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RECENT FEATURES OF LOW-NOISE TRANSFORMERS

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I. INTRODUCTION

Recently, large capacity transformer substations have often been located close to residential areas in keeping with increased power demand in urban areas and as one aspect of the environmental problem, there have been increasing demands for greater sound-proofing in transformers.

To meet these demands for noise-proofing in a wide range of transformers, Fuji Electric recently conducted detailed research on all aspects of the transformer noise problem and established a series of techniques for the reduction of noise.

The products now produced on the basis of these techniques include the following:

1) 5MVA oil-filled, self-cooled transformer
(Assembly-type concrete panel sound-proof wall) Noise: 42 phons

2) 37.5MVA forced-oil, self-cooled transformer
(Concrete sound-proof wall) Noise: 43 phons

3) 250MVA forced-oil, forced-cooling transformer
(Assembly type concrete panel sound-froof wall) Noise:53 phons

Fig. 1 shows the outer view of a 250MVA transformer with enclosure.

This article introduces Fuji Electric's most recent sound-proofing techniques.

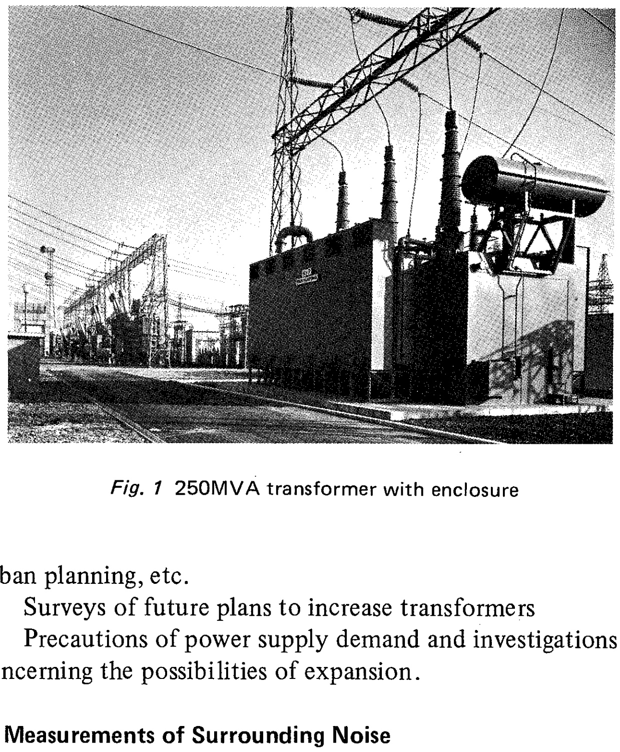


Fig. 1 250MVA transformer with enclosure

II. NOISE REDUCTION PLANNING

Generally, noise reduction plans are investigated by transformer users but planning methods up to the level of deciding the noise levels required of the transformers are given here for reference.

1. Investigations of Site Environment

1) Investigations of standard values and future trends concerning transformer noise

Investigations and surveys concerning noise regulation laws and regulations related to noise prevention in cities, etc.

2) Estimation of changes in conditions in the vicinity of transformers

Surveys of plans concerning proximate environments in urban planning, etc.

3) Surveys of future plans to increase transformers

Precautions of power supply demand and investigations concerning the possibilities of expansion.

2. Measurements of Surrounding Noise

1) Measurement of the noise levels of existing transformers (at the time of expansions)

Measurements in accordance with JEM 1117 (Methods of measuring transformer noise levels).

2) Noise measurements at substation boundary line locations

Measurements and surveys concerning the effects of external sound from nearby factories, etc. Also measurements of background noise at night.

3. Deciding Transformer Noise Level Specifications

1) The damping results of separation from the transformer sound are calculated from the following formula:

$$dB_d = dB_s - 4.4 - 20 \log \frac{d}{\sqrt{A \cdot H}} \quad \ldots\ldots (1)$$

where dB_d : sound at distance d from measuring surface of JEM standard (phons)

dB_s : sound measured according to JEM standard (phons)

d : distance from the JEM standard measuring surface to the problem point (m)
A : width of transformer as seen from the problem point (m)
H : height of transformer (m)

2) Determination of nearby noise sources at the boundary line

The total noise values of the noise (dB_0) from nearby noise sources at the boundary line position and the noise (dB_d) from the transformer is determined as follows:

For example, when dB_d is 43 phons and dB_0 is 40 phons, the difference between the two from *Table 1* is 3 phons and the total sound is as follows:

$$dB_P = 43 + 1.8$$
$$= 44.8 \text{ (phons)}$$

Therefore, the effects of the noise values from nearby noise sources must be taken into consideration.

Table 1 Summation of sound level

dB_0 and dB_d level difference (phons)	Values added to dB_0 or dB_d, whichever is the largest (phons)
0	3.0
1	2.5
2	2.1
3	1.8
4	1.5
5	1.2
6	1.0
7	0.8
8	0.6
9	0.5
10	0.4

3) Deciding the transformer noisle level specifications

The transformer noise levels are decided in consideration of the above conditions.

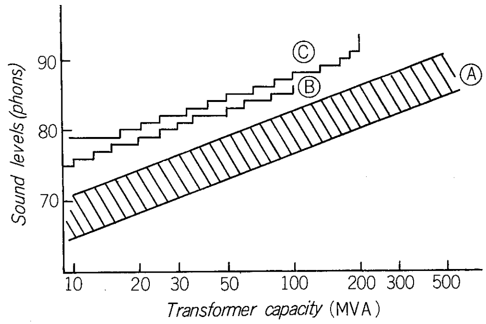
Next, the transformer noise-proofing measures are carried out by the transformer manufactures to meet the noise levels specified by the users. In Fuji Electric, these measures are roughlly as follows:

1) Confirmation of guaranteed noise levels

Investigations are performed to determine if the noise levels specified by the users are can fulfil the various specified values at the substation boundaries after the transformer is installed.

2) Setting of noise dampening amounts

By estimating the noise generated by the transformer, the required amount of noise dampening is determined from the difference between this estimated value and the guarantee value. At this time, a highly accurate estimation of the unit noise value for the transformer concerned requires above all the execution of rational noise reduction measures. *Fig. 2* shows examples of the relation between transformer outputs and sound levels.



A: Fuji transformer noise level standard
B: JEM standard value (No. 140, oil-filled self-cooled, forced-oil self-cooled and forced oil water cooled transformers)
C: JEM standard value (No. 140, forced oil air oil air cooled transformers.

Fig. 2 Transformer output and sound levels

3) Deciding on noise reduction measures

The unit related noise reduction measures, cooling unit related noise reduction measures and the transport conditions and construction techniques of the acoustic enclosure are decided on the basis of the required amount of noise dampening.

The characteristics of Fuji Electric noise reduction measures are as follows:

(1) Standard series of acoustic enclosures have been developed for each noise level.
(2) Concrete is used in addition to steel plates as noise-proofing material.
The specific gravity of concrete is only about 2.3 and does not exceed 30% of that of steel plates but in the case of the sound-proofing capacity of a wall with a high surface density, it is neast to manufacture concrete of 100~200mm thick even in cases where the steel plates must be 30~60mm thick.
(3) Assembly-type acoustic enclosures are widely used for large scale transformers for easy site assembly. For medium and small capacity transformers, the trans-

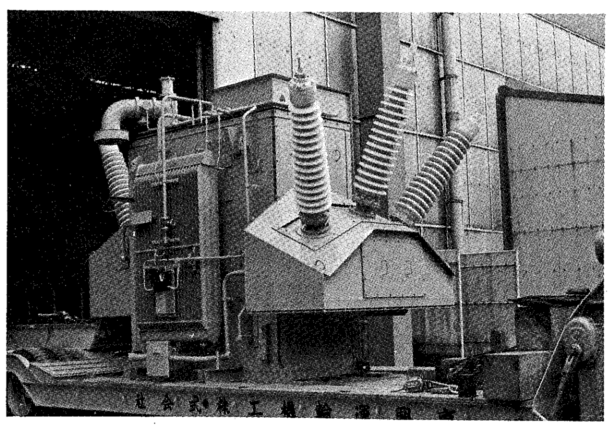


Fig. 3 Small transformer with enclosure

formers are mounted in acoustic enclosures and transported as complete types.

(4) A large installation area was required because of the self-cooling type coolers which have been used conventionally at noise levels of 60 phons or less but this installation area can be minimized by the use of the low-noise type forced cooled coolers up to the minimum noise levels.

(5) Iron core measures such as the use of Hi-B silicon steel plates and a decrease in the flux density have been undertaken and there have been many cases where these methods have been used in conjunction external noise reduction measures such as acoustic enclosures to reduce noise to some extent.

III. NOISE REDUCTION MEASURES

Transformer noise is mainly caused by iron core magnetic distortion vibrations transferred to the tank via the oil. These vibrations cause the tank walls to vibrate and the noise is released to the exterior.

The main anti-noise measures include first with respect to the transformer unit, measures to minimize the core magnetic distortions, the source of the sound, and the use of shields to prevent release of the noise. Various anti-vibration measures are also used to prevent secondary noise from arising in surrounding structural components via the foundation and piping, etc.

Noise also arises from such accessories as cooler fans and forced oil pumps. Some of this noise is released directly to the exterior and some is in the form of vibrations due to fans and pumps which is transferred to solid bodies such as the fan cabinet and radiator and released.

Measures against accessory noise involve mainly the use of low-noise pumps and fans and the employement of appropriate vibration-proof construction.

Economic transformer noise reduction can be achieved by an appropriate combination and application of these measures.

1) Measures related to the main transformer unit
(1) Measures to prevent tank vibrations
(2) Measures to prevent tank vibrations
(3) Schielding by sound-proof walls
(4) Various types of anti-vibration measures
(5) Ventilation port measures
(6) Noise leak prevention measures
2) Measures related to the cooler
(1) Low-noise type forced-oil, forced-air cooled coolers
(2) Self-cooled radiators
(3) Vibration-proof joints

Fig. 4 shows an example of noise-prevention measures applied to a large scale transformer and *Fig. 5* shows the case of a small transformer.

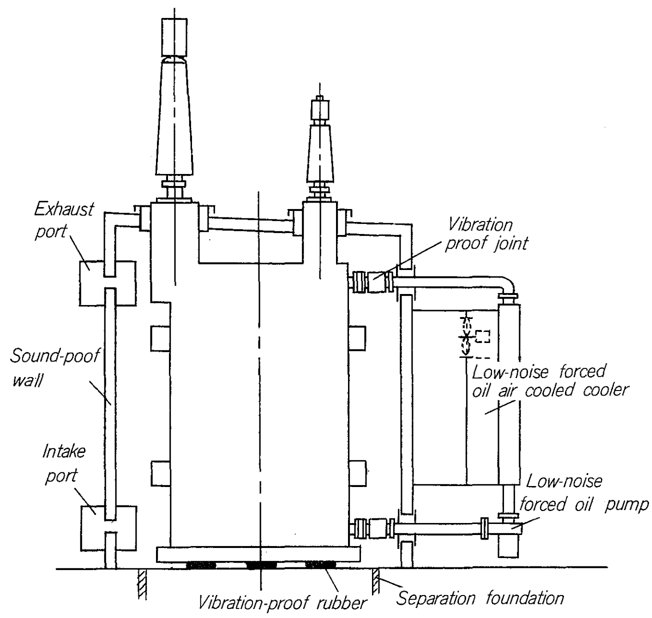


Fig. 4 Consformer capacity (MVA)

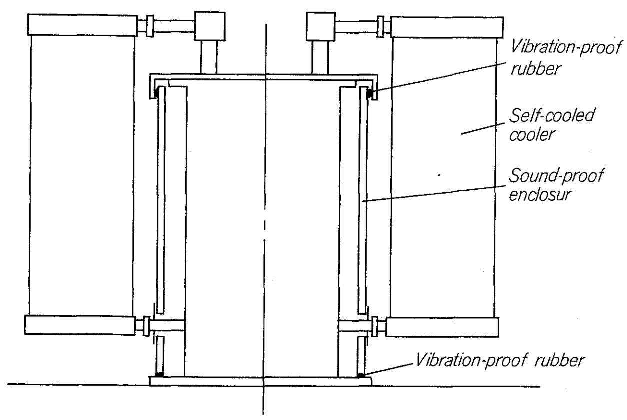


Fig. 5 Construction of a coustic enclosures for small transformer

1. Measures Related to The Main Unit

1) Iron core measures

These measures are aimed at lowering the magnetic distortion vibrations in the iron core which are the main source of noise.

(1) Use of silicon steel plates with low magnetic distortion

Silicon steel plates (Hi-B steel plates, etc.) with low magnetic distortion reduce the magnetic distortion because they are covered with an insulating film which gives tensile force to the steel plates. Compared with normal silicon steel plates, the noise is reduced by 2~4 phons. An example is low noise of 7 phons in a 150 MVA transformer.

(2) Decreased core flux density

By reducing the core flux density, the noise can be decreased by 2~3 phons per 0.1 Tesla. However, there are many cases where the use of such measures makes the transformers large and uneconomical and it is effective only when slight noise reductions are required.

(3) Others

The cores also have a structure and tightening pressure

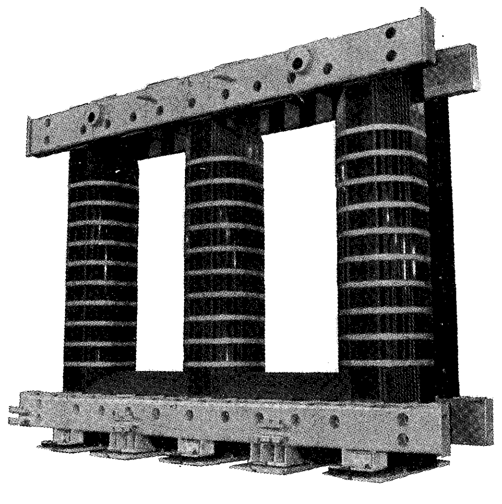
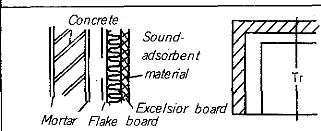
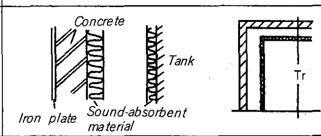
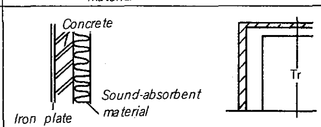
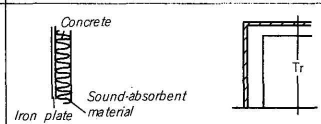
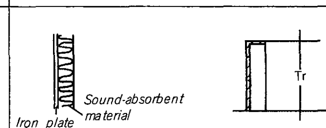
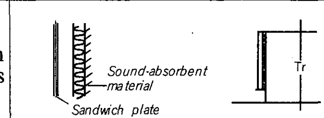
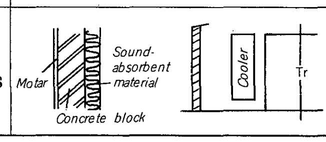


Fig. 6 Construction of core cramp for large transformer

Table 2 Construction of the enclosures

Type	Amount of noise reduction	Construction
Concrete sound-proof enclosure	30 phons or more	
Prefabricated-type concrete panel sound-proof enclosure	30~25 phons	
	25~20 phons	
Prefabricated-type iron panel sound-proof enclosure	20~15 phons	
	15~10 phons	
Sandwich plate sound-proof enclos	Less than 10 phons	
Impact enclosure	About 10 phons	

so that there are no undulating bends in the steel plates due to tightening. This is an important measure in reducing magnetic distortions. The iron core is also dimensionsed to avoid resornance by calculating the natural frequency of the core. These measures are generally applied in all transformers. *Fig. 6* shows the core cramp construction for a large transformer.

2) Measures to prevent tank vibrations

Since transformer tank directly releases sound to the exterior because of vibrations casued by the core, reinforced structures, layout, etc. are decided to avoid resonance. The soild transfer of vibrations from the core to the tank is prevented by the insertion of oil-resistant vibration-proof rubber between the core and the tank.

3) Shielding by acoustic enclosures

Acoustic enclosures shield against the sound released from the tank surface and they are the most simple noise prevention method.

The amount of noise stopped by the enclosures can be calculated by equation (2) according to the law of mass action:

$$TL = \eta \{ 18 \log (f \cdot m) - 44 \} \quad \ldots\ldots (2)$$

where TL : amount of noise stopped by the enclosure (dB)
f : frequency (Hz)
m : area density of the enclosure (kg/m^2)
η : correction coefficient

In the case of transformers the main components of the noise frequency spectra are up to the third harmonic with a fundamental frequency double the power source frequency. Therefore, in noise blocking calculations, noise frequencies of 100, 200 and 300Hz should be considered when the power source frequency is 50Hz. The correction coefficient η is determined on the basis of the enclosure support structure and the effects of the construction for passing through holes and normally a value of about 0.6 is used. However, the prevention of the transfer of vibrations from the transformer to the enclosure as much as possible is particularly important in improving the noise shielding effects of the enclosure.

At present, Fuji Electric uses the standard acoustic enclosures shown in *Table 2* on the basis of long years of experience. The attaching of noise absorbent materials inside the enclosure reduced the interior build-up to less than 3 phons. The build-up is calculated by equation (3)

$$BUL = 10 \log \left\{ 1 - \frac{16\pi}{2.3S \log(1-\alpha)} \right\} \quad \ldots\ldots (3)$$

where BUL : build-up (dB)
S : sound reflection area $S = \Sigma\, Si(\mathrm{m}^2)$
α : average sound absorption rate $\alpha = \frac{\Sigma \alpha Si}{S}$

(1) Concrete enclosure

Concrete enclosures are used for transformers where the noise is to be reduced by more than 30 phons and the sound-proofing effects are excellent. However, they are often impractical in low noise remodeling of existing transformers since there are many parts requring site work and the construction period is long.

(2) Prefabricated type concrete panel enclosure

The prefabricated type concrete panel enclosure is used in transformers where the noise is to be decreased by 20~30 phons. Concrete is poured in steel frames in the factory to make the panels which are assembled at the site. Unlike the concrete enclosures, only simple panel assembly is required at the site and only a short period is needed.

The sound-proofing dffects are improved by preventing the transmission of vibrations to the enclosure walls and improving various types of wall hole constructions and such enclosures are replacing the concrete enclosures used formerly for ultra-low noise transformers.

(3) Prefabricated iron panel enclosures

Prefabricated iron panel enclosures are best used when the noise level is to be reduced by 10 to 20 phons. As in the case of the prefabricated concrete panel enclosures, the panels are made in the factory and assembled at the site.

(4) Sandwich plate enclosures

Sandwich plate enclosures are used for noise reductions of less than 10 phons. The sandwich plates consist of two thin steel plates attached together by an adhesive and since the steel plates are special plates with a high level of self-damping characteristics against vibrations, the reduction in the noise blocking effect is very small even when the plates are attached directly to vibrating parts such as the tank walls. Because of the direct attachment for tank wall reinforment, there is almost no increase in external dimensions and they transformers can be transported directly with the enclosures attached, which are important advantages. In addition, they are also east to use for site low noise remodeling.

(5) Impact enclosures

The impact enclosures are used in transformers where the noise is to be reduced by about 10 phons. The main advantage is the extremely easy construction work involved since direct remodeling of the transformer is not required in noise reduction construction, the power need not be interrupted, etc. However, sufficient ventilation measures are required since the cooler surface is completely surrounded.

4) Various types of anti-vibration measures

To increase the noise blocking effects of enclosures, it is important that the enclosure does not vibrate and the following anti-vibration measures are taken.

(1) Vibration-proof rubber

Vibration-proof rubber is arranged between the unit and the foundation to prevent the transfer of vibrations from the transformer unit to the foundation. In addition to vibration-proof rubber, anti-vibration materials include air and coil springs. In the case of air springs, the natural frequency can be made sufficiently small but equipment costs are high and maintenance and inspections are required. With coil springs, the natural frequency can also be small but there are cases where the surging phenomenon occurs. Therefore, such springs are used only in special cases and vibration-proof rubber is the most common material. The vibration-proof rubber can be any shape, and a suitable vibration transmission rate can be selected at about 0.1 to 0.01. Vibration-proof rubber is weather resistant chloroprene rubber.

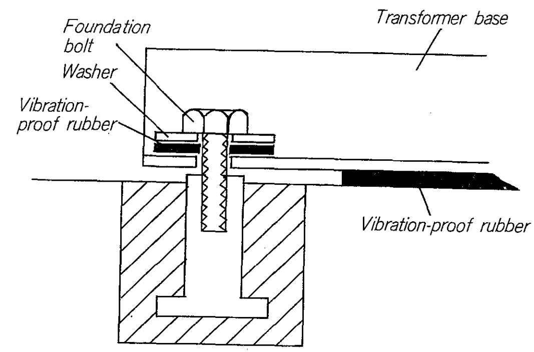
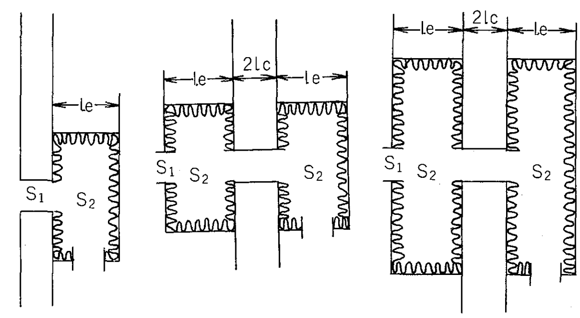


Fig. 7 Section of foundation bolt



(a) 15 phon dampening (b) 20 phon dampening (c) 30 phon dampening

Fig. 8 Noise-proof ventilating duct

(2) Vibration-proof foundation bolts

These bolts are used to prevent the transfer of vibrations from the foundations bolts attached to the transformer unit to the foundation. The structure is as shown in *Fig. 7*. The rubber used is weather resistant chloroprene rubber.

(3) Separate foundations

Vibration insulation from the transformer unit is provided by means of vibration-proof rubber and foundation bolts but separate foundations are often also used to enhance the effects (refer to *Fig. 4*). Asphalt, etc. is used as the vibration-proof material.

5) Ventilation duct measures

Ventilation ducts are provided since men must enter the enclosures of large transformers for inspections. These ducts are used for both air intake and exhaust and an expansion type sound-absorbing construction is used to prevent noise leaks. They are designed in keeping with the noise blocking amount of the enclosure. *Fig. 8* shows the amount of damping and the construction of ventilation ducts. The amounts of damping are determined by the following equations:

Single stage expansion

Amount of damping due to expansion

$$TL_1 = 10\log\left[1+\frac{1}{4}\left(m-\frac{1}{m}\right)^2\sin^2 kle\right] \text{ (dB)} \quad \ldots\ldots(4)$$

Amount of damping due to opening

$$TL_2 = 10 \log \frac{\alpha S_0}{S_1} \text{ (dB)} \qquad \ldots\ldots(5)$$

Total amount of damping

$$TL = TL_1 + TL_2 \text{(dB)} \qquad \ldots\ldots(6)$$

Double stage expansion

Amount of damping due to expansion

$$TL_1 = 10 \log (a^2 + b^2) \text{ (dB)} \qquad \ldots\ldots(7)$$

$$a = \frac{1}{16m^2} \; 4m(m+1)^2 \cos 2k(le+lc) - 4m(m-1)^2 \cos 2k(le-lc) \qquad \ldots\ldots(8)$$

$$b = 2(m^2+1)(m+1)^2 \sin 2k(le+lc) - 2(m^2+1)(m-1)^2 \sin 2k(le-lc) - 4(m^2-1)^2 \sin 2k\,lc \qquad \ldots(9)$$

Amount of damping due to opening

$$TL_2 = 10 \log \frac{\alpha S_0}{S_1} \text{ (dB)} \qquad \ldots\ldots(10)$$

Total amount of opening

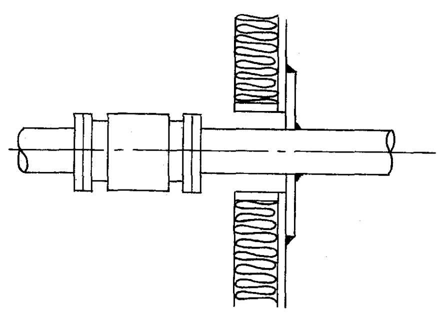
$$TL = TL_1 + TL_2 \text{ (dB)} \qquad \ldots\ldots(11)$$

where $m = S_2/S_1$
$k = 2\pi f/c$
f : frequency (Hz)
c : sound speed (m/s)
α : average sound absorption rate inside ventilator duct
S_0: sound absorption area inside ventilator duct (m^2)
Refer to *Fig. 8* for S_1, S_2, lc and le

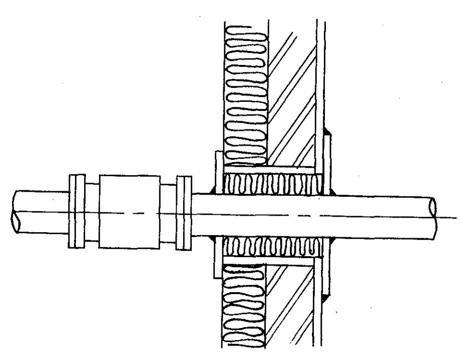
The inside of the enclosures are normally ventilated naturally but there are cases of forced ventilation using fans. In this case, fans with lower noise than the transformer noise are selected and attached to the exhaust side but the decision concerning fan capacity and numbers must also be based on consideration of the loss resistance of the expansion chamber, the amount of heat generated in the enclosure and the temperature rise inside the enclosure.

6) Noise leak prevention measures

Oil pipes, bushing pockets, through-holes and doors are provided in the enclosures and consideration must be given to noise leaks through these openings when considering noise-proofing measures. *Fig. 9* shows an example of the construction for a cooling pipe passing through the enclosure. In the case of enclosures with large noise dampening effects, measures such as double-door construction must be used.



(a) Prefabricated type iron panel sound-proof enclosure



(b) Prefabricated type concrete panel sound-proof enclosure

Fig. 9 Section for the cooling pipe through the enclosure

2. Measures Concerning Coolers

In the construction of low noise transformers, measures against cooler noise are extremely important. In low noise cases, self-cooling radiators are better than forced-cooling type with respect to price but they require a large installation area.

Fig. 10 shows a comparison of self-cooling and forced-cooling systems for a 100MVA, 60 phon power transformer. It is evident that low noise type forced-oil, forced-cooling cooler, which is compact and has a noise level comparable to that of self-cooled radiators, is desirable.

1) Low noise-type forced-oil, forced-cooling coolers

Fuji Electric has completed a series of high efficiency forced-cooling type coolers. Low noise fans have been perfected by the development of blades which sufficiently reduce air noise and a multi-pole motor series with low mangetic noise. Development of low noise pumps, improved radiator piping, etc. have also been completed.

As a result, extremely low noise forced-cooling coolers which conventionally have noise levels exceeding 45 phons

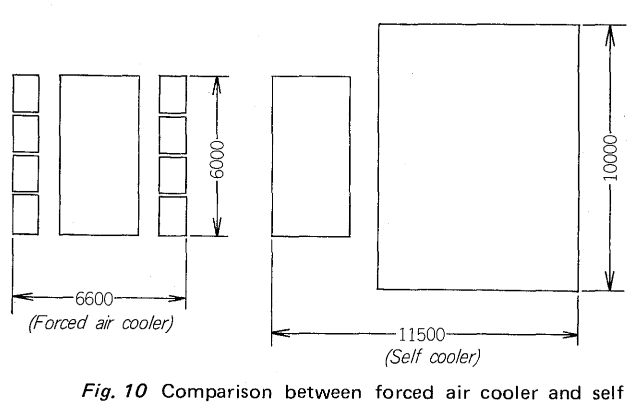
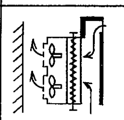
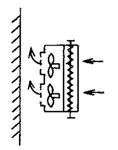
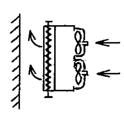


Fig. 10 Comparison between forced air cooler and self cooler [100MVA, 60dB(A)]

Table 3 Series of forced-oil forced-air cooler (60Hz)

Transformer noise (phons)	Cooler noise (phons)	No. of fan motor poles	Cooler construction
50	45	20	
55	50	16	
60	55	20	
65	60	16	
70	65	12	
75	70	10	
80	75	8	
85	80	6	

have been completed and the manufacture of 50 phon forced-oil, forced-cooling transformers is now possible.

Table 3 shows an example of the low noise cooler series. *Fig. 11* shows a section of an ultra-low noise cooler of less than 50 phons. In such cases, measures to insulate against vibrations from the transformer unit are also taken.

Fig. 12 is a photograph of a low noise fan used in this series. *Table 4* shows an example of such fan ratings.

2) Self-cooling radiators

The great majority of the noise of self-cooled radiators occurs because of vibrations transferred to fixed objects

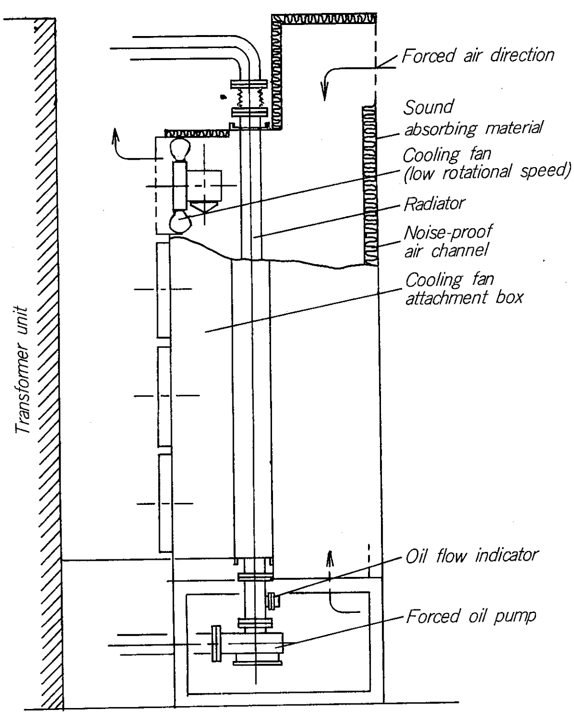


Fig. 11 Construction of farced-oil, forced-air coolers for low noise levels

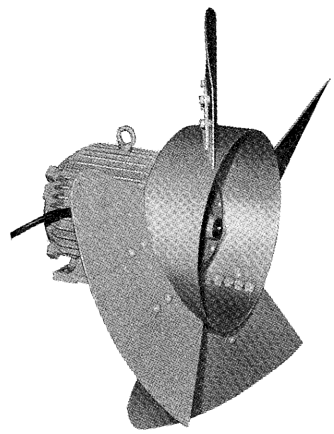


Fig. 12 Low noise fan

Table 4 Specifications of low noise fan

Type	Fre-quency	No. of motor poles	Motor rate output	Forced air flow	Static pressure	Noise (phons)
aBLA 75	50	20	0.15	50	1.5	49
	60	20	0.15	60	2.0	53

via oil pipes from the transfomer unit. Therefore, self-cooling radiators without vibration-proof joints only decreases this noise by 10 to 15 phons but when vibration-proof joints are used, the noise drops by 20~35 phons.

In addition, in forced oil systems, it is necessary to take measures against sound generated from the forced oil pump and to give careful consideration at the prevention of bivration transmission.

3) Vibration-proof joints (flexible couplings)

Vibration proof joints are used to prevent the transmission of vibrations to the cooler via cooler oil pipes. These joints can reduce noise by 10 to 20 phons. Standard vibration-proof joints are made of stainless steel with good corrosion resistance.

Fig. 13 shows the construction of a vibration-proof joint.

IV. EXAMPLE OF NOISE REDUCTION REMODELING

1. Transformer Specifications

3-phase 60Hz, 275/77kV, 150MVA, forced-oil,

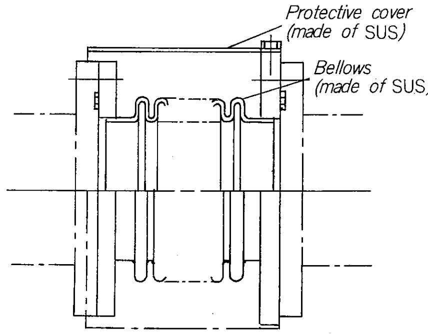


Fig. 13 Flexible coupling

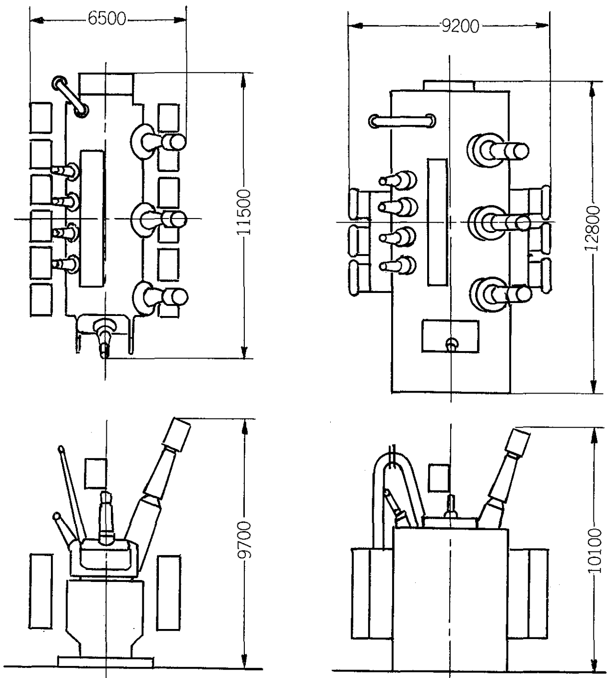


Fig. 14 Comparison of outlines in cases of remodeling at site

forced-cooling transformer.

2. Noise

before remodeling (measured value)	84.1 phons
after remodeling (guaranteed value)	60.0 phons

3. External Dimensions

The dimensions are shown in *Fig. 14.*

4. Soundproof Construction Plan

1) Transformer noise before remodeling

The total noise including that of the cooler is to be 84.1 phons and the value for the cooler only 72 phons. The difference is 84.1~72.0 = 12.1 phons. Threfore the cooler noise can not be disregarded with respect to the total noise and therefore, the total transformer noise is given as 84.1 phons.

2) Planning policies

Since the noise is to be 60 phons after remodeling, the plan involves a combination of a total noise of 60 phons and a cooler noise of 55 phons. Therefore, an acoustic enclosure is to be provided for the main unit and the cooler is to be replaced with a low-noise, forced-oil, forced-cooling type.

3) Required noise reduction for the transformer unit and the sound-proof construction

The required noise reduction for the transformer unit is as follows:

Required noise reduction = (Unit noise before remodeling)− (unit noise after remodeling)

= 84.1 − 60.0

= 24.1 phons

Therefore, from *Table 2,* the enclosure should be of the prefabricated concrete panel type.

When the enclosure surface density is taken as m = 410 kg/m^2 in such cases, the enclosure sound dampening amount *TL* is calculated as follows:

$$TL = \eta \ \{18 \log (f \cdot m) - 44\}$$

$$= 0.6 \times \{18 \log (120 \times 410) - 44\}$$

$$= 24.3 \text{ phons} > 24.1 \text{ phons (required noise reduction)}$$

4) Selection of coolers

Since the cooler noise value is to be 55 phons, a low noise cooler without a sound-proof air tunnel and with a 20P fan motor is suitable according to *Table 3.* Vibration-proof joints (flexible couplings) are to be inserted in the oil pipes connecting the cooler and transformer unit.

5) Other sound and vibration-proofing measures

(1) Use of vibration-proof rubber under the tank

(2) Two stage expansion in the ventilation duct

(3) Measures to prevent noise leaks oil pipe and bushing through-hoes

(4) Use of double enclosure doors

5. Total noise value after remodeling

The noise was under the guaranteed value of 60 phons.

V. RELATION BETWEEN TRANSFORMER NOISE AND TANK WALL ACCELERATION

Transformer noise measurement is performed using a noise meter/indicater according to JEM 1117 (Methods of measuring transformer noise levels). The measurements can not be performed in places where there is only a slight

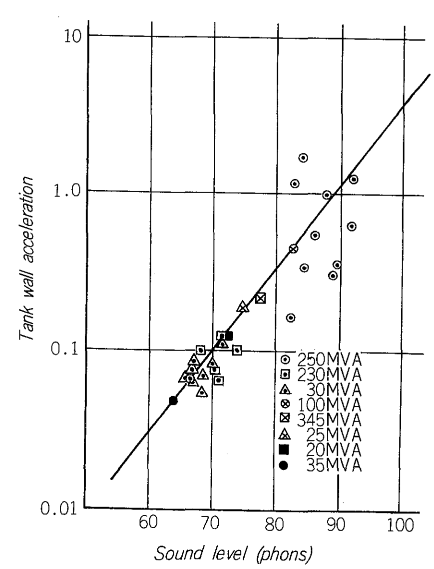


Fig. 15 Relation between sound level and acceleration of tank wall

difference between the transformer noise and background noise (less than 3 phons in JEM) at the time of measurement.

In the results of many experiments concerning the relation between noise levels and acceleration, the correlation shown in *Fig. 15* was obtained. This correlation can be expressed by the following equation:

$$SPL = 20 \log \alpha + 90$$

where SPL : transformer noise level

α : vibrational acceleration (G)

From these results, it is evident that the noise value can not be determined when the difference between the background noise and total noise is small but with this method, it can be estimated with considerable accuracy. More detailed noise measures are possible by measuring the vibrational acceleration in various parts and also improve low noise design techniques.

A theoretical analysis of the relation between the tank wall vibrational acceleration and transformer noise is as follows.

When noise is radiated due to vibrations of a medium in the vicinity of the vibration surface, the sound power W is as follows where R is the radiation resistance and U the volume velocity:

$$W = RU^2 \quad \ldots\ldots (12)$$

When S is the noise radiation area, u the particle velocity and r the specific fadiation resistance:

$$R = r/S \quad \ldots\ldots (13)$$

$$U = u \cdot S \quad \ldots\ldots (14)$$

Equation (12) becomes:

$$W = ru^2 S \quad \ldots\ldots (15)$$

In the case of disk S as part of a rigid wall moves with a lower frequency piston movement, and ρ is the air density, C the sound velocity and W the angular frequency:

$$r = \frac{1}{2} \cdot \frac{\rho}{C} \cdot \frac{Sw^2}{\pi} \quad \ldots\ldots (16)$$

When the amplitude is expressed as x, the particle velocity u becomes:

$$u = wx \quad \ldots\ldots (17)$$

From equations (15), (16) and (17), the sound power becomes:

$$W = \frac{1}{2\pi} \cdot \frac{\rho}{C} S^2 w^4 x^2 \quad \ldots\ldots (18)$$

Since the relation between the sound power W and the pressure P is as follows:

$$W = \frac{1}{\rho C} P^2 S \quad \ldots\ldots (19)$$

The sound pressure from equations (18) and (19) becomes:

$$P = \sqrt{\frac{\rho^2}{2\pi}} Sw^2 x \quad \ldots\ldots (20)$$

The vibration acceleration α is:

$$\alpha = w^2 x \quad \ldots\ldots (21)$$

Therefore, P is as follows:

$$P = \sqrt{\frac{\rho^2}{2\pi}} S \alpha \quad \ldots\ldots (22)$$

The relation between the noise level SPL and the pressure is:

$$SPL = 20 \log \frac{P}{P_0} \quad \ldots\ldots (23)$$

Therefore, the relation between the noise and vibrational acceleration becomes:

$$SPL = 20 \log \alpha + 20 \log \frac{\sqrt{\frac{\rho^2}{2\pi}} S}{P_0} \quad \ldots\ldots (24)$$

From the experimenta results obtained in section 2:

$$SPL = 20 \log \alpha + 90 \text{ (phons)} \quad \ldots\ldots (25)$$

VI. CONCLUSION

This article has described recent transformer noise reduction measures used by Fuji Electric. At the current technical level, it is considered alomost impossible to develop revolutionary new techniques in the future which differ completely from the present noise prevention methods.

At present, we are devoting all of our energies to the development of a rational low noise system by the effective combination of generally known theories and techniques.

The noise distribution near substations can be estimated with good accuracy using a computer and transformer side measures can be decided more appropriately than before. It is also possible to predict correctly the noise distribution after the measures are taken.

Based on long experience and the manufacture of several hundred low noise transformers with excellent results, Fuji Electric is continuously endeavoring to produce more rational low noise transformers to meet increased future demands.