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IMPROVMENT OF GENERATOR EFFICIENCY

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I. FORWARD

The noticeable rise in the cost of energy has led to a strong desire for high efficiency generating equipment. Increasing the efficiency of the component devices themselves has a direct effect on energy-saving. The efficiency of the generator is higher than the efficiency of prime movers. However, the recent development of new technology through advances in analysis techniques and various model tests allows the realization of still higher efficiency and an efficiency approaching 99%in large capacity machines has become possible worldwide.

The losses generated inside a generator are classified as shown in *Table 1*.

Table 1 Losses of generator

Name	Classification	Main generation part	Supporting physical quantity
Mechanical loss	Bearing friction loss	Bearing	Speed, lubrication oil viscosity, bearing pressure
	Windage friction loss	Rotor surface, fan	Speed, air flow, hydrogen pressure
Core loss		Stator core	Flux density, core loss coefficient
I^2R loss	I^2R loss in armature winding	Armature winding	Current density
	I^2R loss in field winding	Field winding	Current density
Additional load loss		Armature winding, stator core end part	Magnetomotive force
Other losses		Brush, etc.	

Mechanical loss is the friction loss accompanying rotation. It consists of the bearing friction loss generated at the bearing, and windage loss which is the sum of the rotor surface and cooling gas friction, and the power that causes the cooling gas to flow. The core loss is the loss generated with the changes in the magnetic flux necessary for voltage generation, and is distributed in the stator core, rotor surface and the stator core end part structures. The loss generated in the stator and field windings when current flows through the winding is generally called the copper loss. The other generated by the load current are called additional load losses. These losses are distributed among the stator winding, core, and structures, rotor surface, and other internal parts of the machine. These generator losses are caused by various physical phenomena, and the composition ratio of each differs considerable with the specifications of the machine. *Table 2* shows the typical loss ratio of each loss of a hydraulic turbine generator and steam turbine generator.

Table 2 Typical example of loss ratio

(Units: %)

Loss \ Classification	Hydraulic turbine generator	Steam turbine generator
Bearing friction loss	10	8
Windage loss	15	19
Core loss	33	11
I^2R loss in armature winding	14	12
I^2R loss in field winding	15	32
Additional load loss	13	18

The example of the hydraulic turbine generator is the case of a low-speed high-capacity machine. The example of the steam turbine generator is the case of a direct hydrogen cooled high-capacity machine. In a hydraulic turbine generator, the ratio of the core loss is high and in a steam turbine generator, the ratio of the I^2R loss in the field winding is high. These facts shows that the former is actually an iron machine and the latter is actually a copper machine. Reducing these main losses is most effective in increasing the efficiency of the generator. However, since the machine must be made larger to reduce the core and copper losses directly, economy must be amply considered.

The main techniques used to improve the efficiency of the hydraulic turbine generator and steam turbine generator are introduced.

II. IMPROVEMENT OF HYDRAULIC GENERATOR EFFICIENCY

Since the specifications and construction of the hydraulic generator differ considerably from machine to machine, a positive grasp of the relationship between each loss and the specifications and structure of the machine is extremely important in developing loss reduction techniques. The present state of core loss and additional load loss analysis, loss reduction measurement based on this analysis, and mechanical loss reduction technology based on experients are described.

1. Core loss reduction technology

Core loss L_c is the generic term for the hysteresis loss and eddy current loss generated by flux changes, and mainly consists of the stator core yoke portion loss L_{CY} and teeth portion loss L_{CT}. It also includes the higher harmonic eddy current loss L_{CS} generated at the rotor surface by changes in the magnetic resistance caused by the slots, and the eddy current loss L_{CE} generated at the core end structures by the leakage flux of the core end part. Therefore, core loss L_C is,

$$L_C = L_{CY} + L_{CT} + L_{CS} + L_{CE} \quad \ldots\ldots\ldots (1)$$

If the weight of each part is made G_Y and G_T, the flux density is made B_Y and B_T, and the core loss coefficient of the core material is made P_C, the stator core yoke portion and teeth portion losses L_{CY} and L_{CT} have the relation.

$$L_{CY} = B_Y{}^2 \cdot G_Y \cdot P_C \cdot K_f \cdot K_Y \quad \ldots\ldots\ldots\ldots (2)$$

$$L_{CT} = B_T{}^2 \cdot G_T \cdot P_C \cdot K_f \cdot K_T \quad \ldots\ldots\ldots\ldots (3)$$

Where K_f is the correction coefficient versus frequency and K_Y and K_T are the core loss increase ratio depending on the flux waveform.

A direct method of reducing L_{CY} and L_{CT} is to make the flux density B_Y and B_T small. However, since this increases the size and weight of the core, it is determined by overall economical value. One method of reducing the core loss without affecting the size and weight of the core is to use high quality material having a small loss characteristic value P_C.

Generally, non-oriented silicon steel (JIS Class S) is used as the stator core material. In the past, S14 to S18 was widely used. However, recently, S9 to S12 is being widely used for large machines oriented toward high efficiency. Besides Class S, there is grain oriented silicon steel sheet (JIS Class G) having a low P_C value. Since the core loss characteristic value of steel sheet differs considerably with the direction in which the sheet is rolled and the direction perpendicular to this direction, the relationship between the rolled direction and the direction in whcih the flux flows in each part of the core must be accurately known.

With advances in computer use, the flux distribution can be accurately found by the analysis techniques such as finite element method. Matching the rolled direction at the teeth portion is effective with a hydraulic turbine generator. However, Class G sheet is more expensive than Class S, and its use is presently limited due to economical considerations. If the cost of energy continues to rise in the future, the use of Class G steel sheet is expected to increase.

Besides the silicon steel considered above, losses that cannot be ignored are also generated in the duct piece of the air duct used to feed the cooling gas to the core and the end plates of the core blocks. When oriented toward noticeably high efficiency, the use of a duct piece made of nonmagnetic material is effective.

The eddy current loss L_{CS} generated in the surface of the magnetic poles by the harmonic flux caused by the core slots can be calculated from the equation.

$$L_{CS} = A_S P_S (\tau_S B_S)^2 (nN_1)^{1.5} K_S \quad \ldots\ldots\ldots\ldots (4)$$

Where A_S is the surface area, P_S is the loss coefficient depend on the material and thickness of the part at which the surface loss is generated, τ_S is the slot pitch, n is the rotating speed, N_1 is the number of slots, and K_S is the correction coefficient due to the air gap distribution, etc. B_S is the peak value of the slot harmonic flux density. B_S increases as the slot width b_S and air gap length g ratio b_S/g becomes larger. Since the air gap length g of a low-speed machine is small, B_S is large, and large eddy current loss is generated in the surface of the pole end plate made of solid steel. This loss can be effectively reduced by cutting tangential grooves around the outside of the magnetic pole core end plate facing the stator core. This can reduce the surface loss of this part by one half.

The eddy current loss generated in the surrounding structural parts of magnetic material by the leakage flux from the core end part can be expressed by the equation.

$$L_{CE} = f^{1.5} \cdot DiAT_{GT}{}^2 \cdot K_E \quad \ldots\ldots\ldots\ldots\ldots (5)$$

Where f is the frequency, Di is the stator inner diameter, AT_{GT} is the air gap and stator core teeth magnetomotive force, and K_E is a correction coefficient dependent on the stator core end structure and material. This loss can be effectively reduced by using nonmagnetic material at the fan shields, stator core end, and other parts in which a large eddy current is generated.

The core loss L_C can be calculated at excellent precision from *Eqs. (1)* to *(5)*, and reduction measures appropriate for each cause can be employed. *Fig. 1* is an example of the core loss distribution of a low-speed high-capacity hydraulic turbine generator.

2. Additional load loss reduction technology

The additional load loss is the loss caused by the load current flowing in the conductors, core and surrounding structural material except the winding I^2R loss. Quantizing this loss is difficult and was usually found experimentally. However, today it can be calculated quantitively for each cause from the equation,

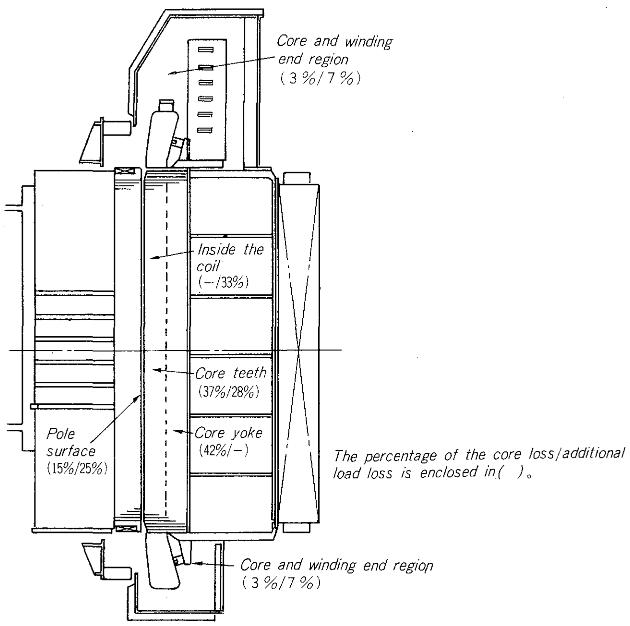

Fig. 1 Distribution of componnents of core and additional load loss

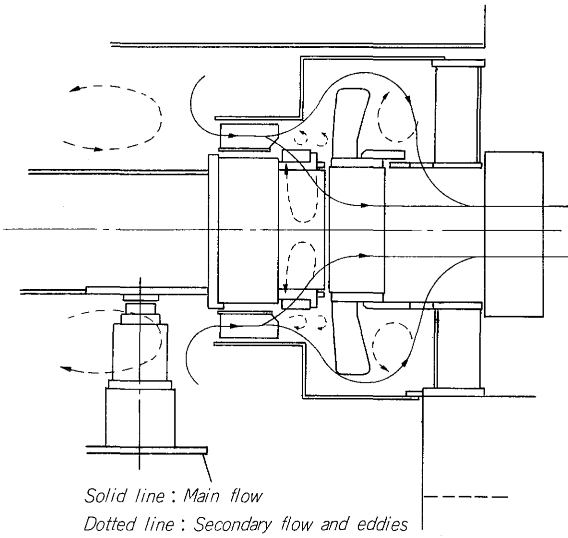

Fig. 2 Air flow in generator

$$L_S = L_{SW} + L_{SC} + L_{ST} + L_{SS} + L_{SE} \quad \ldots\ldots (6)$$

Specifically, it consists of the a.c. resistance loss L_{SW} caused by the affects of the leakage flux of the stator winding slots, amount of increase in the I^2R loss L_{SC} caused by the cross current in the stator winding, loss at the stator core teeth L_{ST} caused by the air gap harmonic flux, eddy current loss L_{SE} of the pole-face, and the core end and coil end parts eddy current loss L_{SE}.

Of these five components, L_{ST}, L_{SS}, and L_{SE} are the same as core losses L_{CT}, L_{CS}, and L_{CE}, and can be calculated from equations resembling *Eqs. (3)* to *(5)*.

The countermeasures against each component of the core loss are also effective in reducing these losses. The a.c. resistance loss L_{SW} for a single turn coil is reduced to 20% or less of the I^2R loss by Roebel's transposition of 360 degrees. The main cause of the cross current loss is the affect of the leakage current of the coil end part. This loss can be reduced by about one-half by transposition so the wire positions are interchanged at the coil end part conductor connection part.

3. Mechanical loss reduction technology

1) Reduction of windage loss

The windage loss is the power needed to feed the cooling air of the generator and consists of,

(1) windage loss caused by the wind flowing through the generator (called the main flow)

(2) windage loss caused by the rotating wind (called the secondary flow) and eddies inside the generator.

Fig. 2 shows the main flow, secondary flow, and eddies in a generator.

Air pressure is needed to feed the necessary amount of cooling air of the generator. The windage loss L_W is the quotient of the product of this air flow Q and air pressure P divided by efficiency η, and is expressed by,

$$L_W = PQ/\eta \quad \ldots\ldots (7)$$

Rewritten with generator stator core inner diameter Di, rotating speed n, and specific weight of air ρ,

$$L_W = \Lambda \rho n^3 Di^5 \quad \ldots\ldots (8)$$

Λ in this equation is called the windage loss coefficient and has the following relation,

$$\Lambda = f(\varphi, L/Di, Re, \text{ventilation system, rotor and stator structure}) \quad \ldots\ldots (9)$$

where,

φ : Flow coefficient (Q/nDi^3)

L/Di : Stator core length and stator core inner diameter ratio

Re : Reynold's number

Fig. 3 shows the relationship between Λ, φ, and L/Di obtained from the large number of machines delivered by Fuji Electric for machines having virtually the same ventilation system and rotor and stator construction.

Since the wind flow in an actual machine is a turbulent flow, Λ is usually unaffected by Re.

The basic items associated with reduction of the windage loss by taking the above into consideration are discussed below.

(1) Reduction of air flow and air pressure

To reduce the windage loss, the air flow must be reduced. To reduce the air flow, the cooling effect must be improved. To reduce the air pressure, the ventilation resist-

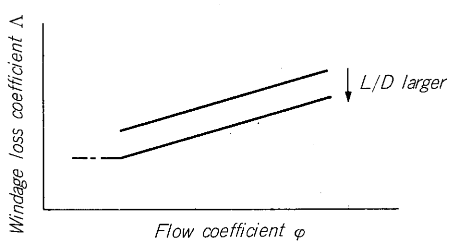

Fig. 3 Relation of windage loss coefficient to flow coefficient

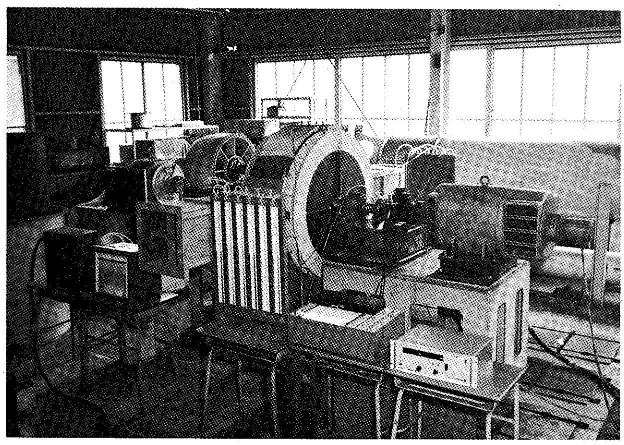

Fig. 4 Ventilation model test

ance must be reduced. These are basic problems of ventilation and cooling technologies. Fuji Electric is developing technology related to these problems through basic experiments, model tests, and prototype measurements. *Fig. 4* shows a typical model test.

(2) Improvement of efficiency

To improve efficiency, the generation of the secondary flow and eddies shown in *Fig. 2* must be suppressed to a minimum. To do this,

(1) The flow collision, sharp curves, and expansion must be eliminated.
(2) The rotor surface must be made smooth.
(3) Counterflow must be prevented.
(4) The passages must be made as narrow as possible.

Fuji Electric uses an axial fan as the self-fan as much as possible as one means of achieving this. This fan is used because the pressure loss at the fan outlet is smaller and the fan efficiency is higher compared to the radial fan.

Comparison measurements made on an extremely smooth rotor and on a common rotor show that the windage loss decreases considerably as the rotor is made smoother.

(3) Optimization of basic dimensions

From the standpoint of reducing the windage loss, the stator core length and inner diameter ratio L/Di should be made as large as possible. This is clear from *Eq. (8)* and *Fig. 3*. Of cause, a high L/Di makes cooling more difficult and

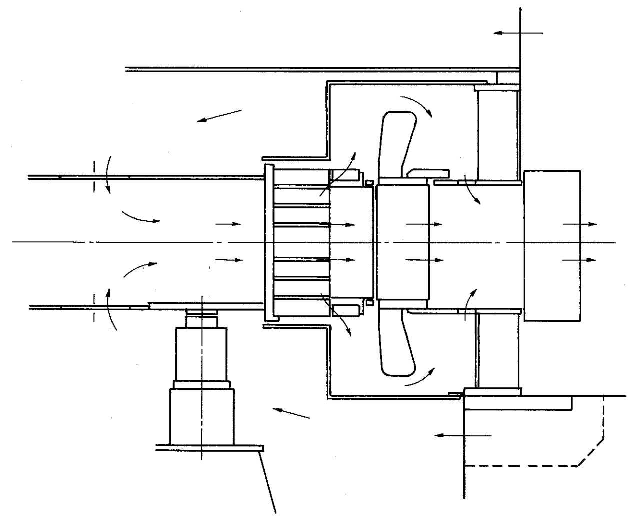

Fig. 5 Rim-ventilation and its air flow

increases the weight of the rotor needed to obtain the desired GD^2,

The theme taken up by Fuji Electric on the basic considerations on reducing these windage losses is the adoption of a cylinderized rotor and the reduction of the air flow by the improvement of cooling. The rim-ventilation widely used for high capacity machines in recent years is a desirable ventilation system from this standpoint and is expected to be adopted not only for high capacity, but also medium capacity machines. *Fig. 5* shows the air flow of the rim-ventilation system. Rim-ventilation has the following features:

(1) Since cooling effect is excellent, the air flow can be reduced.
(2) Since the inter-pole space can be reduced, the outside surface of the rotor can be made nearly cylindrical.
(3) Uniform cooling is possible even if the core length is long. That is, the cooling difficulties for a large L/Di machine disappeared.
(4) Since a self-fan is unnecessary, the top and bottom ends of the rotor can be made smooth.

2) Reduction of bearing loss

The rotor of a hydraulic turbine generator is supported by a thrust bearing and a guide bearing. Therefore, the bearing loss consists of thrust bearing loss and guide bearing loss.

Fig. 6 shows the relationship between the thrust bearing loss and thrust load. Note that even when the load is zero, a fairly large loss is generated. This is called stirring loss and is caused by stirring of the oil. The loss generated at the sliding surface is called the sliding surface loss. The stirring loss is proportion to 2 – 3 power of the spherical velocity and the sliding surface loss is proportion to about 1.5 power of the spherical velocity. Therefore, the stirring loss is not much of a problem with low-speed machines. However, it occupies a aignificant proportion of the losses in a high-speed machine.

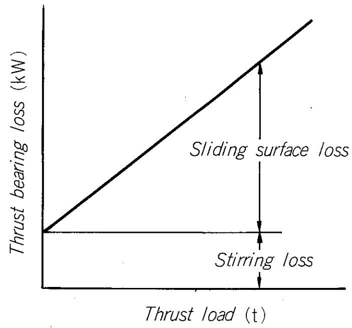

Fig. 6 Relation of thrust bearing loss to thrust load

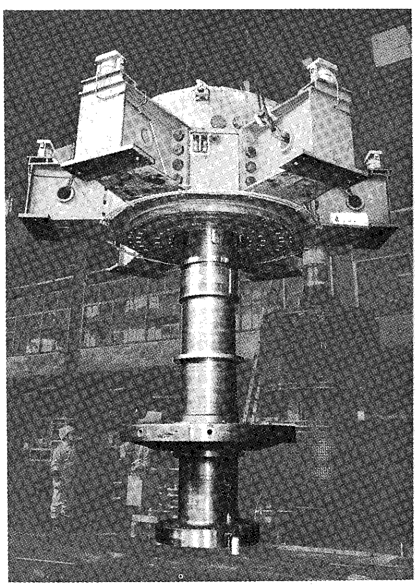

Fig. 7 Magnetic thrust bearing

The guide bearing loss is proportional to about the square of the spherical velocity, proportional to the area of the sliding surface, and inversely proportional to the bearing clearance. When the self-pumping effect is used to circulate the lubricating oil, the self-pumping loss is added.

(1) Reduction of thrust bearing loss

The following three main methods of reducing the thrust bearing loss are considered.

(1) Lightening the thrust load

Using the magnetic thrust bearing, which suspends the rotor by magnetic force, the thrust bearing load can be substantially reduced. Fuji Electric has rich supply experiences on the magnetic thrust bearing. *Fig. 7* is an outer view of the magnetic thrust bearing. Because, the thrust bearing can be made smaller, the sliding surface loss and stirring loss simultaneously reduced, and the thrust bearing loss substantially reduced even when the excitation loss of the magnetic thrust bearing is considered.

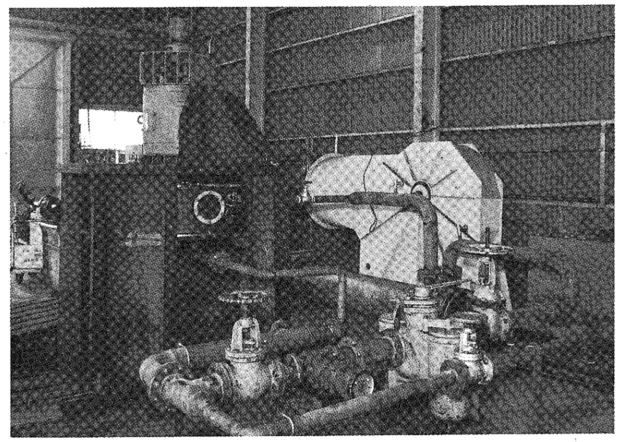

Fig. 8 Oil flow model test for thrust bearing

(2) Reduction of spherical velocity

To reduce the spherical velocity, the thrust bearing must be made samller. Therefore, a thrust bearing capable of withstanding the high surface pressure must be developed. For example, reducing the average diameter of the thrust bearing by 10% by increasing its surface pressure the thrust bearing loss will be reduced by 20%. Fuji Electric is developing technology for this purpose by actual load thrust bearing tests.

(3) Reduction of stirring loss

The flow inside the bearing oil pan consists of various circular flows and eddies and is violent in concept. These flows are almost all losses. Reduction of this stirring loss is especially significant in high-speed machines. Fuji Electric is conducting oil flow model tests for this purpose and is proceeding with research and development to reduce the circular flow and eddies. *Fig. 8* shows the outer view of the oil flow model test equipment.

(2) Reduction of guide bearing loss

The most effective method of reducing the guide bearing loss is reducing the spherical velocity by making the journal diameter small. However, since making the journal diameter small reduces the oil film rigidity, care must be exercised. Basides, bearing clearance the sliding surface area, etc. also have an effect on the guide bearing loss. However, many times there is vibration and other causes, and effective measures cannot be taken.

3) Reduction of self-pump loss

Since the self-pump loss is the product of the oil flow and pump discharge pressure divided by efficiency, the oil flow and pump discharge pressure must be optimized. The self-pump outside diameter must be selected careful so that the pump discharge pressure is not too high. To improve efficiency, the form of the pump inlet must also be considered.

Since the bearing loss is caused by shearing of the lubricating oil, it can be reduced by lowering the visocosity of the oil. For example, for a 300 MW class generatormotor for pumped-storage power station, the bearing loss when #90 turbine oil is used is 10 – 15% less than that when #140 turbine oil is used. Since forming of the oil film is not much of a problem with high-speed machine at which bearing loss is a problem, low viscosity oil should be used.

III. IMPROVING THE EFFICIENCY OF THE TURBO-GENERATOR

The unit capacity of the turbo-generator has been increased by development of the cooling technology. *Fig. 9* shows the cooling system and weight per unit output (kg/kVA) at each output.

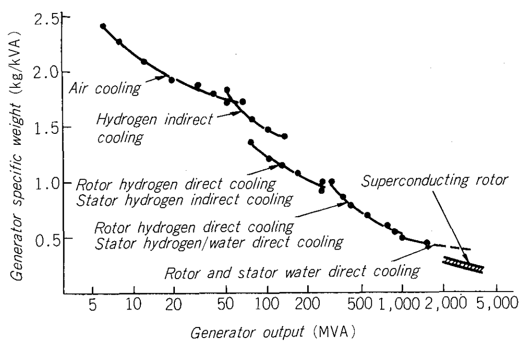

Fig. 9 Relation of output and specific weight of turbo-generator

As the output is increased, cooling is made strong from air cooling, to hydrogen indirect cooling, hydrogen direct cooling and finally water direct cooling, and the specific weight (kg/kVA) is reduced noticeably. The composition ratio of the losses corresponding to the differences of such cooling systems is also noticeably different. Generally, as the output becomes high, the ratio of the fixed loss (mechanical loss and core loss) decreases corresponding to the strengthening of the cooling, and the load loss (resistance loss and additional load loss) increases. The characteristics of the turbo-generator are considered and efficiency improvement technology centered about reduction of the additional load loss is described.

1. Suitable selection of the hydrogen pressure

In the case of hydrogen cooling, better cooling effect by increasing the hydrogen pressure reduces the dimensions and weight of the machine, but also reduces the efficiency. Therefore, the hydrogen pressure at each output depends on the economical evaluation of the efficiency. *Table 3* is an example of the results of comparison when the hydrogen pressure was changed 3, 4, and 5 kg/cm^2 for a 700 MVA, 50 Hz hydrogen direct cooled stator and rotor winding machine.

At 3 kg/cm^2, the efficiency is 0.04% higher than at 4 kg/cm^2, but the weight is also 8% greater. At 5 kg/cm^2, the weight is 4% less than at 4 kg/cm^2, but the efficiency drops a substantial 0.34%. Considering overall efficiency and economy, selection of a hydrogen pressure of 4 kg/cm^2 is suitable at the present time. Fuji Electric selects the optimum pressure at which the highest efficiency is realized while considering today's energy cost for each output in this way.

Table 3 Comparison of influence of hydrogen pressure

Hydrogen pressure (kg/cm^2)	3	4	5
Stator outside diameter (%)	100	100	102
Stator core length (%)	110	100	92
Weight (%)	108	100	96
Efficiency difference (%)	+0.04	±0	–0.34

2. Reduction of additional load loss generated at the stator winding.

The circulating current between strands caused by the leakage flux of the slots is suppressed by Roebel's transposition at the stator winding. However, eddy current loss is generated inside the strands. This loss can be reduced by making the height of the strands smaller, but this worsens the space factor of the conductors. *Fig. 10* is an example of the results of studies on the relationship between the strand thickness and winding resistance loss and eddy current loss for the hydrogen direct cooling system. In this case, the loss is minimum for a strand thickness of 1.3 mm. The loss is lowered by optimum design by conducting the same study for each model.

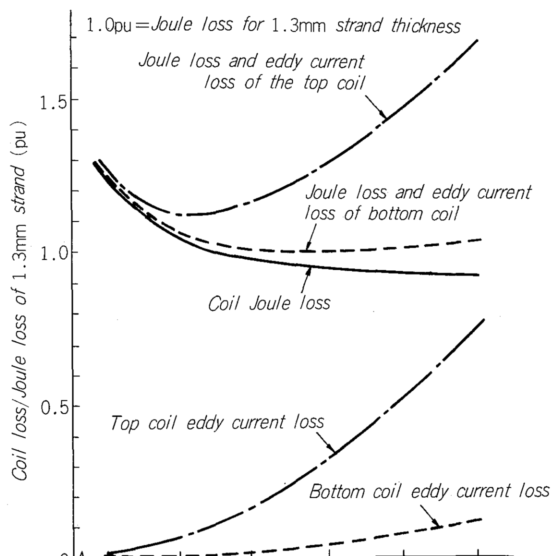

Fig. 10 Relation between conductor thickness and losses

The leakage flux of the end of the stator winding generates a difference in the induced voltage in the stator winding height direction (radial direction) and a circulating current flows and an addition loss is generated.

The leakage flux in the radial direction of the winding end also generates a voltage difference between strands placed side by side and a circulating current flows. These losses are large for the direct cooling system. Special transposition in which the left and right conductors of the cooling pipes at the connecting parts of the conductors at the end of the winding are interchanged is effective in reducing this loss, and can substantially reduce the additional load loss.

3. Reduction of the eddy current of the core end part, etc.

To prevent overheating of the stator core end part at leading power factor operation, a magnetic shield consisting of a laminated core is installed and the core end part is stepped. These are effective in reducing the eddy current loss caused by the leakage flux produced by the stator winding end.

The stator core end teeth part slit and press ring slit are effective in reducing the loss by increasing the length of the eddy current circuit and are used as standard. Non-magnetic material is used at the stator core end finger plate, stator core duct-piece, winding end part ventilation guide plate, multi-steps axial fan guide vane mounting part, etc. to reduce the eddy current loss.

IV. CONCLUSION

Analysis and research on loss by various tests are indispensable in realizing improved generator efficiency. Various loss reduction technologies for the hydraulic turbine generator and turbo-generator were introduced. The applicability of the technologies described here depends on the economical evaluation for efficiency improvement, and an overall decision should be made by considering the magnitude of the reduction result at each machine.

The authors will be happy if this paper serve as reference on generator efficiency improvement technology.

Reference:

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