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Introduced the Development of low-Noise (50dBA) Technology for 154kV Class Power Transformers

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SUMMARY

This study introduced the development of a power transformer of less than 50dBA with combined noise through the development of low noise technology and product application for a 154kV class ultra-high voltage transformer. The noise of the transformer is a typical structural vibration-induced noise caused by the radiation of the tank's vibration, and the causes of the vibration are divided into the vibration generated by the electromagnetic force of the winding and the vibration generated by the magneto-strictive phenomenon of the core. The vibration generated by this cause is transmitted through the insulating oil and the tank. Therefore, the most important thing to reduce noise is to reduce the vibration of the transformer tank that emits noise, and for this purpose, not only research to reduce the vibration of the tank, but also vibration that isolated the path through which the vibration generated from the winding and core is transmitted to the tank. Studies on vibration-decouple design are also needed. We developed design technology for noise reduction with four directions, and studied factors affecting no-load and load noise in terms of production. In addition, evaluation and standards were established for the transformer noise measurement environment. In order to predict the noise level of the transformer to which the low-noise technology is applied, a high-accuracy no-load and load-noise prediction technology was studied. Finally, we succeeded in developing a transformer with a combined noise of 50 dBA or less without increasing the weight and volume of the transformer.

KEYWORDS

Power Transformer - Low Noise Technology – Low Noise Transformer - Noise Prediction

1. Introduction

The demand for large-capacity, high-voltage transformers is increasing with the increase in power demand worldwide. In addition, as the economy develops and the population is concentrated, urban areas are gradually expanding. Due to this phenomenon, the number of substations installed near the residential areas is increasing recently, and the issue of environmental noise has also increased. In the past, in order to satisfy these demands, efforts were made to reduce noise by using classical methods such as soundproof walls and soundproof rooms. Another method was to install a power transformer and a shunt reactor inside the building to reduce noise through the exterior wall of the building and sound absorbing material. Although this method is a method that can be applied simply to reduce noise, it requires an additional space equivalent to 2-3 times that of a transformer, and incurs high cost. In the past, we tried to achieve low noise of power transformers by designing the low magnetic flux density of the core and using the double tank design method in which the sound insulation plate and sound absorbing material are combined. However, this method was difficult to satisfy the noise level required by the environmental noise standards (usually 50 dBA during daytime and 45 dBA or less at night), and the weight and volume of the transformer increased by 10 to 15%, and the cost increased by about 15% or more. In 2008, other company developed a low-noise design technology that satisfies environmental noise, but this case was also a design method that increased the volume by 10-20% compared to the existing transformer. [1]

In this paper, we introduced a method for developing a low-noise technology in the design, manufacturing and test environment that can minimize the increase in volume, weight, and cost and maximize noise reduction. In addition, by applying this to a 154kV class power transformer, the development of a transformer less than 50dBA with combined noise was completed. Finally, to predict the noise level evaluation and reduction effect of low-noise transformers at the design calculation stage, a prediction technology with high accuracy for no-load and load noise was obtained by combining theory, load and no-load noise measurement data base, and regression equations.

2. Power transformer Noise generation principle

Basically, transformer noise is a typical structural vibration-induced noise that appears due to the vibration of the tank. The causes of vibration can be divided into two cases. First, there is the vibration in the load state caused by the Lorentz force of the winding by the transformer current, and the second is the vibration in the no-load state caused by the magnetostrictive force that depends on the magnetic flux density of the core by the magnitude of the voltage. As shown in Fig. 1, the generated vibration is transmitted through two vibration paths. Vibration generated by the core and winding can be divided into a path (red arrow) that is transmitted to the tank through insulation oil and a path (blue arrow) that is transmitted from the active part through the tank. In addition, increasing the vibration due to resonance induction is combined by the natural frequency existing for each component of the power transformer on the vibration transmission path, thereby generating noise. Therefore, in order to reduce noise, a design for predicting the natural frequency of each transformer component and avoiding resonance is fundamentally required, and research is required to reduce the vibration energy of the tank of the power transformer the final noise radiation surface. In addition, it is also necessary to study the vibration isolation design that decouple the path through which vibrations generated from windings and cores are transmitted to the tank.

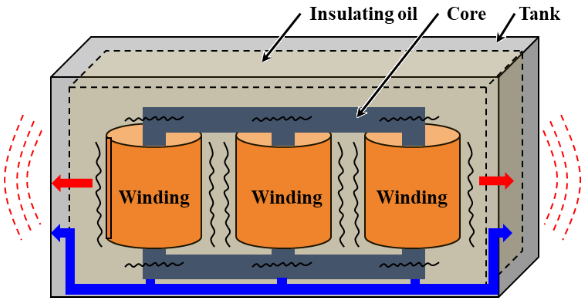

Fig. 1 Transmission path of vibration and emission noise for power transformer

3. Development of low-noise technology for 154kV class power transformer

In this study, low noise technology was developed for design, manufacturing, and testing. In the design part, resonance avoidance, tank vibration reduction, vibration insulation of vibration transmission path, and resonance avoidance and vibration insulation technology of attachments were introduced. First, the technology for predicting the natural frequency of the main components of the power transformer, such as tank, core, winding and piping was established, and noise increase was prevented by suppressing vibration amplification caused by resonance of the main components. As shown in Fig. 2, the natural frequency prediction technology was established as a numerical analysis technique based on the finite element method (FEM), and the equivalent property values necessary for simple model of a complex product were obtained. For this, the predictive model was verified by conducting natural frequency experiments and analysis using about 200 experimental data as shown in Fig.3. Through the above study, it was confirmed that when the natural frequency of the core, winding, and tank exists near the electromagnetic excitation frequency of 120Hz and its harmonic component, the noise rises by about 2~4dB. Therefore, the foundation for the development of low-noise transformers is “stabilization of vibration and noise by avoiding mechanical resonance of the product” as the first step. Second, as mentioned in the previous section, the noise caused by structural vibration proceeds through the vibration source (winding and core), the transmission path (insulation oil and the active part), and the mechanism of noise radiation, and a simple method to directly reduce noise One of them is to reduce the vibration of the tank.

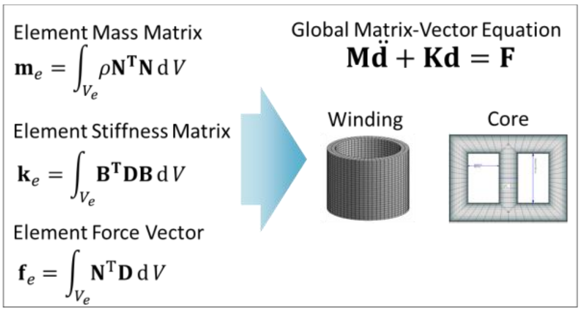

Fig. 2 FEM Modeling of the Winding and Core for prediction natural freqeuncies

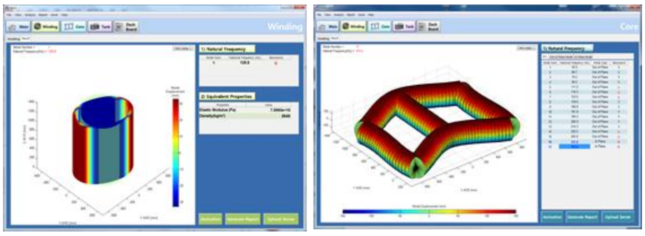

Fig. 3 Resonance avoidance design through natural frequency analysis

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In the past, to reduce the vibration of the tank, an increase in the thickness of the tank enclosure, double walls, sound absorption and sound insulation construction were designed. This method is not suitable for a limited substation site due to an increase in volume, weight, and excessive cost, and the performance is also not excellent for reducing low-frequency noise such as 120Hz. In this study, to overcome these disadvantages, as shown in Fig. 4, noise reduction was maximized while maintaining the same tank thickness through vibration analysis, acoustic resonance avoidance of reinforcement, and acoustic radiation efficiency, and this was applied to the transformer.

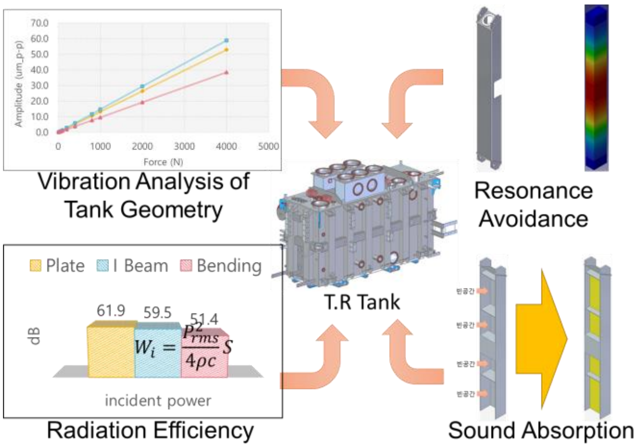

Fig. 4 Design of transformer tank with noise radiance efficiency taken into account

In addition, as shown in Fig. 5, the latest construction method such as CLD (Constrained Layer Damper) was applied to reduce the radiated noise caused by the vibration of the power transformer tank. This method is a vibration damping method that suppresses vibration by using a viscoelastic material between the tank and a restraint having a certain area, and can effectively reduce the vibration of the structure. As a result of the study, the most cost-effective noise reduction method was the case of applying the CLD vibration damping method and confirmed the excellent noise reduction effect compared to other methods (double wall, sound absorbing and insulating material). As a result of applying the optimization method through experiments and analysis on various design factors, and deriving the key design factors, an average noise reduction effect of 4 to 6 dB was confirmed. The results of this study were possible because the vibrations generated in the tank were suppressed as much as possible to reduce the radiated noise. Based on these results, the CLD vibration suppression method using the tank surface inside the transformer and existing structures was reflected in the mass production design to establish the noise reduction technology through the low-vibration tank.

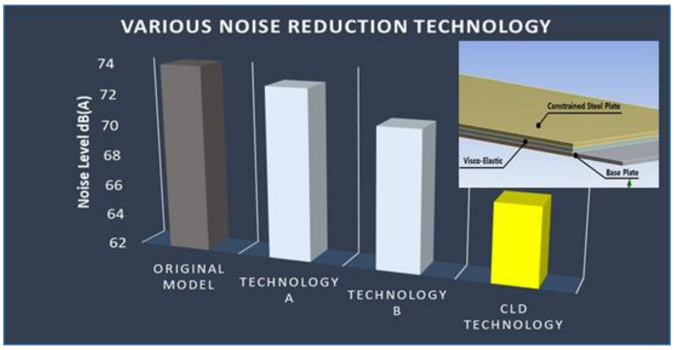

Fig. 5 Difference in noise level when using different methods

Third, by establishing the technology to insulate the vibration transmission path between the active part and the tank using viscoelastic materials, the excitation force generated from the active part (core magnetostrictive excitation force and the Lorentz force of the winding) is transmitted to the tank and noise is emitted by minimizing it. It has been studied and applied as a standard design for low-noise transformers. As mentioned above, the path through which the vibration of the active part is transmitted to the tank can be divided into fluid transfer through insulation oil and structural transfer through upper and lower support structures of the active part. As shown in Fig. 6, the vibration damping design (CLD) to reduce the vibration of the final tank and the upper/lower vibration insulation design of the main body should be considered together. If the clamping force between the active part and the tank is increased, the excitation force generated by the winding and the core is transmitted to the tank at a high transmission rate, causing greater vibration. Therefore, it is necessary to design a vibration insulation using viscoelastic materials as shown in Fig.7. Vibration isolation is closely related to natural frequency, and it is very important to select a material with appropriate stiffness and sufficient damping. Here, the condition in which the chemical properties must be kept constant while maintaining the initial mechanical properties during the life of the transformer operating for more than 30 years is an important factor in the discovery of materials.

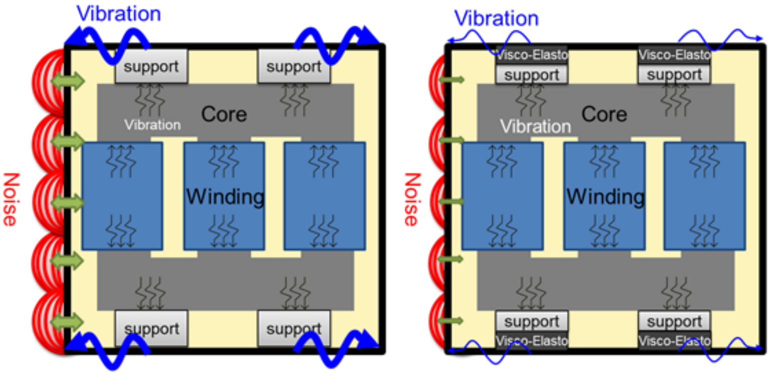

Fig. 6 Vibration insulation concept between active part and tank

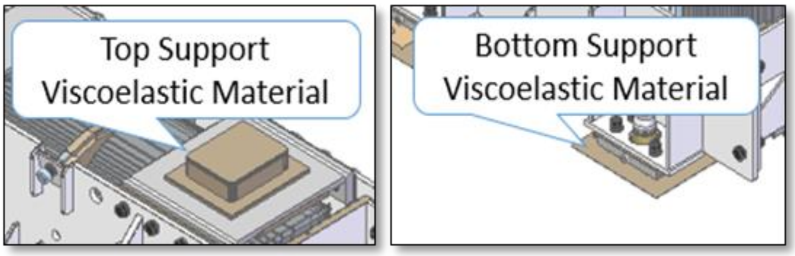

Fig. 7 Use of a viscoselactic material at the top&botto, of the active part

Finally, the design of excessive support between the tank and the piping and instrumentation in the past increases the system stiffness, which increases the natural frequency, and the vibration transmission path from the tank is added to increase the vibration. In addition, excessive vibration of instruments may cause damage due to malfunction or damage of instruments, so a vibration isolation design for this is essential. This problem is called the Base Excitation Model as shown in Fig. 8, and the vibration is increased and has a tendency to decrease due to the relationship between the frequency component of the vibrating tank and the natural frequencies of pipes and instruments. [2] In general, it may be considered good to design a structure in which the piping outside the tank and the instrumentation are very strongly coupled. However, from a vibration design point of view, this design results in a greater amplification of the vibrations of pipes and instruments than vibrations of the tank. In fact, as a result of analyzing the data in which the vibration of pipes and instruments was higher than the vibration level of the tank, it was observed that about 70% of the cases where the natural frequency of the tank attachment was designed to be higher than the excitation frequency of the tank. As shown in Fig. 9, a low rigidity design was carried out by removing the supports of pipes and instruments to lower the natural frequency, and it was confirmed that the vibration was reduced by about 50 to 90% compared to the vibration amplitude under the high natural frequency condition. When the excitation frequency of the tank is 120Hz, it is desirable to design the natural frequency of the attachments to be 70Hz or less, and we have established and applied the resonance avoidance design calculation formula for piping and instruments to the design.

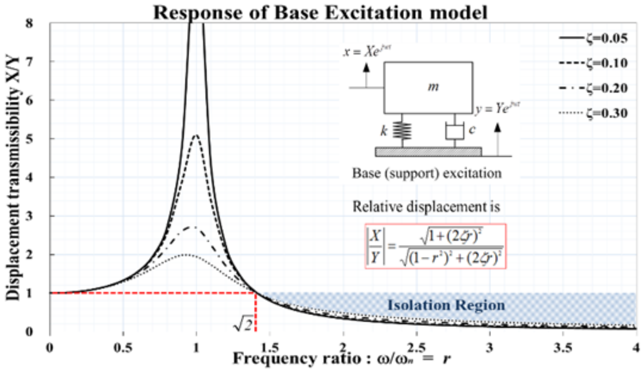

Fig. 8 Vibration insulation in piping and meters in tank

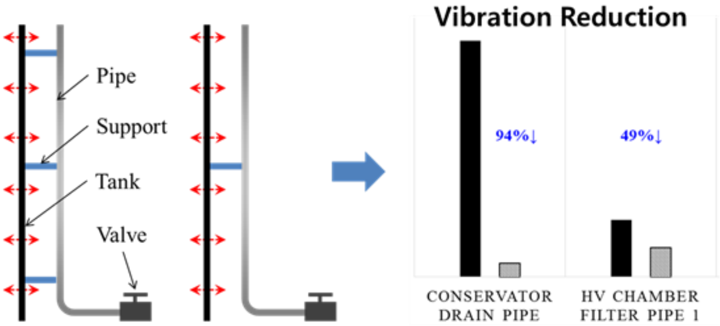

Fig. 9 Reduction of vibration using vibration insulation

In the manufacturing and testing part, various studies were conducted on each part and environment to reduce vibration and noise. When the clamping force of the core has a high local pressure during the manufacturing process, the noise level is somewhat higher than the noise expected in the design. For these parts, the structure and method for uniform compression of the core as shown in Fig. 10 were verified through research and experiments. Through this, the manufacturing process was improved to prevent high noise by calculating the tightening torque that minimizes vibration and noise to prevent noise deviation that may occur between products in advance. In addition, the effect on noise reduction is evaluated through noise evaluation by manufacturing quality such as the joint gap of the core, the compression force of the winding, the shape and number of wrought iron and the position and number of the yoke band, and the noise impact of various manufacturing parts such as the shape of the core support. It was verified and applied to the design of a low-noise transformer.

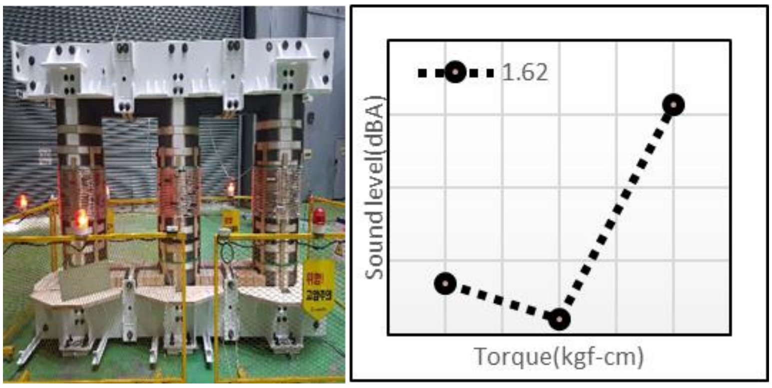

Fig. 10 Noise analysis by core compression torque

Since accurate measurement and analysis of low-noise transformers cannot be performed unless the environmental analysis for noise evaluation is done, the P-I Index, a major indicator of noise measurement environment evaluation, is used to determine and apply the measurable noise limit of power transformers. In the IEC standard, the limit of noise measurement reliability based on the P-I Index is defined to be within 8dB. The P-I Index is an index indicating the difference between sound pressure and intensity, and the size of the Index increases as the reverberation noise and background noise increase. In order to conduct accurate noise evaluation of low-noise transformers, it is necessary to manage the above P-I Index, and in particular, background noise management is the key. In this study, as a result of evaluating the P-I Index for the test room that measures the noise of the power transformer, it was confirmed that the measurable noise of the transformer is 50 dBA when it is managed under the 45 dBA level as shown in Fig. 11. and analysis was performed. In addition, a study was conducted on the noise difference according to the standing condition when measuring the noise of the power transformer. As shown in Fig. 12, it was confirmed that there was a noise difference of about 3 dB through the analysis and experimental verification, and this was improved.

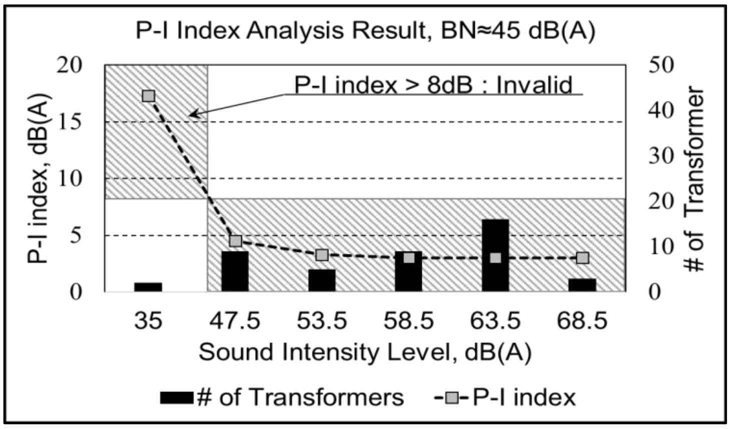

Fig. 11 measurement limit noise when background noise is 45dB

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4. Development of noise prediction technology for power transformers

In this study, the technology to accurately predict the noise of a power transformer based on the above-mentioned technologies is a very important factor in design, manufacture, and test a low-noise transformer. If accurate noise prediction is not possible based on transformer design factors and low-noise technology, and thus the measurement and prediction results are different, it can cause a very large economic loss to the manufacturer and customer damage the trust relationship. Therefore, transformer manufacturers are conducting research to make an accurate prediction model by predicting noise in their own way and updating the prediction model by comparing it with the test results. In this study, a high-accuracy mathematical model using theory and experimental date base was established to predict the load noise caused by the Lorentz force of the winding and the no-load noise caused by the magnetostrictive excitation force of the core. First, to predict the load noise caused by winding that generates vibration by Lorentz force, a finite element model was established as shown in Fig. 12, and the equivalent Lorentz force acting in the radial direction of the winding was calculated, as shown in Fig. 13.

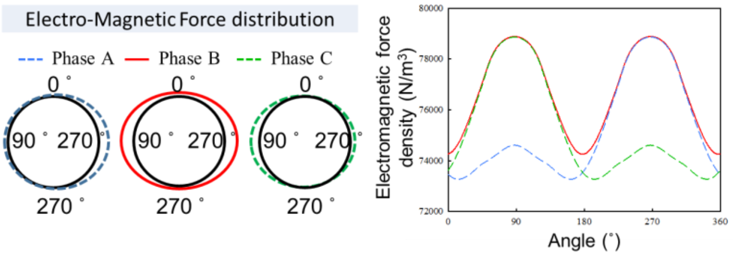

Fig. 12 Lorentz Force calculation result of the winding

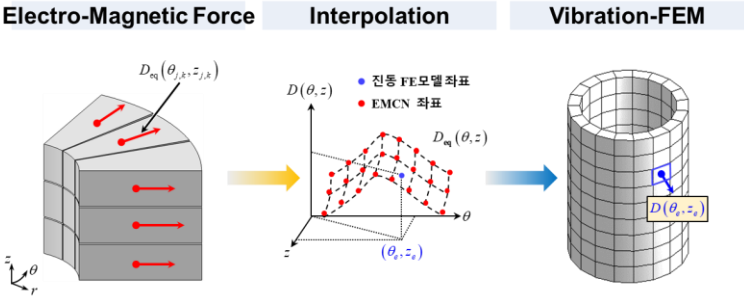

Fig. 13 Lorentz force mapping for vibration model

The mechanical response was calculated and converted into the vibration response of the winding. The results of establishing the predictive model as shown in Fig. 14 through correlation analysis with the load noise test data base measured using the regression equation consisting of the vibration response of the winding obtained from the mathematical model and numerical analysis of the electromagnetic-mechanical coupling and various design factors Table 1 As shown above, the result was obtained with an error level of less than 0.2 dB on average and 1.3 dB of standard deviation. This can be said to be a result with high accuracy within a short time compared to the multi-body FEM coupling analysis, which is performed only through analysis and takes a lot of time.

Table1. evaluate prediction accuracy of the noise

	Mean Error (dB) (Test – Estimation)	Standard Deviation (dB) (Test – Estimation)
Load Noise	0.2	1.3
No-Load Noise	0.5	1.8

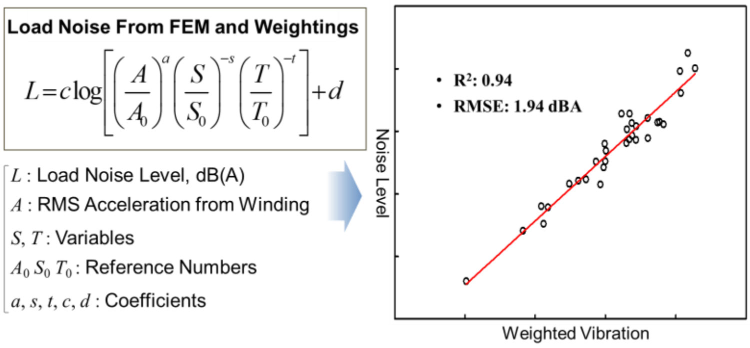

Fig. 14 Load noise prediction regresion model and accuracy

In addition, in order to predict the no-load noise generated by the core, the regression equation as shown in Fig. 15 is taken into account based on the noise equation according to the magnetic flux for each core material, considering the design, manufacturing and test environmental factors that affect the no-load noise. In addition, in order to predict the no-load noise generated by the core as shown in Fig. 15, the regression equation was calculated by considering the design, manufacturing and test environment factors that affect the no-load noise based on the noise calculation formula for each magnetic flux density and size of iron core material. When compared with about 200 noise measurement data for the no-load noise prediction model, as shown in Table 1, it was confirmed to have high prediction accuracy with an average of 0.5 dB and a standard deviation of 1.5 dB or less. Finally, for the cooling of power transformers, a cooling system is often designed attached to the transformer. In this case, the flow noise by the cooling fan attached to the cooling system also affects the noise of the transformer, and predictable technology is required. To predict the noise of a cooling fan, after acquiring the measured data of the noise of the cooling fan + transformer itself and the noise of the transformer itself, the noise of the cooling fan is calculated as a log formula, and then combined cooling fan according to the noise information of each cooling fan and the number of operations After calculating the fan noise, the difference from the actual noise was analyzed to obtain a correction equation. Through this, the noise prediction accuracy of the cooling fan was able to secure an average of 0.1dB and a standard deviation of 1.2dB.

$$\textbf{No load sound} = \left(\boldsymbol{A_i T^2} + \boldsymbol{B_i\, T} + \boldsymbol{C_i}\right) + \sum_{\boldsymbol{k=1}}^{\boldsymbol{n}} \left(\boldsymbol{D_k} \log \boldsymbol{X_k}\right)$$

i : Core Type
$A_{i,}$ $B_{i,}$ C_i : Coefficient due to core type
T: Magnetic flux density
N : Number of design parameter
D : Weighting coefficient
X_k : Design parameters

Fig. 15 No-load noise prediction regresion model

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5. Conclusion

In this study, in order to actively respond to the growing demand for low-noise transformers from customers, we conducted research on the development of low-noise transformers. Vibration/noise stabilization was carried out by applying the resonance avoidance design first, and the noise caused by vibration transmission was minimized by designing the vibration insulation of the tank, active part and instrumentation, and vibration suppression technology of the tank to minimize radiated noise. In addition, research on the noise measurement environment suitable for low-noise transformers was conducted, and finally, a high-accuracy load and no-load noise prediction model was developed to minimize the difference with the measured value of the product. Based on the research as in the previous section, we conducted a verification of the development of a low-noise transformer with a capacity of 60MVA or more for a total of 4 154kV-class ultra-high voltage transformers. As a result, the load noise was estimated to be about 43 ~ 45 dBA, and the no-load noise was evaluated to be 47 ~ 49 dBA, and the synthetic noise was able to satisfy less than 50 dBA. In addition, the weight and volume were maintained at the same level as the existing standard transformer, and the increase in cost was about 3% or less.

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