

Fuzzy Neural Network Surrogate Model-Based Efficient Calculations For Transformer Interturn Short-Circuit Faults

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Current calculation methods for interturn short-circuit (ITSC) faults face significant challenges in achieving an optimal balance between computational accuracy and efficiency. An efficient calculation method for ITSC faults is developed in this work using a fuzzy neural network (FNN) surrogate model. The finite element method (FEM) model of transformer ITSC faults is used to generate training, validation, and testing datasets. Different inputs, including the number of shorted turns and the fault position, are investigated to determine the leakage factors. These leakage factors are then integrated into the circuit-based model to obtain the calculated results. The proposed method effectively captures the variation in leakage factors under different conditions, offering a comprehensive combination of data-driven and model-based approaches. Comparisons between the surrogate model results and the field-circuit simulation results reveal that the proposed method is calculated accurately and more rapidly.

Index Terms—Fuzzy neural network (FNN), interturn short-circuit (ITSC) faults, surrogate modeling, transformers.

I. INTRODUCTION

POWER transformers are crucial and expensive components of electrical systems. An interturn short-circuit (ITSC) fault occurring within the transformer affects the operation of the connected power system and pose serious economic losses. Accurate and fast simulation calculations of ITSC faults in transformers is a challenging task. Several studies have been conducted on ITSC fault modeling in power transformers. Existing methods include circuit-based methods and the finite element method (FEM). The accuracy of the equivalent circuit-based model heavily depends on the precision of the leakage factors, which are influenced by the number of shorted turns and the fault position, and are difficult to obtain precisely [1]-[2]. ITSC fault simulation calculations based on the FEM offer significant accuracy advantages [3]-[4]. Nevertheless, their long computation time limits their application in real-time systems. To address these issues, a model-based and data-driven hybrid method is proposed in this paper. Specifically, a fuzzy neural network (FNN) is employed to determine the leakage factors required by the fault BCTRAN model, leading to the development of a fuzzy neural network surrogate model. A comparison of typical results for the terminal currents and the short-circuit currents derived from the proposed method and field-circuit model is presented.

II. THEORETICAL MODELING

The training, validation, and testing datasets are generated using a FEM model. For transformers, the inductance matrix for the internal electromagnetic field can be calculated:

$$L = \frac{1}{I^2} \cdot d \cdot \iint_{\Omega} B \cdot H d\Omega \quad (1)$$

where I is the winding input current, L is the winding inductance matrix, Ω is the computational zone, d is the model depth, and B and H are the magnetic induction intensity and magnetic field intensity, respectively.

The inductance matrix at different fault conditions is obtained via the FEM, and then the leakage factors are calculated, which is used as a training dataset. The leakage factor σ_{ij} is:

$$\sigma_{ij} = 1 - \frac{l}{\mu N_i N_j} \cdot L_{ij} \quad (2)$$

where μ is the permeability, N_i and N_j are the number of turns of windings i and j , respectively, l is the winding length, and L_{ij} is the inductance between windings i and j .

Fig. 1 illustrates the overall process of the proposed FNN-based surrogate model. This method consists of two main parts: offline calculation of the original data and online application of the surrogate model.

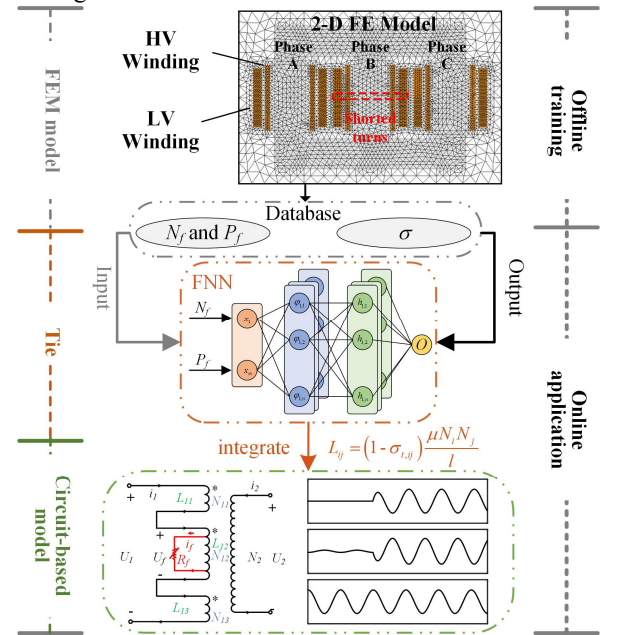


Fig. 1. Overall process of the proposed modeling method.

The process starts by using the FEM to compute the inductance matrix and leakage factors under typical fault turns

and fault positions. The number of shorted turns N_f and the fault position P_f are used as inputs, and the corresponding calculated leakage flux factors σ are outputs. Next, these datasets are utilized to train the FNN. By selecting and optimizing membership functions, the FNN effectively captures the nonlinear and complex relationship between the fault parameters and leakage factors, developing a surrogate model for predicting leakage factors σ_i . Finally, by inputting the fault conditions into the trained FNN, the leakage factor σ_i is predicted and integrated to solve the voltages and currents in the circuit-based model.

The j th fuzzy rule of the FNN at the n -th sample is [5]

$$\begin{aligned} R_j : & \text{IF } x_1(n) \text{ is } A_{1j}(n) \text{ and } \dots x_i(n) \text{ is } A_{ij}(n) \\ & \text{and } \dots x_m(n) \text{ is } A_{mj}(n) \\ \text{THEN } & f_j(n) = v_j(n) \omega_j(n) \end{aligned} \quad (3)$$

where $x_i(n)$ is the i th input, $A_{ij}(n)$ is the membership function of the j th rule and the i th-dimensional input, $v_j(n)$ and $\omega_j(n)$ are the output and weight of the j th normalized neuron, and $f_j(n)$ is the output of the j th fuzzy rule.

Based on the gravity method, the output of FNN is

$$o(n) = \sum_{j=1}^m f_j(n) = \sum_{j=1}^m v_j(n) \omega_j(n) = \mathbf{v}(n) \boldsymbol{\omega}(n) \quad (4)$$

where $\mathbf{v}(n) = [v_1(n), \dots, v_m(n)]^T$ and $\boldsymbol{\omega}(n) = [\omega_1(n), \dots, \omega_m(n)]^T$ are the output and the weight vector of the normalized layer.

III. SIMULATION AND RESULTS ANALYSIS

As a study case, a SG-30/2/0.38 three-phase core transformer was modeled and analyzed. The main nameplate parameters are listed in Table 1. The high-voltage (HV) winding and low-voltage (LV) winding are 400 and 76 turns, respectively.

TABLE I

MAIN PARAMETERS OF THE SIMULATED TRANSFORMER	
Quantity	Value
Rated capacity (kVA)	30
Rated voltage (kV)	2/0.38
Rated frequency (Hz)	50
Rated current (A)	8.66/45.58
Short-circuit impedance	4%

On the basis of ANSYS Maxwell, the FEM model was established to calculate the inductance matrix and the leakage factors between the fault windings and normal windings. The 2-D FE model contained 22788 triangular elements. ITSC faults shorting 20 turns (5%), 40 turns (10%), 60 turns (15%), ... 180 turns (45%), and 200 turns (50%), located in the middle and end of the HV windings, are used to train the FNN for predicting the leakage factors.

In the surrogate model, N_f and P_f are input to the FNN. The predicted leakage flux factors are then used in the BCTRAN fault model to calculate fault currents. The 3-phase symmetrical loads are set as 11.8 Ω , respectively. In this case, a 0.1 Ω resistance shorting 122 turns (30.5%) in the end of the B-phase HV winding occurred at $t=40$ ms. The results of the field-circuit model and surrogate model are shown in Fig. 2. The primary current, secondary current and short-circuit current calculated by field-circuit model (solid lines) and surrogate model (dotted

lines) are presented.

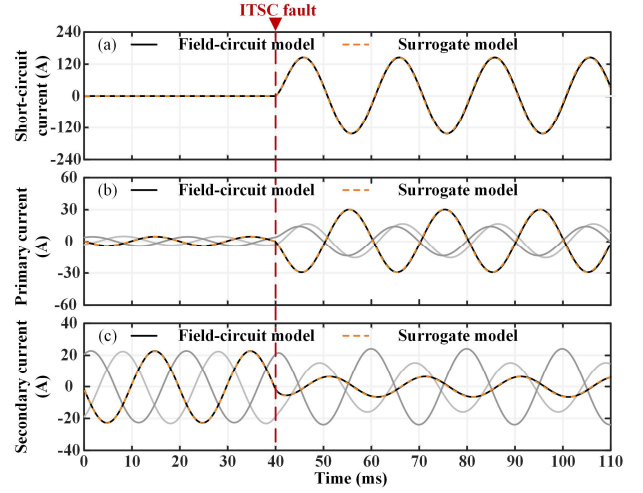


Fig. 2. Typical calculation waveforms using Field-Circuit and Surrogate model. (a) Short-circuit current. (b) Primary currents. (c) Secondary currents.

Notably, the surrogate model-calculated waveforms show consistency with the field-circuit model-calculated waveforms in terms of the variation trend and amplitude range. The actual running time of one timestep for the surrogate model is 1.77 ms, whereas that of the field-circuit-model is 925.58 ms. This shows that an FNN-based surrogate model can achieve an accuracy close to a field-circuit model, while significantly reducing the computational time by a factor of 521.56 compared with that of the field-circuit model (all computations have been achieved with an AMD Ryzen Threadripper 2950X 16-Core Processor, 3.5 GHz, 128 GB RAM). More cases of ITSC faults and the experimental verification of the proposed method and will be presented in the full paper

IV. CONCLUSION

In this paper, an FNN-based surrogate model is presented to investigate transformer ITSC faults, which can accurately and rapidly calculate the shorted current and the terminal current. As study cases, the ITSC faults of a 30 kVA/2 kV transformer are simulated. The results indicate that the FNN surrogate model can accurately calculate the leakage factors required by the BCTRAN model. The proposed FNN surrogate model effectively enables ITSC fault calculations for transformers, providing an effective model for fault detection and analysis.

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