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RECENT FEATURES OF THE FUJI LOW-SOUND-LEVEL TRANSFORMERS (I)

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I. INTRODUCTION

Recently many large power stations and substations have been built near residential areas. Because of improvements in overall efficiency, and widespread trends toward extra-high voltage and large capacity transformers, the noise level of standard type transformers has also tended to increase.

For these reasons, problems of noise reduction are becoming very important as one form of public hazard prevention in cities and noise reduction laws are being enacted. Previously, 22 cities including Tokyo had passed noise prevention regulations, and the number is increasing as time goes on. Therefore, from now on the reduction of transformer noise must be carefully examined.

Fuji Electric has been making considerable efforts in the field of transformer noise reduction for some time. As a result of this work, two special low-sound-level transformers: a 250 kv 230 Mva forced-oil natural cooling on-load tap changing transformer with a concrete enclosure and a noise level of 50 dB_A and a 147 kv 280 Mva forced-oil forced-air cooling transformer with a prefabricated type multi-enclosure and a noise level of 65 dB_A have been developed. This is an outstanding achievement both at home and abroad.

The following article will discuss features and pratical results of Fuji low-sound-level transformers, noise reduction methods and their effects and applications, and design of the noise limiting enclosures. The next issue will contain an article concerning the basic aspects of noise, sources of transformer noise and noise level, and regulations and permissible limits of transformer noise.

II. FEATURES AND PRACTICAL RESULTS OF FUJI LOW-SOUND-LEVEL TRANSFORMERS

Fuji Electric has already manufactured about 100 various types of low-sound-level transformers and these have shown very good results in practice. A list of all the recently manufactured large capacity (100 Mva or over) low-sound-level transformers is given in *Table 1*.

The features of Fuji low-sound-level transformers are as follows:

1) The cover surface is also enclosed by the sound insulation/sound absorption enclosure, and the terminal bushing passes through the sound insulation/ sound absorption enclosure and leads to the exterior.

In the previous double-tank type as shown in *Fig. 1* (*a*) much of the cover surface was exposed, and sound wave diffraction caused, the noise reduction effect to diminish at distances further from the transformer. Therefore, when a large noise reduction effect is desired, this construction is not recommended. The usual methods of covering the cover surface are as shown in *Fig. 1* (*b*) and (*c*). With these methods, the height of the terminal bushing, including the insulation distance to the enclosure wall make the noise proof construction very large. However it is necessary to have the terminal bushing go through the enclosure to the exterior by means of a "through-the-wall enclosure" or cable and the price therefore goes up. These defects can be completely eliminated by using the construction shown in *Fig. 1* (*d*) in which a bushing pocket section formed by combining the terminal bushing pocket section formed by combining the terminal bushing and a "through-the-wall bushing" passes through the enclosure wall. In 140 kv transformers, the enclosure height can be reduced by about half using this construction.

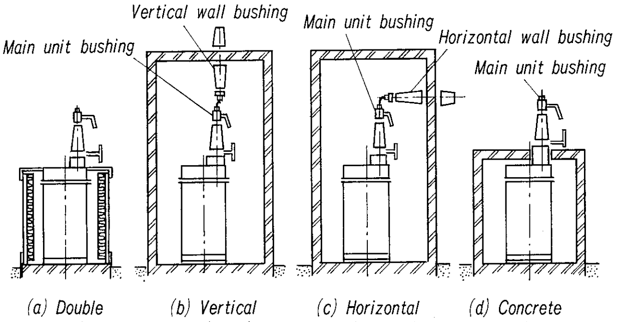


Fig. 1 Construction of various noise-limiting enclosures

Table 1 **List of Low sound Level Transformers, 100 Mva and above with enclosures**

Delivered			Transformer Specifications						Noise Level (dB_A)			Noise Reduction System
Customer	Year	Qu-ant.	No. of phases	Freq. (Hz)	Voltage (kw)	Capa-city (Mva)	On-load tap-changer	Cooling system	JEM	Guaran-teed value	Difference (dB_A)	
Tokyo Electric Co., Hanabata S.S.	1960	2	3	50	147/66/21	120	Not used	Forced-oil air cooled	88	70	18	Prefabrication-type single enclosure
Kansai Electric Co., Shinkobe S.S.	1962	1	3	60	250/77/15.4	172.5	Used	Forced-oil self cooled	More than 85	50	More than 35	Concrete enclosure
Kansai Electric Co., Shinkobe S.S.	1963	1	3	60	250/77/15.4	172.5	Used	Forced-oil self cooled	More than 85	50	More than 35	Concrete enclosure
Tokyo Electric Co., Daishi S.S.	1963	1	3	50	143.5/66/21	115	Used	Forced-oil self cooled	More than 85	55	More than 30	Concrete enclosure
Kansai Electric Co., Shinkobe S.S.	1964	1	3	60	250/77/22	230	Used	Forced-oil self cooled	More than 85	50	More than 35	Concrete enclosure
Tokyo Electric Co., Ikebukuro S.S.	1964	1	3	50	143.5/66/21	115	Used	Forced-oil water cooled	More than 85	65	More than 20	Prefabrication-type single enclosure
Chubu Electric Co., Yokkaichi S.S.	1965	1	3	60	154/77	150	Used	Forced-oil air cooled	89	70	19	Prefabrication-type single enclosure
Chubu Electric Co., Kita-Ichinomiya S.S.	1965	1	3	60	154/77	100	Used	Forced-oil air cooled	87	60	27	Prefabrication-type multi-enclosure
Chubu Electric Co., Chita S.S.	1965	1	3	60	154/77	150	Used	Forced-oil air cooled	89	70	19	Prefabrication-type single enclosure
Tokyo Electric Co., Daishi S.S.	1965	1	3	50	143.5/66/21	115	Used	Forced-oil self cooled	More than 85	55	More than 30	Concrete enclosure
Electric Power Develop. Co., Isogo PS.	1966	1	3	50	13.5/147	280	Not used	Forced-oil air cooled	More than 91	65	More than 26	Prefabrication-type multi-enclosure
Chubu Electric Power Co., Minami-Toyoda SS.	1966	2	3	60	154/77	100	Used	Forced-oil air cooled	87	70	17	Prefabrication-type single enclosure
Electric Power Develop. Co., Takehara PS.	1966	1	3	60	12.3/110	265	Not used	Forced-oil air cooled	More than 91	80	More than 11	Prefabrication-type single enclosure
Chubu Electric Power Co., Nishi-Okayama SS.	1967	1	3	60	110/66/22	115	Used	Forced-oil air cooled	More than 85	76	More than 9	Prefabrication-type single enclosure
Electric Power Develop. Co., Takasago PS.	1967	1	3	60	19/250	265	Used	Forced-oil air cooled	More than 91	80	More than 11	Prefabrication-type single enclosure
Tokyo Electric Power Co., Kinugawa PS.	Now being man-ufac-tured	1	3	50	147/66/10.5	100	Used	Forced-oil air cooled	87	70	17	Prefabrication-type single enclosure
Electric Power Develop. Co., Takasaga PS.		1	3	60	19/250	265	Used	Forced-oil air cooled	More than 91	80	More than 11	Prefabrication-type single enclosure
Chubu Electric Power Co., Kita-Ichinomiya SS.		1	3	60	154/77	100	Used	Forced-oil air cooled	87	60	27	Prefabrication-type multi-enclosure
Chubu Electric Power Co., Minami-Toyoda SS.		1	3	60	154/77	100	Used	Forced-oil air cooled	87	70	17	Prefabrication-type single enclosure
Electric Power Develop. Co., Isogo PS.		1	3	50	13.5/147	280	Not used	Forced-oil air cooled	More than 91	65	More than 26	Prefabrication-type multi-enclosure

2) Concrete is used as sound insulation material instead of steel plates.

The specific gravity of the concrete is about 2.3, only 30% of that of steel plates. The steel plate enclosure thickness of the double tank-type is about 10 mm while that of the concrete enclosure is 100∼200 mm, making the latter easier to manufacture. When comparing the area density, concrete is equivalent to steel plates about 30∼60 mm thick. Since the bending strength is about 30 times greater, the frequency of natural vibration is high and the vibration amplitude is small. Therefore, highly effective sound insulation is possible.

3) The enclosure is of the prefabricated type.

Because of the prefabricated construction, the size of the installation site can be reduced considerably.

4) Cooling system is outside the enclosure

Since the heat from the transformer is removed through the medium of the oil to the outside of the enclosure, the area to be ventilated within the enclosure can be reduced considerably and the enclosure construction can be simplified.

III. METHODS OF NOISE REDUCTION IN THE TRANSFORMER AND COOLING SYSTEM AND THEIR EFFECTS AND APPLICATIONS

To reduce noise, it is necessary to first know the condition of the noise coming from the noise source and on this basis, to devise a means of reduction. In other words, noise can be divided into that propagated through solids and that propagated through air. In the former case, a vibration insulation mechanism is installed in the path of propagation and the noise is reduced by interception of the sound vibrations. In the latter case, when the noise reaches a quiet zone barriers (walls, fences etc.) are built in the noise propagation path and the noise is reduced by cutting off the noise propagation. This is the most simple and effective way to reduce noise by noise insulation. Another method—noise absorption—consists of reduction of the noise energy sufficiently by placing noise absorption materials in the noise propagation path. There are therefore three basic methods of noise reduction : prevention of vibrations, noise insulation and noise absorption. Gnenerally, noise can be best prevented by using a combination of these three methods.

The following methods are available for transformer noise reduction, Fuji Electric employs methods 1) to 7) given in **1**.

1. Methods and Effects of Noise Reduction in Transformers and Cooling System

1) Cold-rolled grain orientated silicon steel.

Cold rolled grain orientated silicon steel exhibits less magnetostriction than hot-rolled materials and has a noise reduction effect of $2\sim3$ dB$_A$. Since this

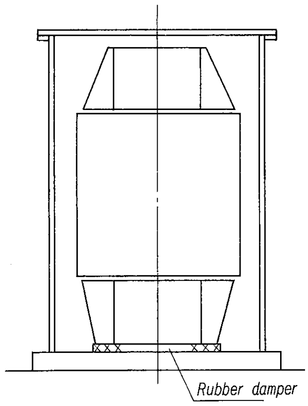


Fig. 3 Noise reduction in inner parts of the transformer

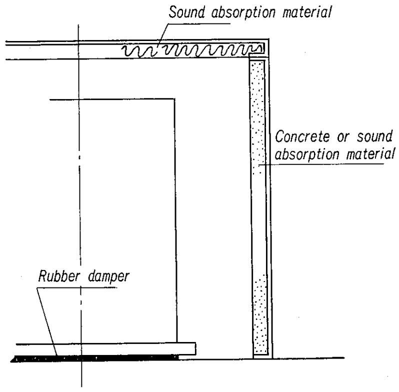


Fig. 4 Prefabrication type single enclosure

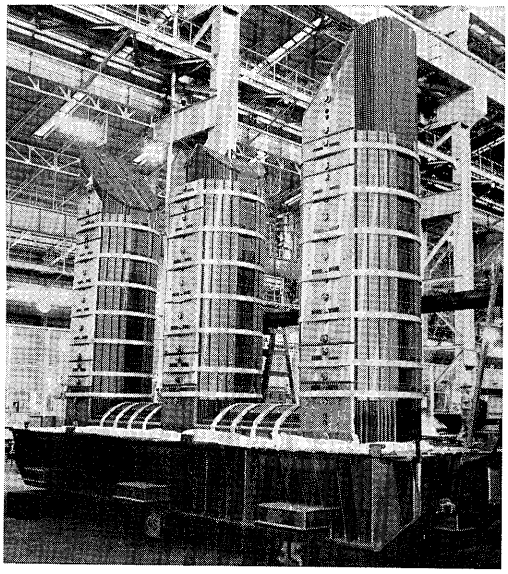


Fig. 2 Center-clamp and band-clamp type core

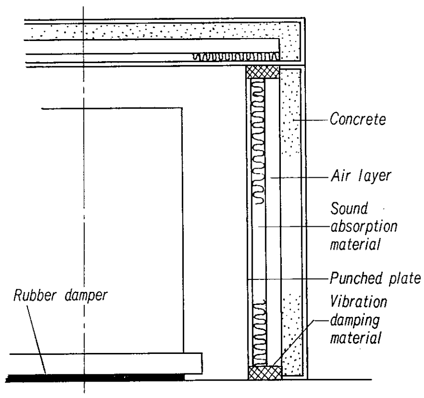


Fig. 6 Prefabrication-type multi-enclosure

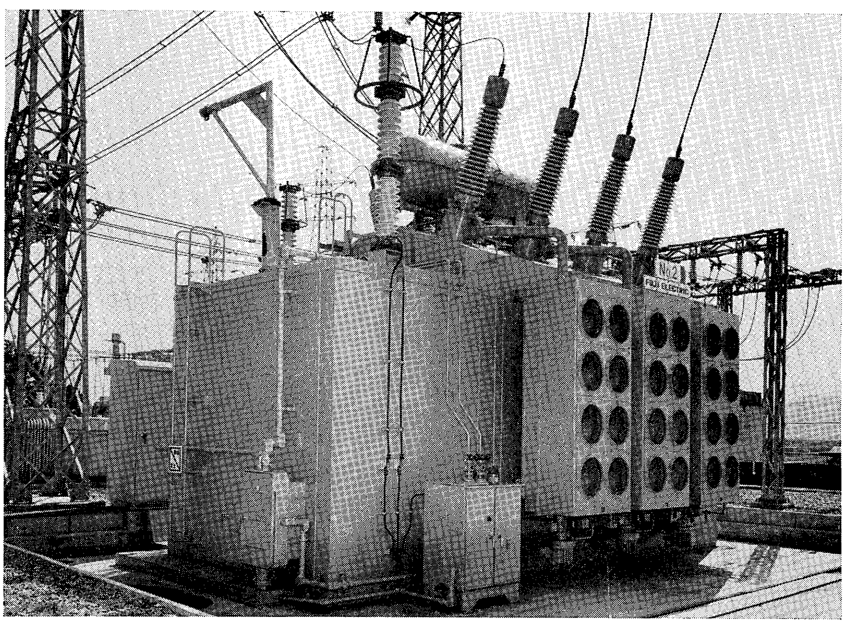


Fig. 5 110 kv 100 Mva forced oil forced air cooling on-load tap changing transformer with prefabrication-type single enclosure

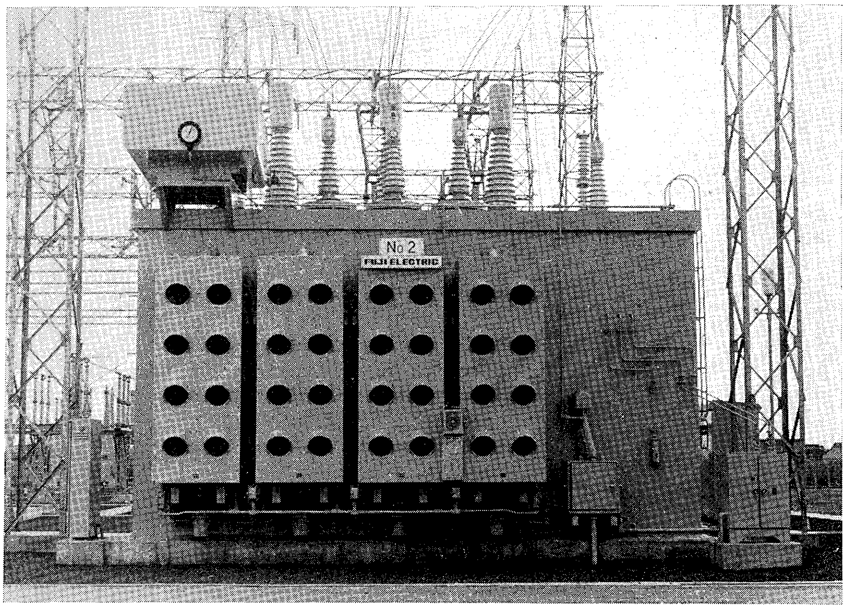


Fig. 7 147 kv 100 Mva forced-oil forced-air cooling on-load tap changing transformer with prefabrication-type multi-enclosure

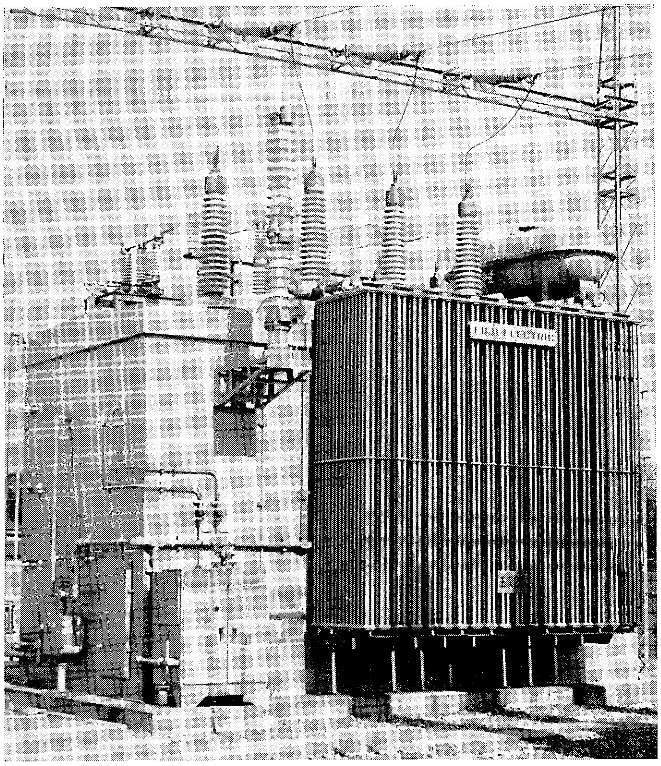


Fig. 8 63 kv 30 Mva oil-immersed natural cooling on-load tap changing transformer with prefabrication-type multi-enclosure

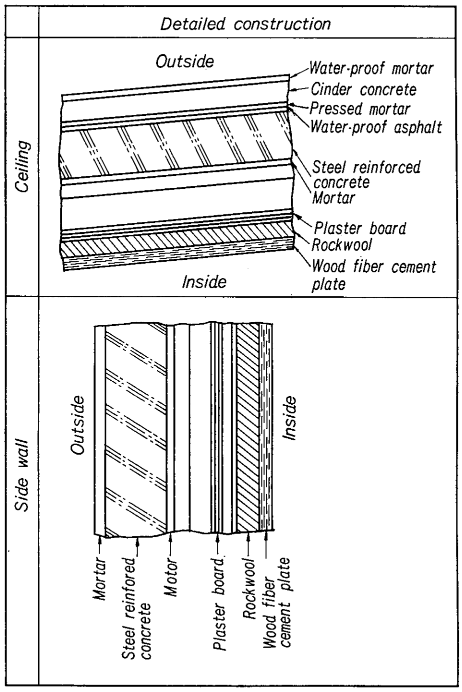


Fig. 9 Wall construction of the concrete enclosure

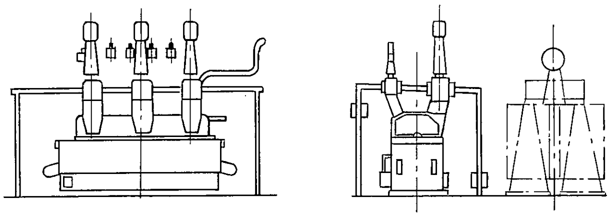


Fig. 10 Concrete enclosure

method also improves the electrical performance of the transformer, it is employed in all models.

2) Improvement of iron core construction (*Fig. 2*)

In comparison with the previous bolt-clamped iron core, a band-clamped iron core employing an FRP resin band, a center-clamped iron core using a cooling duct for tightening, or a center-clamped/band-clamped combination core with FRP resin bands vibrate less and exhibit a noise reduction effect of $2\sim3$ dB_A. Fuji Electric employs the band-clamp iron core in low and medium capacity transformers, the center-clamp core extensively in comparatively high capacity transformers, and the center-clamp/band-clamp combination core in large capacity transformers.

3) Vibration insulation between tank and inner parts (*Fig. 3*)

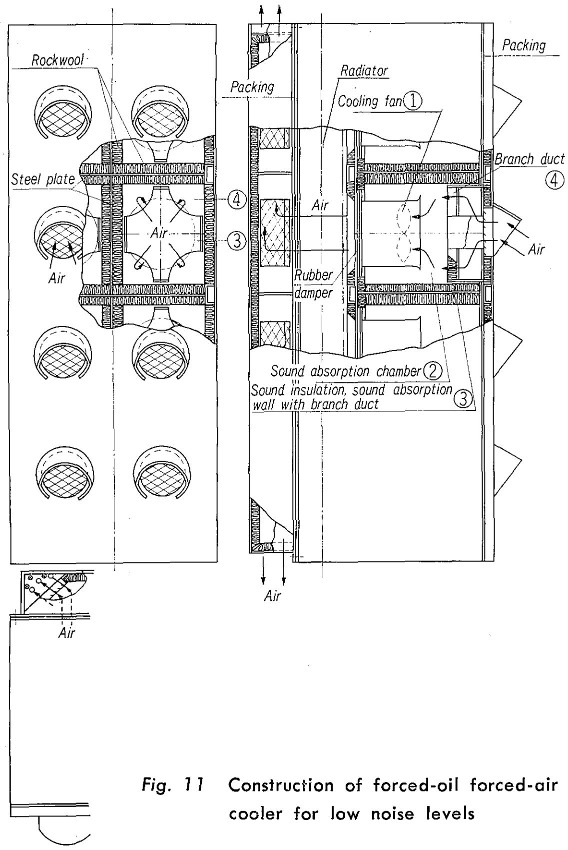


Fig. 11 Construction of forced-oil forced-air cooler for low noise levels

An elastomeric isolator (rubber damper) is inserted between the tank bottom and the lower part of the frame as a means of preventing vibrations from being propagated from the core to the tank. This allows for a noise reduction effect of approximately 3 dB_A. This method is widely used.

4) Prefabricated type single enclosure (*Fig. 4*)

A steel reinforced concrete (plain concrete has a large transmission loss) enclosure to improve the noise insulation factor or an enclosure containing a sound absorption material instead of concrete to improve the noise absorption factor allow for a noise reduction of 10~20 dB_A. These enclosures are used mostly with medium to large 70 dB_A transformers. A typical transformer of this type, the 110 kv 100 Mva forced-oil forced-air cooled transformer, is shown in *Fig. 5.*

5) Prefabricated type multi-enclosure (*Figs. 6~8*)

By providing an air-layer in the above mentioned steel plate and concrete single enclosure and inserting rockwool, glass wool and punched plate, a resonator is provided by the air gap between the concrete and the punched plate. In this way the sound absorption coefficient can be increased over a wide range of frequencies due to the Helmholz resonator effect. With this enclosure, the noise insulation and noise absorption factors are much improved and the noise reduction effect is 20~30 dB_A. This method is used widely in special low-sound-level transformers. Record breaking equipment using this enclosure include the 65 dB_A sound level 147 kv 280 Mva forced-oil forced-air cooling transformer shown in *Fig. 2,* the 60 dB_A noise level 147 kv 100 Mva forced-oil forced-air cooling on-load tap changing transformer shown in *Fig. 9* and the 55 dB_A sound level 63 kv 30 Mva oil-immersed natural cooling on-load tap changing transformer shown in *Fig. 10.*

6) Concrete enclosure (*Figs. 11, 12*).

Since considerable sound absorption material is inserted in the prefabricated type multi-enclosure shown in *Fig. 11,* a noise reduction effect of 30~35 dB_A is achieved. This enclosure is especially effective for large noise reductions in large capacity transformers. Special low-sound-level transformers with this type of enclosure as well as the prefabricated type multi-enclosure are now in use both in Japan and abroad (*Fig. 12*). Record breaking equipment of this type includes the 250 kv 230 Mva forced-oil natural cooling on-load tap-changing transformer with a sound level of 50 dB_A shown in the frontispiece.

7) Lowering the noise level of the cooling system

The transformer cooling system is also an important source of noise. If there is sufficient space in the installation area, the forced-oil natural cooling system solves the problem, but large capacity power stations and substations are now being located near residential areas and there is a strong tendency to place limitations on installation sites. Therefore, it is becoming necessary to provide low-noise-level forced-oil forced-air cooling systems. Because of this, Fuji Electric has developed a 55 and 60 dB_A low-noise-level forced-oil forced-air cooling system.

As shown in *Fig. 11,* the noise-generating cooling

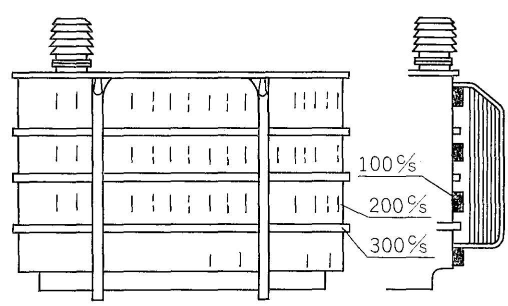


Fig. 12 Example of transformer with rubber dampers

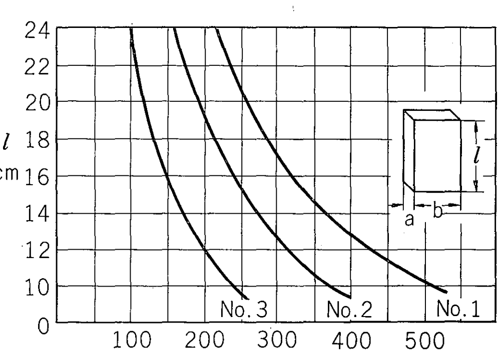


Fig. 13 Resonance frequency of rubber damper

fan ① has a vibration proof support and is placed inside an independent sound absorption chamber. A sound absorption/sound insulation enclosure ③ with branched duct ④ is provided on the air intake side. These measures allow for considerable noise reduction. The air outlet construction is the same as that of the air intake so that the entire cooling system construction insures effective noise reduction.

There are many other methods besides these for reducing noise level.

8) Reduction of flux density

A noise reduction of 2∼3 dB_A can be achieved per 1000 gauss of flux density reduction. This method allows for the reduction of transformer noise at its source but when employed, the transformer becomes very large and the price goes up. For this reason, Fuji Electric uses this method only when small noise reductions are necessary.

9) Cemented iron core

Tension is caused in Si-steel plates by applying a film of special varnish and in this way mangetostriction is reduced. However, the actual extent of this effect is not known and Fuji Electric does not use it as a standard procedure.

10) Placing sound absorption material in the tank interior

Experimentally, it is claimed that a noise reduction of about 15dB_A is possible with this method, but since it has not yet gone beyond the experimental level, Fuji Electric does not use this method.

11) Electro-acoustic noise reduction system

With this method a sound wave with a phase difference of 180° in respect to the transformer noise is radiated, and noise reduction of about 20 dB_A when the object is a single point or 6 dB_A over a range of 35° is claimed on the basis of experiments, but as yet Fuji Electric does not employ this method.

12) Mechanical noise reduction system

With this method, the resonance diaphragm is installed in the upper wall of the tank and it produces a vibration with a phase difference of 180° in respect to the tank vibration and thus eliminates the noise. Experimentally a noise reduction of 10 dB_A is claimed with this method, but it is not employed by Fuji Electric.

13) Rubber damper placed on the outside of the

Table 2 Rubber Damper Characteristics

	a (cm)	b (cm)	Elastic Madulus E (kg/cm²)	Density ρ (kg/cm³)	K
No. 1	2	10	250	1.43	2.5
No. 2	2	10	120	1.31	2.5
No. 3	2	10	55	1.51	2.5

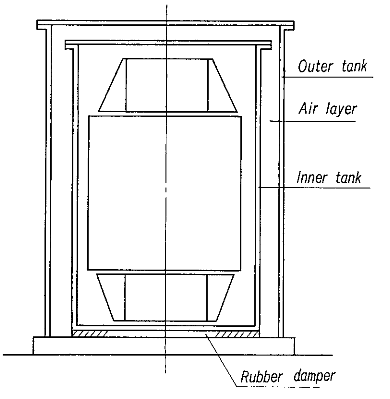


Fig. 14 Double tank wall construction

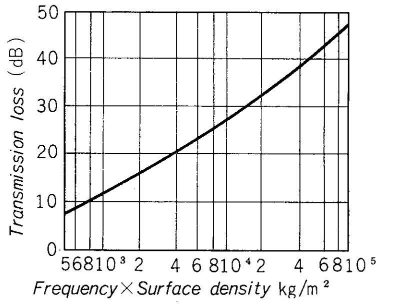


Fig. 15 Mass law of single wall

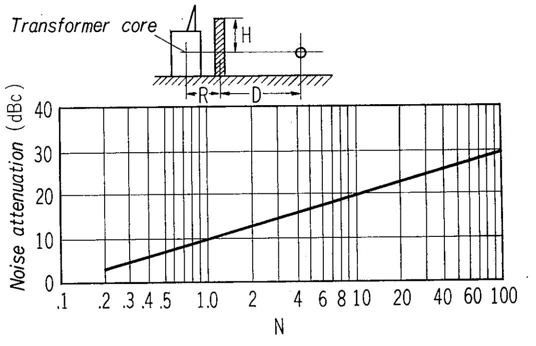


Fig. 16 Noise reduction by the wall

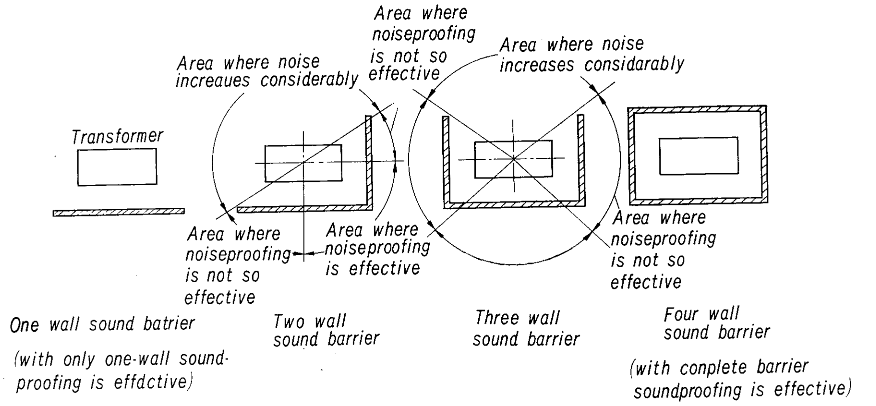


Fig. 17 Noise distribution by the wall

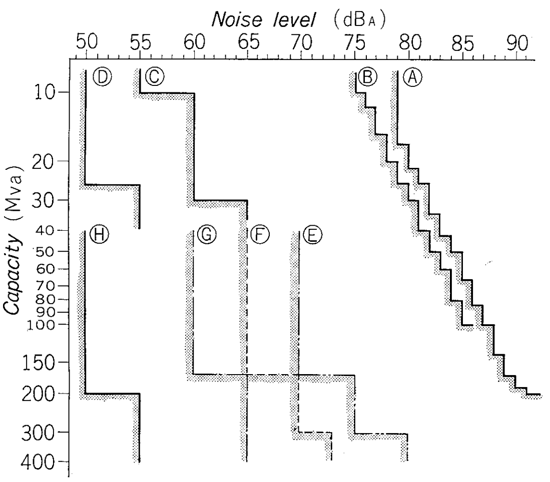
tank wall (*Figs. 12* and *13*, *Table 2*).

With this method, tank wall plate vibration is reduced by means of internal friction loss through a rubber pad which resonates with the tank wall plate. An example of the use of rubber dampers is shown in *Fig. 14*. Tank wall plate vibrations are analysed and, for example, when vibration of 100 Hz predominate, rubber pads which resonate at 100 Hz are inserted. The relation between the length of the rubber pad and the resonance frequency is shown by the following formula:

$$f_0 = \frac{K}{2\pi l}\sqrt{\frac{Eg}{\rho}} \quad \cdots\cdots\cdots\cdots (1)$$

where l: length
E: elastic modulus
p: density
g: acceleration due to gravity
K: constant proportional to the reciprocal of the width b

When the thickness is 2 cm and the width 10 cm the specific resonance frequency of the various materials listed in *Table 2* is shown in *Fig. 15*. The lengthwise end face of the rubber damper is cemented or vulcanized to the tank wall. This method was developed by Siemens Ltd., and in a 30 Mva transformer, for example, 120 pads 100 Hz rubber pads, and 70 pads 200 Hz pads (making a total of 190 pads



Ⓐ Insultion class 140 (BIL 750), JEM standard value for forced-oil forced-air cooled transformer
Ⓑ Insulation class 140 (BIL 750), JEM standard value of oil-immersed natural cooled, forced-oil natural-cooled, forced oil water cooled transformer
Note: If insulation class is 100 (BIL 550), subtract 2dB from Ⓐ and Ⓑ
If insulation class is 70 (BIL 400), subtract 4dB from Ⓐ and Ⓑ
Ⓒ Oil-immersed natural cooled, forced oil natural-cooled, forced-oil water cooled with prefabrication-type single enclosure
Ⓓ Oil immersed natural cooled, forced-oil natural-cooled, forced-oil water-cooled with prefabrication-type multi-enclosure
Ⓔ Standard forced-oil forced air cooled with prefabrication-type single enclosure
Ⓕ Low-sound-level type forced-oil forced-air cooled with prefabrication-type single enclosure
Ⓖ Low-sound-level type forced-oil forced-air cooled with prefabrication type multi-enclosure
Ⓗ Forced-oil natural-cooled with concrete enclosure

Fig. 18 **Principle relations of sound level and noise reduction of the transformer and cooler**

weighing 120 kg) were inserted and at a distance of 150 m, it is reported that a noise level of 63∼65 dB_A can be reduced by about 10 dB_A to 52∼54 dB_A.

14) Double tank construction (*Figs. 14* and *15*).

Since the transmission loss of steel plates only is employed, a 5∼10 dB_A reduction is possible in a 10 Mva transformer. Recently this method has gone out of use.

The greater the area density of the walls, the greater the transmission loss. Since transmission loss obeys so-called mass, law, the following formula holds for single enclosure.

$$L = 18 \log_{10} f \cdot m - 44 \text{ [dB]} \quad \cdots\cdots\cdots\cdots (2)$$

where L: transmission loss
f: frequency
m: area density

From formula (2), it is evident that with a single wall the reduction effect will increase by only 5 dB_C if m is multiplied by 2. However, if a multi-wall is used and sufficient space is allowed between the walls or suitable sound absorption material is inserted, a multiplication of the single wall effect can be obtained. In practice, when thinking only of independent spaces, it is impossible to obtain a sufficiently large gap and, during construction, problems also arise concerning complete insulation against vibrations mutually in the multi-wall. Therefore, magnification of the reduction by the number of walls is not actually possible, but this system is still more effective than the single wall system.

15) Sound barrier walls for transformers (*Figs. 16* and *17*)

By placing sound barrier walls around the transformer, sound-proofing is achieved because of reductions when sound waves are diffracted at the end surface parts or the top of the barrier, or because of transmission loss when sound waves are transmitted through the barrier. The actural reduction is about 15 dB_A. Bricks or concrete can be used as the barrier material.

With this method, care must be taken since, even if the effect is very high in the vicinity of the barrier because of sound wave diffraction, the effect can not be as expected to continue uneffected at distances further from the transformer and in some cases, a concentration of noise will occur in a specified direction.

The noise attenuation is shown by formula (3). By calculating N, the relation shown in *Fig. 16* is obtained.

$$N = \frac{2}{\lambda}\left[\sqrt{R^2+H^2} - R + \sqrt{D^2+H^2} - D\right] \cdots\cdots (3)$$

The higher the barrier wall height H or the shorter the distance R from the sound source, the shorter will be the sound source wave length and the more effective the noise reduction.

The effectiveness of the single-wall, two-wall, three-wall and four-wall sound barriers is considered in *Fig. 17*.

2. Application of the Sound Reduction Methods

When appraising each of the above-mentioned noise reduction methods, it is essential to base judgements on an equal consideration of effectiveness and economy.

From the results of an exhaustive study of the relation between effectiveness and economy, Fuji Electric has found that the prefabricated type multi-enclosure and the concrete enclosure are the best methods at present for use with special low-sound-level transformers. The additional use of Si-steel plates with low magnetostriction; band-clamp / center-clamp or center-clamp/band-clamp combination cores; and vibration insulation between the internal parts and the tank need not be mentioned here. At present Fuji Electric employs as standard the general main unit noise reduction and cooling system combinations shown in *Fig. 18*.

IV. DESIGN OF NOISE LIMITING ENCLOSURES

1. Computation of the Acoustic Power of P Source

It is first necessary to calculate the acoustic power of the sound source of the transformer from the iron core and other specifications. For this calculation, it is necessary to measure the sound level L_0 (dB_A) at a distance d(m) from the transformer placed in the open, using a sound level meter as specified in JIS C 1502. Since L_0 is measured as per JEM 1117, compensation is made by means of the sound level meter frequency response characteristic A; A frequency analysis of the sound is first carried out and this is converted into the intensity level (dB_C) for each frequency (f_i). For example, generally if the transformer is of the 60 Hz class, it is necessary to calculate the intensity levels $L_1(f_1)$, $L_2(f_2)$ and $L_3(f_3)$ for each of the frequency components $f_1=120$ c/s, $f_2=240$ c/s, and $f_3=360$ c/s. Components 2×, 3×, and 4× the power source frequency are especially predominant in the spectrum of sound which developes in ordinary transformers. Therefore, the calculation must be made for these values at least. Since the sound intensity levels are indicated by these $L_1(f_1)$, $L_2(f_2)$ and $L_3(f_3)$ values, they are so-called pure physical quantities and can be converted into sound intensity (watt/m^2) by a simple calculation. Therefore, the acoustic power of the sound source in respect to each frequency f_1 is as follows:

$$P(f_i) = S_t \times I_0 \times 10^{\left(\frac{L(f_i)}{10}\right)} [\text{watt}],\ i=1, 2, 3 \cdots \quad (4)$$

where S_t: the surface area covered at a distance d(m) from the transformer

L_0: intensity of sound at 0 $dB_C = 10^{-12}$

2. Average Sound Intensity Level Inside the Enclosure $\overline{L_r}$

In general, when a sound source with an acoustic power of P (watt) is present in an enclosure with an enclosed inner surface area of S_r the average sound intensity $\bar{I}_r(f_i)$ inside the enclosure can be determined from the following formula.

$$\bar{I}_r(f_i) = \frac{4P(f_i)}{\alpha(f_i)\, S_r} \ [\text{watt/m}^2] \quad \cdots\cdots\cdots\cdots\cdots (5)$$

where $\alpha(f_i)$: sound absorption factor of the wall surface at frequency f_i

$P(f_i)$: acoustic power P (watt) at frequency component f_i

Since $\alpha(f_1)$ is a constant depending on the material, it can be determined experimentally in advance. In this way, the average sound intensity level L_r in the enclosure for each frequency becomes:

$$\overline{L}_r(f_i) = 10 \log_{10} \frac{\bar{I}_r(f_i)}{I_0} = 10 \log_{10} \frac{\frac{4P(f_i)}{\alpha(f_i)\cdot S_r}}{10^{-12}}$$

$$= 10 \log_{10} \frac{P(f_i)}{\alpha(f_i)\cdot S_r} + 126 [dB_C] \quad \cdots\cdots\cdots\cdots (6)$$

Generally, the build-up value in respect to sound in an enclosed space is defined as:

$$\Delta L(f_i) = \overline{L}_r(f_i) - L_i(f_i) \quad [dB_C] \quad \cdots\cdots\cdots\cdots (7)$$

As can be seen from the above formula, the frequency of sound, inner surface area of the enclosed space S_r and the enclosure surface sound absorption factor are bilateral concepts, and therefore the magnitude of dB_C can not be decided unconditionally. Care should be taken since the build-up values obtained by simple calculation without frequency analysis, could be far from the actual values.

3. Required Sound Insulation Value of the Enclosure $L'(f_i)$

When the sound intensity levels/inside the enclosure calculated from formula (6) are plotted against, the frequency characteristics, a curve like Ⓐ in *Fig. 19* is obtained. For the sound intensity level outside the enclosure, L_a (dB_A), it is necessary to trace each point from the Ⓐ curve down to the Fletcher Munson

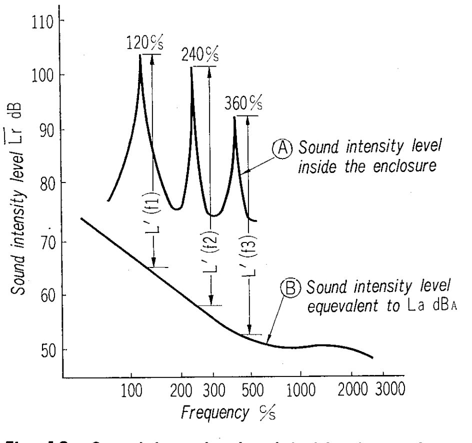


Fig. 19 Sound intensity level inside the enclosure

equal loudness curve corresponding to L_a (dB_A). As was mentioned in Section 1., the most predominant frequency components in the transformer noise spectrum are the f_1 f_2 and f_3 components. Therefore, if the above-mentioned components are sufficient, generally, other frequency components can be disregarded.

From *Fig. 21*, the required sound insulation value $L'(f_i)$ is

$$L'(f_i) = \overline{L}_r(f_i) - L_a(f_i) \quad [\text{dB}] \cdots\cdots\cdots\cdots\cdots (8)$$

where $L_a(f_i)$: the sound level in respect to the frequency f_i from the equal loudness curve of L_a (dB_A)

4. Sound Insulation Value of the Enclorure $\lambda(f_i)$

The sound insulation value of the enclosure can generally be calculated from the following formula.

$$\Lambda(f_i) = 20 \log_{10}(f_i \sum_j M_j) - 42.5\, k \cdot n \quad [\text{dB}] \cdots (9)$$

where M_j: surface density of each layer of the enclosure

f_i: frequency (Hz) $i = 1, 2, 3, \ldots$

n: number of layers mutually insulated against vibrations

K: coefficient

Therefore, substituting $L'(f_i)$ of formula (8),

$$\Lambda(f_i) = L'(f_i) + \alpha \quad [\text{dB}_C] \cdots\cdots\cdots\cdots\cdots\cdots (10)$$

the desired value is abtained. 'α' is the tolerance during manufacturing.

When the construction of the ceiling and side walls of the enclosure differs from that of other parts $\lambda(f_i)$ must be calculated separately for each part, and it is necessary to check whether the required noise insulation value is achieved or not.

It can be easily seen from formula (9) that to make the noise insulation value large, the surface density M_j of the enclosure must be very large, and therefore, the enclosure becomes multiplex and the $k \cdot n$ value increases.

5. Ventilation of the Enclosure Interior

With large capacity transformers, the temperature of the air inside the enclosure rises because of the radiation of heat from the transformer tank walls. Therefore, ventilation of the enclosure is carried out in order to remove any unpleasantness when the room is entered for maintenance checks. In this case, it is better to keep the temperature difference between the ventilation inlet and outlet as large as possible. The provision of a sound proof duct facilitates saving in the amount of ventilation necessary. In general, the temperature difference is maintained at a maximum of 30 deg. As shown in *Fig. 23*, the construction of the ventilation apertures consist of two units connected by a sound-proof ventilation duct in the form of an expansion chamber. It must be considered that by inserting sound absorption material, transmission loss becomes zero and frequency becomes non-existent. It is also necessary to consider the effective operation of the two expansion chambers. Ventilating fans are arranged in the ventilation apertures, but generally, except for high summer temperatures over 30°C, it is not necessary to operate them since natural ventilation is sufficient.

The temperature difference of the ventilation inlet and outlet is given by the following formula.

$$\theta = \frac{Q}{C \cdot \gamma \cdot V} = \frac{Q}{0.275\, V} \quad [\text{deg}] \cdots\cdots\cdots (11)$$

where Q: Amount of heat radiated from the transformer tank wall

C: Specific heat of air

γ: Density of air

V: Amount of ventilation

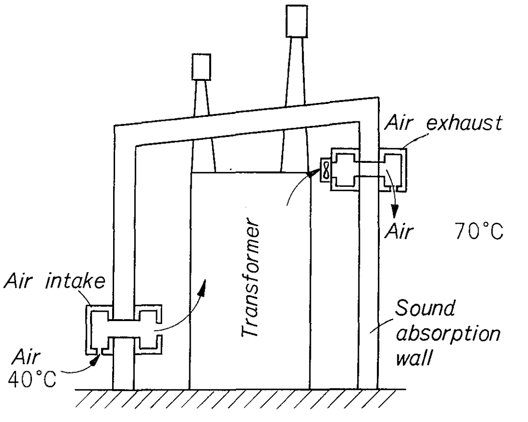


Fig. 20 Section of the enclosure

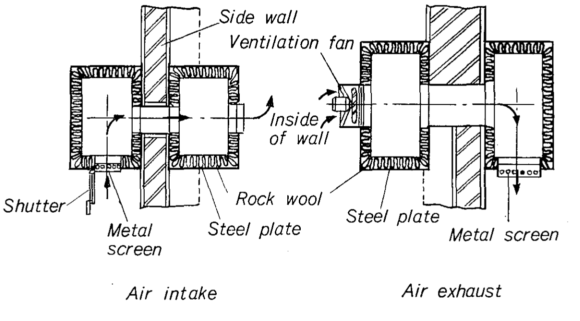


Fig. 21 Section of the noise-proof ventilating duct

(To be continued)