can be used. Future simulations will add a circulation system into the water tank to understand consequence of circulation rates. The convection coefficient of tank walls will also be investigated as a function of temperature difference between steel walls and ambient air.

An accelerated aging experiment using a water filled tank will be performed in the future, through which the results of simulations can be compared with actual experimental measurements. If the simulation results are equivalent to practical results, the temperature derived from simulation will have significance for estimating power cable lifetime under different possible accelerated aging regimes.

V. CONCLUSION

According to IEEE Standard 1407, simulations of cable temperature accelerated aging in water-filled tanks have been accomplished by FEA. Two types of simulation are appraised and contrasted, named Solid Simulation and Fluid Simulation. These two simulations show different temperature distribution results.

The temperature distribution of all cables in a tank and across single cables have been evaluated. Temperature is not uniformly distributed in the tank; the middle cables have higher temperatures; temperature also changes across looped cable lengths due to parts of the cable loops overlapping. The temperature distributions will also influence cable accelerated aging tests as each cable will have different temperature profile.

According to IEEE Standard 1407 and simulation results presented, a water circulation system is necessary for cable accelerated aging tests to control aging temperature and distribute temperature more uniform.

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