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A New Method for Fast Environmental Magnetic Field Assessment of Power Transformers in Substations

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Abstract. As renewable energy increases, the demand for substation construction also needs to increase simultaneously. Before a substation is built, its environmental magnetic field assessment is particularly important to people's health, and most of this environmental magnetic field assessment is only for the outside of the substation. In recent years, the safety and health of occupational personnel have been gradually valued, so the assessment of the environmental magnetic field inside the substation is also very important. Finite element analysis (FEM) is currently most commonly used for accurate environmental magnetic field assessment. However, its calculation consumes a lot of time and computer resources. Therefore, this study proposes a simplified model method for the main magnetic field source inside the substation, that is, the power transformer. This method can not only simplify a lot of simulation time, but also ensure that the overall error of the magnetic field simulation value above 2,500 mG is within 5 %.

Keywords. Environmental electromagnetic field, power transformer, substation, finite element method (FEM).

1. Introduction

In recent years, governments have been promoting the use of renewable energy to combat global warming and reach net-zero carbon emissions by 2025. As a result, the demand for electricity in our country has been steadily increasing. To accommodate the integration of renewable energy into the power grid, more substations are being constructed. However, renewable energy sources produce harmonic components so variable reactors and harmonic filters are installed in the substation. Safety concerns for people exposed to low-frequency electromagnetic fields for prolonged periods have also been considered. Although research suggests potential risks, they have yet to be confirmed [1]-[4]. To address these concerns, Taiwan Power Company has established regulations based on the guidelines suggested by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [5]. According to ICNIRP, the magnetic field (f = 60 Hz) in the working environment of professional personnel should be less than 10,000 mG, while the magnetic field (f = 60 Hz) in the environment where general people

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are exposed should be less than 833 mG. Recently, numerous foreign renewable energy companies have been investing in Taiwan, and the investors prioritize the health and safety of personnel working in substations. Before constructing a renewable energy plant, investors engage a consulting firm to conduct an assessment and testing report of the environmental electromagnetic field that complies with regulatory standards. Traditional electromagnetic field measurements are mostly conducted on-site using a Gauss meter. For more complex calculations, electromagnetic field simulation software is used. If analysis is required before constructing the plant, the magnetic field values can be calculated using formulas such as the Biot-Savart law. However, this method can only calculate the impact of cables in simple underground ducts on the environmental electromagnetic field and cannot compute the magnetic fields of high-voltage winding equipment. Therefore, that is necessary to use electromagnetic field simulation software to further evaluate the distribution of magnetic fields. The study in [6] analyzed electromagnetic force simulations of inductors with nonlinear permeability and investigate the impact of magnetic stress on the resonant size of the inductors using Ansys Maxwell. Furthermore, finite element analysis can also be applied to optimize the shielding design and noise reduction of transformers. Using software analysis to assess different enclosures and support structures. Eventually, there is an opportunity to optimize the transformer and design costs [7].

As shown in the above literature review, finite element analysis is a viable option for evaluating the electromagnetic field in the substation. Therefore, this study will utilize Ansys Maxwell to conduct the analysis. The substation contains various high-voltage winding equipment components such as transformers, reactors, and harmonic filters, all of which generate magnetic fields. However, modeling all these components would be time-consuming and resource-intensive. Although FEM has been used in many applications, there is limited research on large-scale electromagnetic field assessment analysis. Thus, this study will focus on investigating simplified models for high-voltage winding equipment, particularly emphasizing transformers with complex structures. The study will compare the differences between the models of complete structural transformers and simplified models, that include structural simplification, magnetic field distribution, and time efficiency analysis.

2. Introduction to Transformer Structure

2.1. Transformer Rating

In this study, an existing transformer with specifications of a 500 MVA three-phase auto-transformer is utilized. The voltage levels are 345 kV/161 kV/33 kV. The nameplate specification of the transformer is shown in Table 1.

Table 1. Transformer rating

Transformer Parameters	Value	Transformer Parameters	Value
High-voltage rated capacity	500 MVA	High-voltage connection type	Grd.Y
Medium-voltage rated capacity	500 MVA	Medium-voltage connection type	Grd.Y
Low-voltage rated capacity	90 MVA	Low-voltage connection type	Δ

High-voltage	345 kV	High-voltage Current	837 A
Medium-voltage	161 kV	Medium-voltage Current	1793 A
Low-voltage	33 kV	Low-voltage Current	1575 A
High-voltage turns	303	Iron core	27ZDKH90
Tap changer turns	40	Shielding layer	27ZDKH90
Medium-voltage turns	265	Frequency	60 Hz
Low-voltage turns	54	Type	Autotransformer

2.2. Transformer Structure

Figure 1. is the model structure of the 500 MVA transformer in Ansys Maxwell. The winding arrangement consists of four layers. The outermost layer in red color represents the high-voltage winding. The second layer in yellow color represents the on-load tap changer (OLTC) winding. The third layer in blue color represents the medium-voltage winding. The innermost layer in purple color represents the low-voltage winding. The voltage levels from the outermost to the innermost are 345 kV, 345 kV, 161 kV, and 33 kV. The dimensions corresponding to the top view and front view of the transformer are shown in Figure 2. and Figure 3. The structure and dimensions of the transformer windings are displayed in Figure 4. Each winding consists of 26 layers, and the iron core is composed of 20 layers of silicon steel sheets.

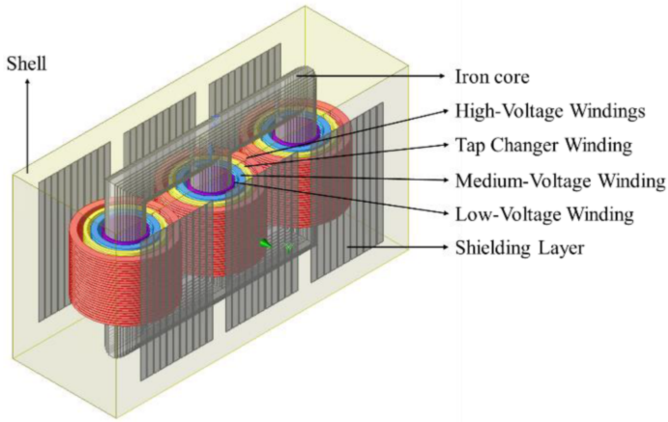

Figure 1. Typical power transformer structure.

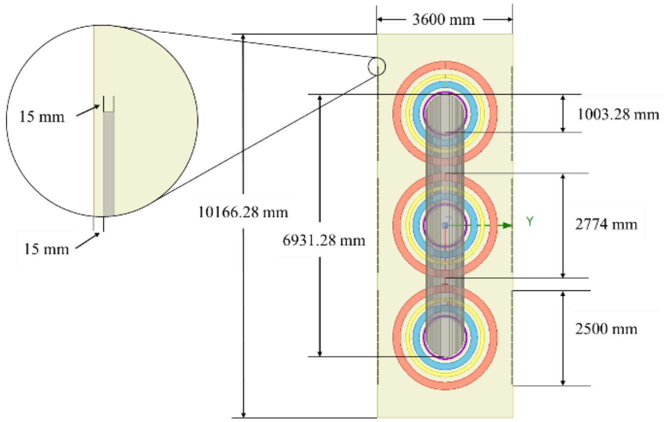

Figure 2. The top view of the transformer structure.

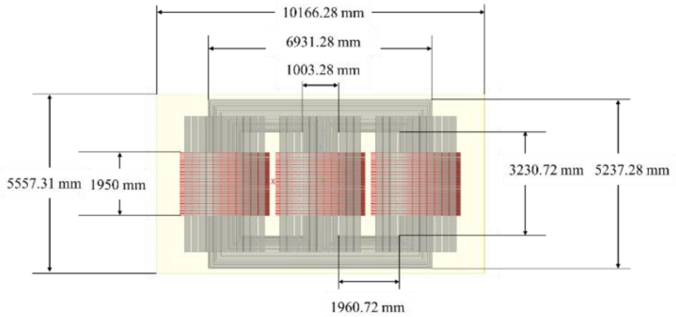

Figure 3. The front view of the transformer structure.

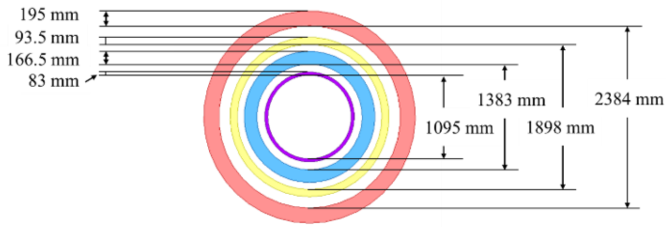

Figure 4. The transformer's winding structure.

2.3. Transformer Concept

A transformer is a device that converts electrical energy from the primary side into magnetic energy and then induces this magnetic energy into electrical energy on the secondary side. Figure 5. displays the energy conversion of a transformer. The relationship between voltage, current, and turns ratio can be expressed using (1), and then the induced voltage can also be determined by (2). During the transformation of magnetic fields, magnetic leakage flux is generated, and the magnitude of the leakage flux will determine the magnitude of the ambient magnetic field.

$$\frac{v1}{v2} = \frac{n1}{n2} = \frac{i2}{i1} \tag{1}$$

$$e_{2ind} = n2\frac{d(\emptyset + \emptyset_{L2})}{dt} \tag{2}$$

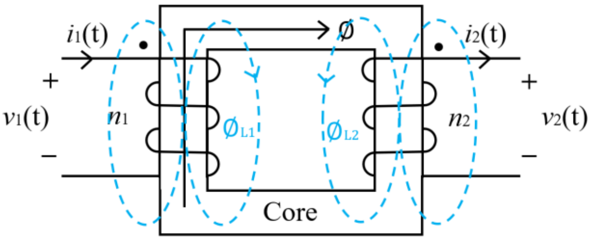

Figure 5. The transformer model with actual magnetic leakage.

where

$v1$: Primary voltage (V)

$v2$: Secondary voltage (V)

$i1$: Primary current (A)

$i2$: Secondary current (A)

$n1$: Primary turns (Turns)

$n2$: Secondary turns (Turns)

$\emptyset$: Magnetic flux (Wb)

$\emptyset_{L1}$: L1: Primary leakage flux

$\emptyset_{L2}$: L2: Secondary leakage flux

e_{2ind} : Secondary-side induced voltage (V)

3. Introduction to the Simplified Model

Due to the significant time and computational resources required for finite element analysis, this study will simplify the geometric shape of the transformer. The simplification method involves simplifying the geometric structure, and mesh partitioning. Then the calculation time can be reduced. The simplified transformer model is shown in Figure 6.

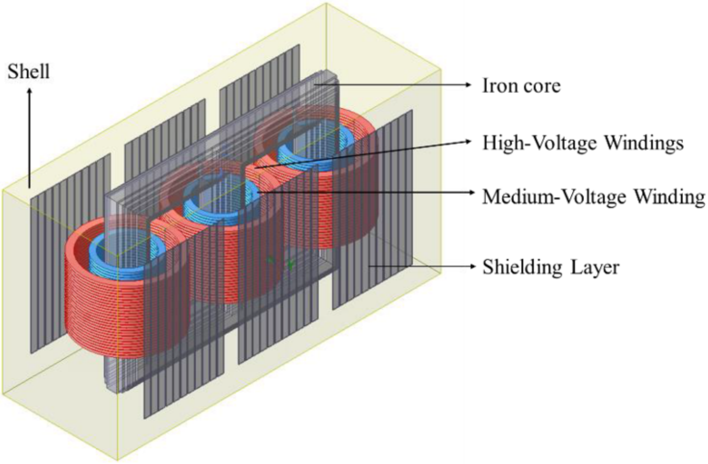

Figure 6. The simplified transformer model.

The latest version of Maxwell can automatically divide the mesh. The precise model has 531,497 meshes, while the simplified model has 220,112 meshes. Using the simplified model significantly reduces the number of meshes by 311,385. This will not only effectively save memory resources but also shorten computer calculation time. A comparison of the meshes of the precise model and the simplified model is shown in Figure 7.

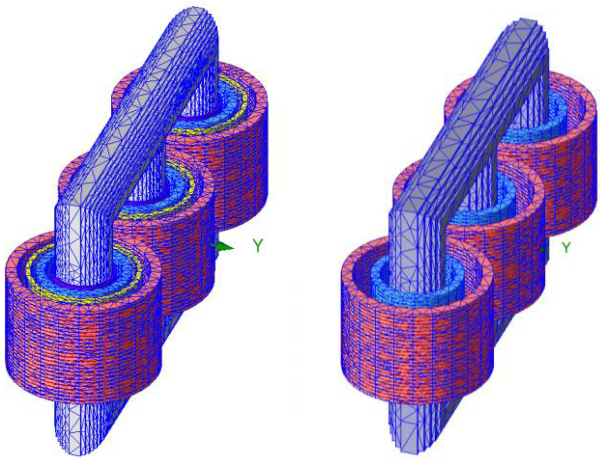

Figure 7. Mesh comparison between the precise model (Left) and simplified model (Right) .

4. Simulation Results and Discussion

4.1. Accuracy Analysis of Model's Environmental Magnetic Field

In this study, measurements are taken along the X and Y directions extending outward from the transformer as shown in Figure 8. Then, several values measured in both precise and simplified models are listed in Tables 2. and 3. It can be seen from Table 2. When distances are within 7 m, all errors are less than 5 %. However, in Table 3, almost all errors are larger than 5 %. The main reason is that the environmental magnetic field value is not large enough, so the error caused by the mesh setting of the simplified model may exceed 5 %. In order to objectively analyze the error of the simplified model, this study takes a quarter limit value as the threshold value, that is, 2,500 mG. This study only evaluates the accuracy of the simplified model when the simulated value of the space magnetic field exceeds 2,500 mG. In fact, the maximum error less than 2,500 mG is 50.94 %. However, the magnetic field value corresponding to this error is less than 100 mG, so the larger magnetic field value caused by the error is still far less than 10,000 mG. In addition, another simulated value is taken for evaluation. This value falls within the range of 1000 mG ~ 2500 mG and the corresponding error is greater than 10 %, that is, 12.10 %. The simplified model simulation value corresponding to this error is 1,511.23 mG. Therefore, compared with 10,000 mG, this value basically does not affect the overall environmental magnetic field assessment result.

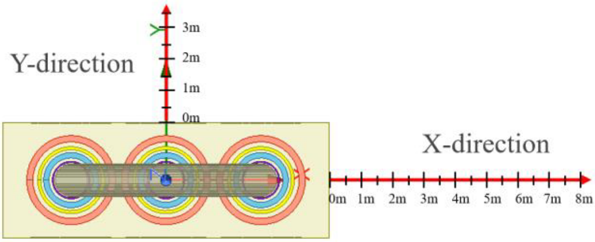

Figure 8. Measurement positions along the X and Y directions.

Table 2. Simulation Results of Precise Model and Simplified Model Along the X-Axis

Distance (m)	Precise model Mag_B (mG)	Simplified Model Mag_B (mG)	Error (%)
0	48,443.90	48,825.44	0.79
0.5	24,444.68	23,449.94	-4.07
1	12,515.44	12,271.04	-1.95
1.5	6,951.18	6,944.57	-0.10
2	4,296.13	4,479.28	4.26
2.5	2,852.21	2,776.52	-2.65
3	1,970.53	1,952.41	-0.92
3.5	1,378.71	1,406.27	2.00
4	1,090.73	1,123.59	3.01
4.5	900.67	937.37	4.08
5	741.27	774.21	4.44
5.5	635.78	644.42	1.36
6	578.69	585.31	1.15
6.5	530.48	552.80	4.21
7	491.64	526.35	7.06
7.5	461.15	496.53	7.67
8	448.67	472.03	5.21

Table 3. Simulation Results of Precise Model and Simplified Model Along the Y-Axis

Distance (m)	Precise Model Mag_B (mG)	Simplified Model Mag_B (mG)	Error (%)
0	1,348.14	1,511.23	12.10
0.5	382.33	351.59	-8.04
1	180.59	173.88	-3.72
1.5	83.70	74.78	-10.65
2	20.47	23.92	16.82

2.5	33.27	50.23	50.94
3	59.08	70.62	19.53

The magnetic field distribution diagram from the transformer's top view observed that the error between the precise model and the simplified model is not significant. Figure 9 depicts the magnetic field distribution in the X-Y plane with the transformer center as the origin for the precise model, while Figure 10 shows the magnetic field distribution in the x-y plane with the transformer center as the origin for the simplified model.

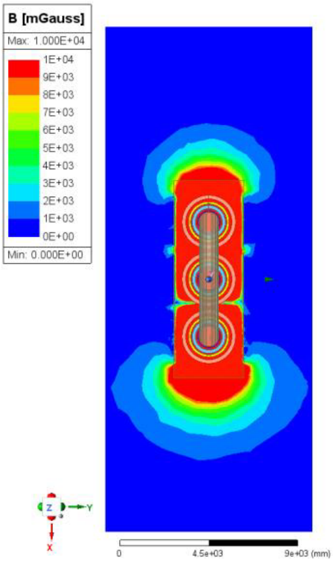

Figure 9. Top view of the magnetic field for the precise model.

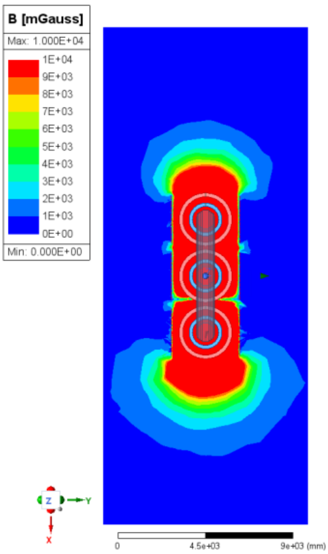

Figure 10. Top view of magnetic field for the simplified model.

A. Simulation Time Analysis of Two Models

This study utilized an industrial computer for simulation, with specifications including 16 CPU cores, 32 logical processors, and 256 GB of memory. Detailed specifications can be found in Table 4. The industrial computers are generally more advanced and typically cost 4 to 5 times as much. Therefore, based on the simulation results, this is possible to save more than half of the simulation time, as shown in Table 5. This means that the simulations can also be performed on regular desktop computers without running into insufficient computer resources. Overall, using a simplified model either saves time or allows for simulations on standard computer configurations. In real substations, there are not only transformers but also other equipment such as cables, reactors, and filters. Although it is possible to perform calculations using precise models, there could be too many mesh elements. That may render the calculations infeasible. Therefore, applying a reasonably simplified model can significantly save time and resources, achieving efficient analysis and assessment.

Table 4. Industrial Computer Specifications

Equipment Name	Specification Model
CPU	AMD Ryzen Threadripper PRO 5955WX 16-Cores
Memory	256 GB 3200 MHz
Hard Drive	Samsung MZ1L2960HCJR-00A07

Table 5. Key Comparison Between the Precise Model and Simplified Model

Model	Mesh Elements	Simulation Time (min)
Precise Model	531,497	143
Simplified Model	220,112	32
Comparison	-311,385	-111

5. Conclusion

This study proposes a simplified model technology for high-voltage winding equipment. Environmental magnetic fields can be quickly assessed when high voltage winding equipment is considered in a substation. By comparing the simulations of the precise model and the simplified model, it can be known that although there are errors, the overall accuracy of the simplified model is acceptable in engineering. This will make practical engineering assessments of environmental magnetic fields more efficient. In addition, this method can also be applied to the environmental magnetic field assessment of other high-voltage winding equipment (e.g. harmonic filter, variable shunt reactor) in substations.

Future work will involve optimizing electromagnetic field assessments for active power electronics devices, such as a static synchronous compensator (STATCOM) or power conversion system (PCS), based on the proposed simplified approach to enhance simulation efficiency.

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