Computation of Magnetic Field Distribution by Using an Adaptive Neuro-Fuzzy Inference System

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Abstract — This paper proposes a set of mathematical models presenting magnetic fields caused by operations of an extra high voltage (EHV) transmission line under normal loading and short-circuit conditions. The mathematical models are expressed in second-order partial differential equations derived by analyzing magnetic field distribution around a 500-kV power transmission line. The problem of study is intentionally two-dimensional due to the property of long line field distribution. To verify its use, i) single-circuit and ii) double-circuit, 500-kV power transmission lines have been employed for test. Finite element methods (FEM) for solving wave equations have been exploited. The computer simulation based on the use of the FEM has been developed in MATLAB programming environment. This paper presents novel approach based on the use of adaptive network-based fuzzy inference system (ANFIS) to estimate magnetic fields around an overhead power transmission lines. The ANFIS approach learns the rules and membership functions from training data. The hybrid system is tested by the use of the validation data. From all test cases, the calculation line of 1.0m above the ground level is set to investigate the magnetic fields acting on a human in comparative with ICNIRP standard.

Keywords — Magnetic Field, Transmission Line, Finite Element Method (FEM), ANFIS, Short-Circuit Faults, Computer Simulation.

I. INTRODUCTION

For decades, due to the increase in electrical power demand, we are in need of enlarging transmission capacity by installing 500-kV extra high-voltage power transmission lines in both AC and DC. The impact of electric fields surrounding the transmission line depends strongly on conductor surface potentials, while load currents flowing through the transmission line result in magnetic field distribution. For the 500 kV systems, high current density transmission is the main purpose. It can cause electrical hazards to people or their livestock nearby. Especially when the power system was faulted, the short-circuit current is much higher than the normal current loading. This paper focuses on utilization of efficient computing techniques to estimate the magnetic field distribution. Obtained estimate solutions can lead to assessment of electrical hazards for 500-kV power transmission systems. This paper presents an online estimation of magnetic fields for live transmission line right of way worker using Generalized Regression Artificial Neural Network.

The FEM is one of the most popular numerical methods used for computer simulation. The key advantage of the FEM over other numerical methods in engineering applications is the ability to handle nonlinear, time-dependent and circular geometry problems. Therefore, this method is suitable for solving the problem involving magnetic field effects around the transmission line caused by circular cross-section of high voltage conductors. By literature, these research works are conducted based on electromagnetic theory or image theory [1], [2]. With defining a line of calculation and assuming very thin power lines, two-dimensional problems of magnetic field analysis governed by empirical mathematical expressions can be applied. However, these conventional methods are unable to include effects of bundled conductors that are typical for EHV power transmission systems. To provide a potential tool of simulation, the FEM is flexible and suitable to estimate magnetic field distribution. As mentioned where a normal steady-state operation is assumed, the current does not suddenly change its value.

Artificial intelligence techniques such as fuzzy logic, neural networks and genetic programming, have been successfully applied to a number of power systems problems during recent years. Artificial neural networks also are used for estimating electromagnetic field, [14]. The purpose of the present work is to investigate whether ANFIS (adaptive network based fuzzy inference systems) may be also used for the estimation magnetic field. ANFIS was trained using data derived from magnetic field calculation. ANFIS can be described as a fuzzy system equipped with a training algorithm. It is quite quick and has very good training results that can be compared to the best neural networks.

Neuro-fuzzy network have been widely used for many different industrial areas such as control, modelling, prediction, identification, pattern recognition. Neuro-fuzzy system represents connection of numerical data and linguistic representation of knowledge. The neuro-fuzzy system works similarly to that of multi-layer neural network. This hybrid system uses the adaptive neural networks (ANNs) theory to characterize the input-output relationship and build the fuzzy rules by determining the input structure. Several approaches have been proposed to generate fuzzy rules, from training data, based on Takagi- Sugeno–Kang-type fuzzy model. One such an approach is called the adaptive-network- based fuzzy inference system (ANFIS). ANFIS is a class of adaptive multi-layer feed-forward
network that is functionally equivalent to a fuzzy inference system. The Adaptive network based fuzzy inference system (ANFIS) model was proposed by Jang in 1993 as a basis for constructing a set of fuzzy rules with appropriate membership functions from a set of input-output examples.

In this paper, magnetic field modelling of power transmission lines is briefed in Section II. Section III is to illustrate the utilization of the FEM for the magnetic field modelling described in Section II. Section IV gives Adaptive Network based Fuzzy Inference System. Section V gives simulation results in both normal and faulted conditions, and discussion. Test cases given in this paper is the 500 kV transmission line. The simulation conducted herein is based on the FEM method given in Section III. All the programming instructions are coded in MATLAB program environment. Moreover, due to excessive magnetic fields that might be harmful to people or livestock living nearby, careful investigation of the magnetic phenomena is taken into account. According to the standard of International Commission of Non Ionizing Radiation Protection (ICNIRP), the satisfactory simulation results are also complied with the ICNIRP standard.

II. MAGNETIC FIELD MODELING FOR A POWER TRANSMISSION LINE

The mathematical model representing magnetic fields (B) caused by a power transmission line carrying high current is expressed in form of the magnetic field intensity (H) in which $B = \mu H$. Utilizing the wave equation (Helmholtz’s equation) as in (1) [3], [4], magnetic field modeling that follows the Ampere’s circuital law is defined.

$$\nabla^2 H - \sigma \frac{\partial H}{\partial t} - \epsilon \frac{\partial^2 H}{\partial t^2} = 0 \quad (1)$$

where $\epsilon$ is the constant dielectric permittivity, $\mu$ is the magnetic permeability, and $\sigma$ is the conductivity. This paper has considered the time-harmonic system by representing $H = He^{j\omega t}$ [8], therefore

$$\frac{\partial H}{\partial t} = j\omega H \quad \text{and} \quad \frac{\partial^2 H}{\partial t^2} = -\omega^2 H$$

where $\omega$ is the angular frequency, therefore, refer to (1) can be rewritten into the following equation.

$$\nabla^2 H - j\omega \mu \sigma H + \omega^2 \epsilon \mu H = 0$$

Considering the problem in two dimensional $(x,y)$ plane, then

$$\frac{\partial}{\partial x} \left( \frac{1}{\mu} \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{1}{\mu} \frac{\partial H}{\partial y} \right) - (j\omega \sigma - \omega^2 \epsilon)H = 0 \quad (2)$$

As can be seen, to obtain an exact solution of (2) is difficult. In this paper, the FEM has been employed to find an approximate solution [5].

III. FEM FOR THE POWER TRANSMISSION LINE

A. Discretization

This work is to focus on a power transmission system of especially single- and double-circuit, 500-kV power transmission line. Both circuits are 4-bundled conductors as illustrated diagrammatically by Fig. 1 and Fig. 2, respectively. The height of the lowest conductors at midspan (maximum sag allowance) for both circuit types is 13.00 m above the ground level [6]. Phase conductors used are 795 MCM (diameter = 0.02772 m) while overhead ground wires (OHG) are 3/8 inch (diameter = 0.009114 m).

Fig. 1. Single circuit 500 kV transmission with dimension (m)

Fig. 2. Double circuit 500 kV transmission system with dimension (m)

The working region for modelling magnetic fields using FEM is defined by Fig. 3 and Fig. 4, which are discretized by using linear triangular elements.
or in the compact matrix form

\[
[M + K][H] = 0
\]

\[
M \frac{1}{\mu} \left( \nabla \times \frac{\partial \mathbf{B}}{\partial \mathbf{r}} + \frac{\partial \mathbf{B}}{\partial \mathbf{r}} \right) + \frac{1}{\varepsilon} \left( \nabla \times \mathbf{J} \right) = 0
\]

For one element containing 3 nodes, the expression of the FEM approximation is a 3x3 matrix. With the account of all elements in the system of n nodes, the system equation is sizable as an nxn matrix.

C. Boundary Conditions and Simulation Parameters

The boundary conditions applied here are zero magnetic fields at the ground and the OHG. For the boundary conditions at outer perimeters of 12-single circuit power lines and 24-double circuit power lines has applied with the research of [9], [10], which boundary conditions of magnetic field depends on the load current. Both single and double circuits are considered by the maximum load current of 3.15 kA per phase [10] and assumed to be a balanced load condition. For faulted conditions [11], the single line-to-ground faults is assumed that phase A is shorted to ground so that \( I_A = 4.95 \text{ kA} \) p.u., \( I_B = I_C = 0 \). The double line-to-ground faults between phase B and C caused the fault currents of \( I_A = 0 \), \( I_B = 3.36 \text{ kA} \) p.u., \( I_C = 2.33 \text{ kA} \) p.u. For the line-to-line faults of phase B and C, \( I_A = 0 \), \( I_B = I_C = 3.34 \text{ kA} \) p.u. The last fault case is the balanced three-phase faults in which \( I_A = 3.23 \text{ kA} \), \( I_B = 3.23 \text{ kA} \), \( I_C = 3.23 \text{ kA} \). The conductors used for test are Aluminum Conductor Steel Reinforced (ACSR) having the following properties: conductivity (\( \sigma \)) = \( 0.8 \times 10^7 \) S/m, the relative permeability (\( \mu_r \)) = 300 and the relative permittivity (\( \varepsilon_r \)) = 3.5. It notes that the permittivity of free space (\( \varepsilon_{\text{ref}} \)) = \( 8.854\times10^{-12} \) F/m and the permeability of free space (\( \mu_{\text{ref}} \)) = \( 4\pi\times10^{-7} \) H/m [12].
IV. ADAPTIVE NETWORK BASED FUZZY INFERENCE SYSTEM

The Adaptive-Network-based Fuzzy Inference System (ANFIS) was proposed by [15]. It combines the features of fuzzy logic and neural networks. ANFIS neural network has been used to determine the magnetic field in transmission line system shown in fig.1& fig. 2, for various faulted condition. The network was trained using the analysis data. Using the trained data network was able to predict the type of fault.

It is supposed that there are three input linguistic variables x, y, z which describes height above ground level, magnetic field, relative values of magnetic field and each variable has five fuzzy sets. Fig. 5 shows a Sugeno fuzzy system with three inputs, one output and 125 rules, [16]. Takagi-Sugeno-type fuzzy if-then rule is could be set up as:

**Rule 1**: If (x is A₁) and (y is B₁) and (z is C₁) then
\[ f₁ = p₁x + q₁ \]
\[ y + r₁ z \]

**Rule 2**: If (x is A₂) and (y is B₂) and (z is C₂) then
\[ f₂ = p₂x + q₂ \]
\[ y + r₂ z \]

**Rule 3**: If (x is A₃) and (y is B₃) and (z is C₃) then
\[ f₃ = p₃x + q₃ \]
\[ y + r₃ z \]

\[ pᵢ, qᵢ, rᵢ, i=1,2,3,4...,125 \] are the parameters set, referred to as the consequent parameters. The node functions in the same layer are of same function, there are 286 nodes.

**Layer 1**
Every node in this layer is an adaptive node with node function as:
\[ Oᵢ^{1} = u_{Aᵢ}(x), \quad i = 1,2,... \]

where \( x \) (or y or z) is the input of the node, \( Aᵢ \) (or Bᵢ or Cᵢ) is a fuzzy set associated with this node.

Usually it is chosen \( \mu_{A}(x), \mu_{B}(y) \) and \( \mu_{C}(z) \) to be bell-shaped such as:
\[ u_{Aᵢ}(x) = e^{-\left( \frac{x-cᵢ}{aᵢ} \right)^{2}} \]

where \( aᵢ, bᵢ \) and \( cᵢ \) are the parameter set.

**Layer 2**
The nodes in this layer are fixed. The outputs of these nodes are given by:
\[ Oᵢ^{2} = uᵢ = u_{Aᵢ}(x) \times u_{Bᵢ}(y) \times u_{Cᵢ}(z) \]

where * denotes t-norm

**Layer 3**
Each node in this layer is a circle node. The outputs of this layer can be represented as:
\[ Oᵢ^{3} = \bar{uᵢ} = \frac{uᵢ}{\sum_{i=1}^{125} uᵢ} \quad i = 1,2,...,125 \]

**Layer 4**
Every node in this layer is an adaptive node, with node function:
\[ Oᵢ^{4} = \bar{uᵢ} fᵢ \quad i = 1,2,...,125 \]

**Layer 5**
The node in this layer is a circle node that computes the overall output as the summation of all incoming signals:
\[ Oᵢ^{5} = \sum_{i=1}^{125} \bar{uᵢ} fᵢ \]

![Fig. 4. Structure of ANFIS network](image)

Generally, the ANFIS has a capability to approach several nonlinear unknown systems. In this work, we are going to exploit ANFIS to forecast a material unknown.

V. RESULT AND DISCUSSION

A. Normal Loading
The FEM-based simulation is coded with MATLAB programming for calculation of magnetic field dispersion. To utilize a graphical feature of MATLAB, the contour of magnetic field distribution through the cross-sectional area of the working domain for the single and double-circuit transmission systems is given by a working area of the 70x55 m² rectangle are presented in Fig. 5 and Fig. 6, respectively.
for single and double circuit Table II shows comparative results among average magnetic field for all the cases. It is considered that at the same height, the double circuit distributes more intensive magnetic field than the single circuit does due to twice of the conductor number. As can be seen, the magnetic field intensity caused by the faulted cases is remarkably higher than that of the normal conditions. However, due to the reliable operation of protective devices in electric power systems this could not harm human or other living things underneath the EHV power lines.

The magnetic field distributions simulated are determined by balanced currents in the phase conductors. Magnetic field distribution of the double-circuit case is higher than that of the single-circuit case respectively. To describe possible effects of magnetic field strength on human or other living things underneath the power line, the line of calculation, 1.0 m above the ground (y = 1 m) is defined.

The comparative result of magnetic field for both single and double-circuit cases is shown in Fig. 7. It notices that each graph has two peaks near the center position. An average of magnetic field through distance x of single and double circuit when consider the height of transmission line at midspan and consider at maximum load current are 65.88 μT and 74.18 μT, respectively, which is less than magnetic field level that hazard to human. It is regulated by ICNIRP [13], which the level of magnetic field safe to human for general public up to 24 hours/day must not greater than 100 μT and for occupation whole working day must not over 500 μT. Table I shows magnetic field values for single line to ground fault and double line to ground fault.
Table II
Comparing of average of magnetic field at each height for all case

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Normal</th>
<th>1-T fault</th>
<th>2-T fault</th>
<th>3 phase fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.10</td>
<td>1.09</td>
<td>1.08</td>
<td>1.11</td>
</tr>
<tr>
<td>2</td>
<td>1.12</td>
<td>1.11</td>
<td>1.10</td>
<td>1.12</td>
</tr>
<tr>
<td>3</td>
<td>1.14</td>
<td>1.13</td>
<td>1.12</td>
<td>1.14</td>
</tr>
<tr>
<td>4</td>
<td>1.16</td>
<td>1.15</td>
<td>1.14</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Fig. 5. ANFIS testing data error

The results obtained according to the proposed ANFIS method are very close to those calculated by method based on analysis, which clearly implies that the proposed method ensures acceptable accuracy and satisfying convergence. Maximal absolute error is minimized when ANFIS is used.

V. CONCLUSION

This paper has studied the magnetic field distribution surrounding EHV transmission line in both normal loadings and faulted conditions in which the single line-to-ground faults, double line-to-ground faults, line-to-line faults and balanced three-phase faults were situated. Single and double-circuit, 500-kV transmission lines, are investigated. The computer simulation is performed by using finite element methods instructed in MATLAB programming codes. The results of the normal loading case revealed that the magnetic fields from both single- and double-circuit, 500-kV transmission lines at a level of 1 m above the ground that are assumed to be the level of human working, do not exceed the maximum allowance when compiled with the ICNIRP standard. Additionally, the results also showed that the magnetic intensity of the double circuit cases is normally stronger than those of the single circuits. It can be concluded...
that ANFIS is a very efficient tool for the study of magnetic fields generated for various faulted condition, which clearly implies that the proposed method ensures acceptable accuracy and satisfying convergence. Maximal absolute error is minimized when ANFIS is used. Advantage of this method would be obvious when considering large sensor network data set for network training. It is shown that proposed approach ensures satisfactory accuracy and can be a very efficient tool and useful alternative for such investigations.

REFERENCES


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