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500/√3 kV 50/3MVA SHUNT REACTORS FOR CTM, ARGENTINA

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I. FOREWORD

The increase in the demand for power has been accompanied by a worldwide trend to increasing the transmission voltage for economical transmission costs. On the other hand, power stations are being increasingly constructed in remote areas, because of geographical conditions, and transmission lines are, naturally, becoming longer. Moreover, because of the difficulty of securing power transmission routes, development of cables, etc., HV and EHV underground cable transmission is increasing.

This increase in the transmission voltage, lengthening of transmission lines, and increase in underground transmission have substantially increased line charging capacity to ground and have resulted in the following problems in the system:

(1) Rise of receiving terminal voltage due to Ferranti effect at light load or no load.
(2) Increase in the power loss caused by leading power.
(3) Switching transient overvoltage of the line.

To suppress such phenomena, it is necessary to compensate the charging capacity by installing the lagging phase modifier equipment of the leading current. Shunt reactor is to be used to absorb the leading reactive power being connected in parallel to the transmission lines. Moreover, shunt reactor is frequently used for switching surge suppression in EHV systems, because it is also effective for the purpose.

We have manufactured 500/√3 kV 16.66 MVA (bank 50 MVA) shunt reactors for COMISION TECNICA MIXTA DE SALTO GRANDE PROYECTO, Argentina. A total of 30 units was manufactured; 15 units in both 1977 and 1978.

Since the 500 kV shunt reactors manufactured at this time have many special features, they will be introduced here.

II. RATINGS AND SPECIFICATIONS

There are two kinds of specifications. Twenty-four units do not have a secondary winding and 6 units have a secondary winding.

The specifications are given in *Table 1*.

There is a special voltage-current characteristic specification. As shown in *Fig. 1*, the inductance at 160% voltage or greater is smaller. This specification is required to increase the voltage suppression effect at an overvoltage.

Table 1 Specification

Type	Outdoor singlephase shunt reactor	Same as at left (with secondary winding)
Rated frequency	50 Hz	50 Hz
Rated capacity	$\frac{50}{3}$ Mvar	$\frac{50}{3}/\frac{1}{3}$ Mvar
Rated voltage	$\frac{500}{\sqrt{3}}$ kV	$\frac{500}{\sqrt{3}}/\frac{13.8}{\sqrt{3}}$ kV
Reactance	5,000 Ω	5,000 Ω
Voltage-current characteristic	Conforms with *Fig. 1*	Same as at left
Impedance between primary and secondary	–	350% (at 50/3 Mvar)
Cooling system	ONAN	ONAN
Temperature rise winding	65°C	65°C
oil	60°C	60°C
Noise level	80 dB A	80 dB A
3-phase connection	人	人/人
Test voltage		
500 kV line terminal		
Lightning impulse	1,550 kV	1,550 kV
Switching impulse	1,300 kV	1,300 kV
AC 1 min.	680 kV	680 kV
AC 30 min.	455 kV	455 kV
Neutral terminal		
Lightning impulse	325 kV	325 kV
AC 1 min.	140 kV	140 kV
Secondary line terminal		
Lightning impulse	–	110 kV
AC 1 min.	–	34 kV
Secondary neutral terminal		
Lightning impulse	–	110 kV
AC 1 min.	–	38 kV

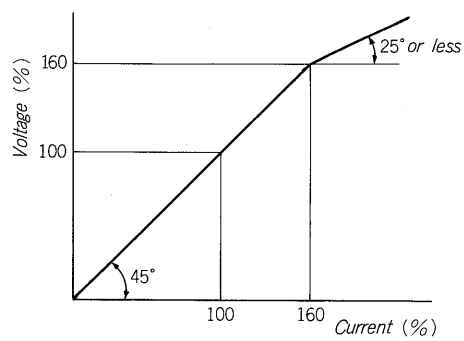


Fig. 1 Voltage-current characteristic

The secondary winding is used as an emergency power source.

III. CONSTRUCTION

Generally there are two kinds of shunt reactors; gapped-core type reactor and shell type reactor. However, since the saturation characteristic of this shunt reactor is specified as shown in *Fig. 1*, the gapped-core type is used. The core has a two leg construction with the winding on one leg as illustrated in *Fig. 2*.

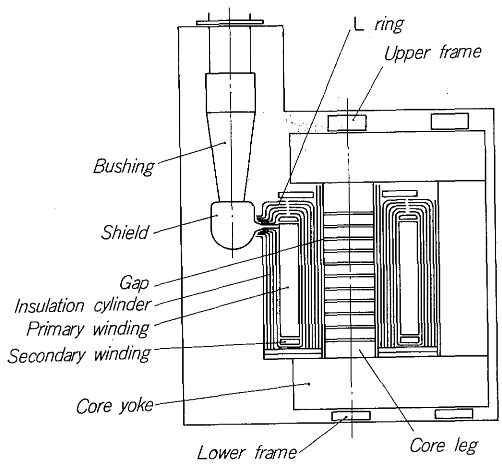
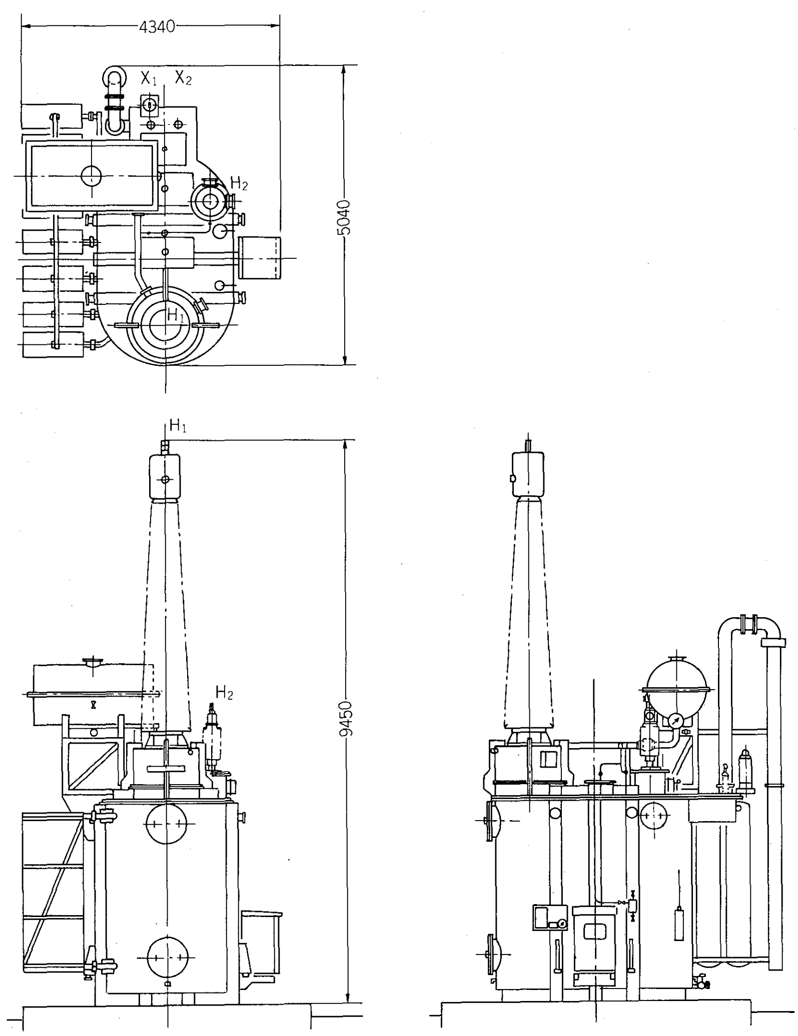


Fig. 2 Core and coils

Vibration, noise and leakage flux countermeasures are most important in EHV large capacity shunt reactor. Careful attention has been given to these in the manufacture of this reactor. At first to avoid excess vibration the gap material has an elasticity equivalent to, or better than, that of core material and a characteristic without shrinkage due to aging. The high precision of the flatness of gap fillers and core surfaces is necessary and to avoid vibration resonance the dimensions of the core have been selected to assure ample rigidity stiffness.

The gap dimensions and core construction has been decided to minimize the losses caused by flux fringing at the core gap.

Furthermore, the connecting bolts which fasten the core at the top and bottom and the clamping bolts which clamp the core in the laminating direction are made of high tension stainless steel to reduce loss and prevent local over-



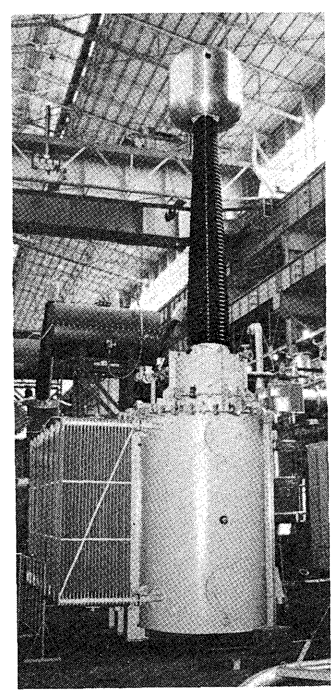


Fig. 3 Outline

Fig. 4 Outline drawing

heating.

The winding is installed at one leg and is continuous disc winding with the 500 kV terminal side at the top. Since the capacity of the secondary winding is extremely small, the secondary winding is installed at the bottom of the primary winding for simple tightening. The insulation barrier arrangement is decided to lie along the equi-potential surfaces of field mapping. In addition, the potential distribution of each coil of the windings has been calculated with an electronic computer and the insulation strength has been increased by suitable insulation at the end of the coils.

The 500 kV lead is connected directly to the bushing from the end of the winding so that it is as short as possible.

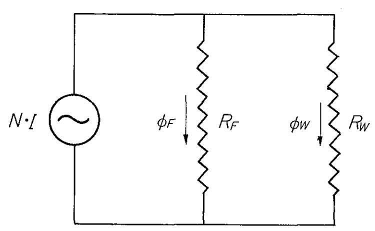
To minimize the vibration the shape of the tank has been determined by the analysis of fininite element method and a simple oval type has been adopted.

A photograph of the unit at factory test is shown in *Fig. 3* and an outline drawing is given in *Fig. 4*.

IV. CHARACTERISTICS

1. Reactance

As previously described, this shunt reactor is of gapped-core type. In a gapped-core type reactor, almost all the flux flows in the core with gap. However, since the insulation spacing between the core and winding is large for high voltage, the leakage flux that flows in the insulation space is also large. Therefore, the magnetic equivalent circuit of the gapped-core type reactor is presented as shown in *Fig. 5*.



N : Number of turns
I : Winding current
R_F : Gapped-core magnetic resistance
R_W : Leakage magnetic resistance
Φ_F : Core flux
Φ_W : Leakage flux

Fig. 5 Equivalent circuit of gapped-core reactor

The gapped-core magnetic resistance R_F and leakage flux resistance R_W are expressed by,

$$R_F = \frac{l_g \cdot k_F}{\mu_o \cdot Q_F} \quad , \quad R_W = \frac{W_\ell}{\mu_o \cdot Q_W \cdot k_W}$$

Where, μ_o : Space permeability
Q_F : Sectional of area core
l_g : Total gap length
k_F : Correction factor<1
k_W : Correction factor<1
Q_W : Sectional of area leakage magnetic path
W_ℓ : Winding height

In other words, the gapped-core magnetic resistance at the unsaturated region of the core is decided almost exclusively by the gap, and because of the fringing effect, its equivalent magnetic length becomes smaller than the total length of the actual gap. Moreover, since the magnetic flux curves, the length of the leakage flux path becomes larger than the winding height. Therefore, inductance L is,

$$L = N \cdot \frac{\Phi_F + \Phi_W}{I} = N^2\left(\frac{1}{R_F} + \frac{1}{R_W}\right)$$

Where $\Phi_F = \dfrac{N \cdot I}{R_F}$, $\Phi_W = \dfrac{N \cdot I}{R_W}$

Φ_F : Core flux , Φ_W : Leakage flux
N : Number of turns I : Winding current

The calculated value of the inductance by the above equation and the actual measured value were well matched and the variation relative to the average value was within 1%.

Next, it is said that the voltage-current characteristic in the overvoltage region is different for a shell type reactor and a gapped-core reactor. Before manufacturing, we produced and tested small models of a shell type and gapped-core type reactor, and decided on the gapped-core type as mentioned before because it satisfied the saturation characteristic in the overvoltage region.

2. Secondary Induced Voltage and Impedance

Since the resistance component is substantially smaller than the reactance, the secondary induced voltage is approximated as follows,

$$E_2 = \frac{L_{1-2}\, E_1}{L_1}$$

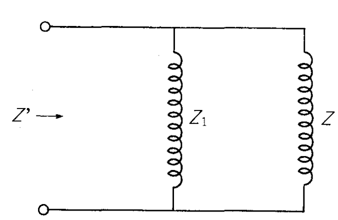
E_1 : Primary voltage
E_2 : Secondary induced voltage
L_1 : Primary self-inductance
L_{1-2} : Matual inductance between primary and secondary

In the case of reactor different from transformer, there are many flux interlinking the primary winding only, the secondary voltage is smaller than the value calculated with the turn ratio.

The number of turns of the secondary winding of the actual reactor was selected by testing this relation with the small model mentioned above. For the calculation of the impedance value between the primary and secondary, we decided the winding arrangement by model testing and also confirmed the coincidence between the measurement and calculation shown in *Fig. 6* in the actual reactor.

3. Loss

The losses of a gapped-core reactor can be grouped by



Z_1 : Primary impedance = 100 (%)
Z' : Primary converted impedance at shorting of secondary
Z : Impedance between primary and secondary

$$Z = \frac{Z_1 \cdot Z'}{Z_1 - Z'}$$

Fig. 6 Impedance between primary and secondary generation point and cause as shown below.

○ Winding loss { Winding resistance loss / Winding eddy current loss

○ Core loss { Iron loss / Eddy current loss by fringing

○ Structural loss by leakage flux

All these losses, except the winding resistance loss, are caused by flux, and accurate understanding of the magnetic field distribution and the losses generated by it is important. We calculate the magnetic field distribution in simple construction by using vactor potential method. However, when the construction is complex, the magnetic field distribution is accurately calculated by field mapping by the analysis of finite difference method, as shown in *Fig. 7.*

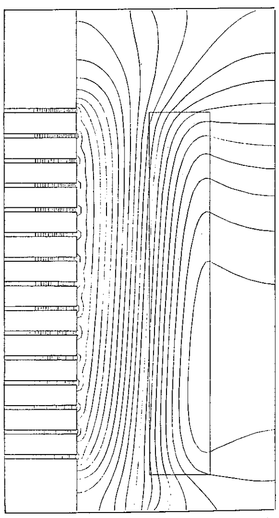


Fig. 7 Magnetic field mapping

The size of the conductor was determined by electronic computer to minimize the eddy current losses in the winding. Moreover, the iron loss and eddy current loss by fringing were grasped by studying the distribution of the flux in the core by field mapping and by experimenting with a small model and the construction which minimized these losses was selected.

Furthermore, a silicon steel magnetic shield was placed at the top and bottom of the yoke and at the tank walls to absorb the leakage flux.

4. Vibration and Noise

Whereas the vibration of shell type reactor is mainly generated by the magnetic attraction force between the windings and the shielded core at the top and bottom of the windings, that of a gapped-core type reactor is mainly generated by the magnetic attraction force of the core gap and has a main vibration frequency of twice the power frequency. To minimize this vibration of the flux density of the gap was selected at a suitable value, a special gap material was used, and the core was securely tightened in the axial direction.

Furthermore, the dimensions, shape, etc. were considered so that vibration is prevented by separating the inherent frequency of the structural components from the gap main vibration frequency as much as possible.

As a result, noise was 76 ~ 77 dBA and the average amplitude of the tank wall vibration was 15 μm.

5. Other

The 3rd, 5th and 7th harmonics of the current were within 1% of the specified value.

V. TESTS

1. Insulation Test

Since the shunt reactor differs from a transformer in that the reactor windings are directly excited, the excitation capacity of the reactor increases proportionally to the square of the applied voltage at the shunt reactor induce test. Therefore, since a large capacity power transformer and compensative condenser are necessary as the test facility, and difficulties are often encountered from the standpoint of the facility, the induce test is generally substituted by the impulse voltage test. The induce test was also substituted by the impulse voltage test for these shunt reactors.

At the primary line lightning impulse voltage test, 1,550 kV was impressed and at the switching impulse test, 1,300 kV was impressed.

Moreover, a partial discharge test was performed for 30 minutes at a voltage of 150% of the rated voltage and the absence of partial discharge was confirmed.

2. Loss and Temperature Rise Test

Since reactive power of the rated capacity must be supplied, a high voltage, large capacity transformer and compensating condenser are necessary in shunt reactor loss measurement. When the rated voltage cannot be applied because of the facility, it is authorized that the losses are measured at a voltage as close as possible to the rated voltage and conversion by the square of the current is confirmed. However, the losses of these shunt reactors were measured by applying the full rated voltage with a 500 kV testing transformer.

Since the power factor of the shunt reactor is extremely low, special consideration must be given to loss measurement. Since accuracy is a problem in the ordinary wattmeter method of measuring loss, the Tellex bridge method and the calorimatric method (the DC method and the watercooler method) were used and coinciding of the result of all three methods was confirmed.

VI. CONCLUSION

By commercialization of numerous shunt reactors with stable quality, the tremendous advances was made in shunt reactor manufacturing technology and the EHV shunt reactor manufacturing system was established. In the future we intend to continue our development in the EHV, large capacity shunt reactors.