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IMPACTS ON TURBINE GENERATOR DESIGN BY THE APPLICATION OF INCREASED THERMAL CONDUCTING STATOR INSULATION

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SUMMARY

The increase of power density (capacity /weight ratio) of indirect-cooled generators can be achieved by improving the thermal conductivity of stator coil insulation. Of several concepts, this is the most reliable from the viewpoint of a long lifetime. This newly developed HTC (High Thermal Conducting) insulation system has achieved double the thermal conductivity by replacing a part of the epoxy resin with a high thermal conducting filler, while keeping almost the same breakdown and voltage endurance characteristics compared to conventional insulation systems.
By adopting this HTC insulation system, the maximum unit capacity of air/hydrogen indirect-cooled generators can be increased up to 400 MVA and 600 MVA respectively. Lower electrical losses in coils and decreased windage loss due to a reduced cooling gas can contribute to high generator efficiency, because of the lower coil working temperature. An industrial use 350 MVA class generator with HTC insulation shows remarkable reduction of coil temperature in shop tests. At rewinding of operating generators, this increases generator output by 10 - 15 % without any change of coil design, except for the insulation system.

KEYWORDS

Turbine - Generator - Stator - Winding – Insulation - Cooling - Thermal Conductivity - Control

1. INTRODUCTION

Recently, there have been rapidly increasing commercial applications of electric power generating systems incorporating gas turbines. Gas turbine driven generators require a simple structure, improved operationability, high reliability, low life cycle cost, and short production period. Turbine generators with indirectly air/hydrogen-cooled stator coils have experienced successful long-term operations, and their operationability and reliability have been certificated. And also, these advantageous features respond to requirements. In particular, the unit capacity enlargement of turbine generators with long and large indirect-cooled stator coils is becoming a critical issue. This has been brought about by the recent demand for increasing unit capacity of gas turbines that characterize frequent start/stop operations and fast loading to full power. To achieve unit capacity enlargement while maintaining high reliability, the world’s first high thermal conducting (hereinafter called HTC) stator insulation system has been developed and it has been successfully applied to industrial and large capacity turbine generators [1].
This paper introduces the impacts on generator design by the application of increased thermal conducting stator insulation and its advantages.

2. BASIC CONCEPTS FOR UNIT CAPACITY ENLARGEMENT

The unit capacity enlargement of indirect-cooled generators is limited mainly by the current capacity of stator coils. While coil insulation is required to provide appropriate dielectric characteristics that are maintained throughout the life of generators, conventional insulations act as a thermal barrier. Therefore, these kinds of insulation are a critical factor for generators with indirect-cooled stator design where the heat generated in the conductors is transmitted through the insulation walls.
In response to two consistent features, several design concepts are proposed, as shown in Fig.1. These are reduced insulation wall, global vacuum pressure impregnation (GVPI), HTC insulation and high thermal class insulation. Coil temperature decrease along with increased electrical stress as a result of reduced insulation thickness is shown in Fig.2.

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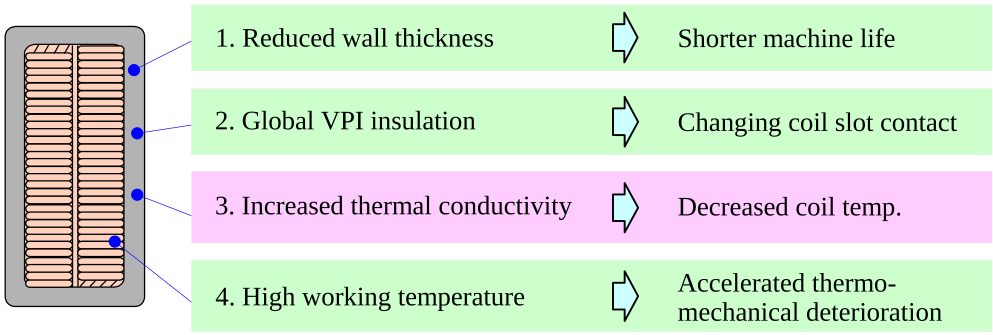

Fig.1 Design concepts for upgrading/uprating

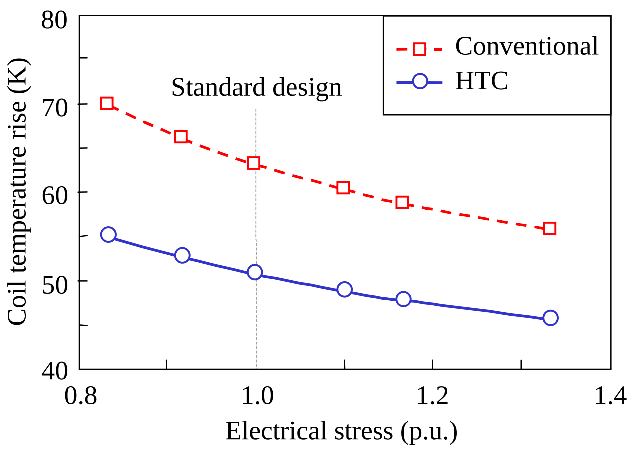

Fig.2 Coil temperature decrease with doubled thermal conductivity and increased electrical stress

Less insulation thickness has a minor effect on lowering the coil temperature, having a rather small impact on generator capacity change while increasing electrical stress. For example, even if the electrical stress is increased 1.2 times of standard design, the coil temperature reduction will remain only 5K while the machine life is shorten. On the contrary, the doubled thermal conductivity of stator insulation could ensure the remarkable decrease of coil temperature more than 10K.

Meanwhile, GVPI system is a reasonable concept from the viewpoint of thermal transmitting in slot, because the initial coil/slot gaps are eliminated. This system is well suited to small and medium capacity generators with rather short coils. However, for large generators with long and large coils, the initial coil/slot contact condition seems rather difficult to maintain over a number of years due to thermal expansions and shrinkages of the coils, resulting from frequent start/stop and adjustable load operations [2].

For high thermal class generators, long stator coils operated at elevated temperature will have the harmful influence on coil end support structure and slot packing system due to increased thermal expansion [3]. Furthermore, insulation deterioration will be accelerated by high thermo-mechanical stresses resulting in electrical and mechanical wearing at rapid and transient temperature changes during adjustable load and frequent start/stop operations on gas turbine driven generators.

Apart from these design concepts, HTC insulation designed at F-class/B-rise is adopted with top priority given to long-term reliability. The increased thermal conductivity of the main insulation effectively suppresses the coil temperature rise without any design change including wall thickness. As shown in Fig.3, HTC insulation will reduce the temperature difference between the internal and the external surfaces of the insulation layer. When the measured temperature is kept at the same level as the conventional design generators, the stator current could be larger and the generator capacity could be increased without changing frame size. On the other hand, if the stator current is kept as same as the conventional generators and quantity of cooling gas is reduced in proportion to stator coil losses, the conductor temperature could be effectively downed as shown in Fig.4, resulting in higher generator efficiency. This design concept will provide remarkable design flexibility along with greatly improved design freedom range.

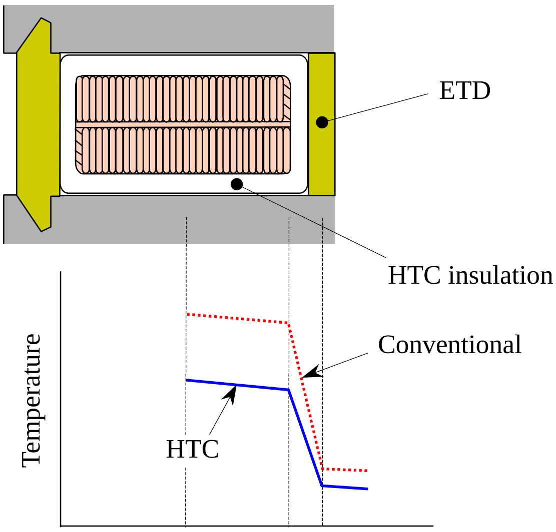

Fig.3 Impacts of HTC insulation on generator

3. CONCEPTUAL DESIGN OF HTC INSULATION SYSTEM

Indirect-cooled coils generally operated at higher temperatures than direct-cooled ones must have higher reliability under thermal cycling.

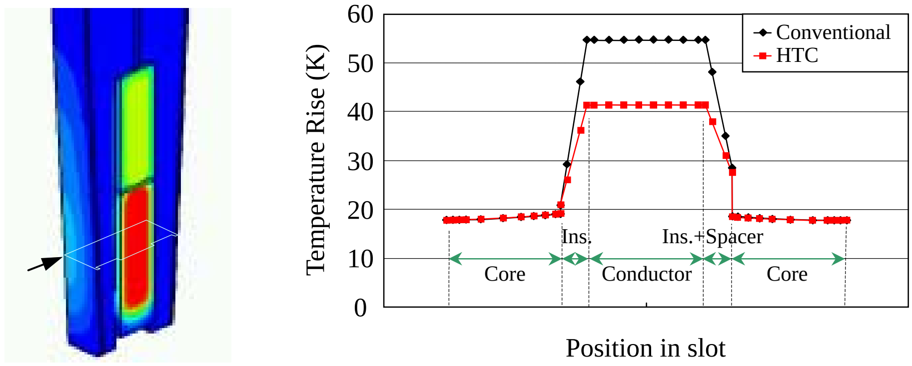

Fig.4 Simulated coil temperature distribution

Therefore, development of HTC system is finally decided to take into consideration of the maximum utilization of the same material composition and VPI process for half-turn coils as the existing F/B insulation system, whose reliability has been proven by many applications to indirect-cooled generators and long-term operational experiences. This means that impregnating resin, manufacturing process and coil assembling procedure would be kept as the same, giving substantial advantages from the viewpoints of productivity and economy.

The target of the newly developed HTC insulation system is to double the thermal conductivity of the insulation, while preserving the well-proven characteristics inherent in conventional ones (Fig.5).

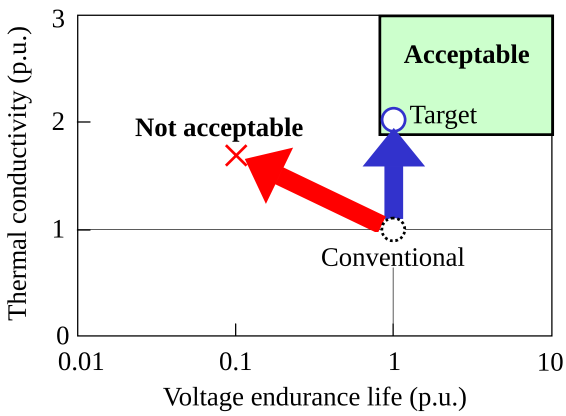

Fig.5 Basic concept of HTC insulation system

Among the major compositions of conventional insulation, the thermal conductivity of resin is by far the lowest when compared with mica paper and glass cloth. Therefore, epoxy resin was to be partly replaced by a high thermal conducting filler. This improvement involving the modification of mica tape only is the most advantageous for the common use of existing manufacturing facilities for the conventional insulation system. However, there was a requirement to make sure that modification of mica tape necessitated by adoption of the filler would not influence any physical properties other than thermal conductivity.

However, for development, in order to prevent loss of filler during taping and to maintain impregnability during impregnating, type of filler, filler grain size, filler quantity and its arrangement have been optimized through comprehensive experimental studies.

4. DEVELOPMENT AND EVALUATION OF HTC INSULATION SYSTEM

4.1 Evaluation tests on HTC mica tape

In the course of mica tape development, the filler quantity and the manufacturing process were optimized to avoid any change of other characteristics. Conformity with the existing coil manufacturing process in respect to tapingability, impregnability and compatibility with the impregnating resin were confirmed.

The thermal conductivity of the insulation is influenced with taping tension, pressing process after impregnation and final physical dimensions in addition to mica tape quality itself [4]. Measurements of thermal conductivity on specimens taken from industrial use coils showed around twice the conventional value and meet with the basic concept (Fig.6), and the conductivity distribution along the longitudinal direction also showed stable values.

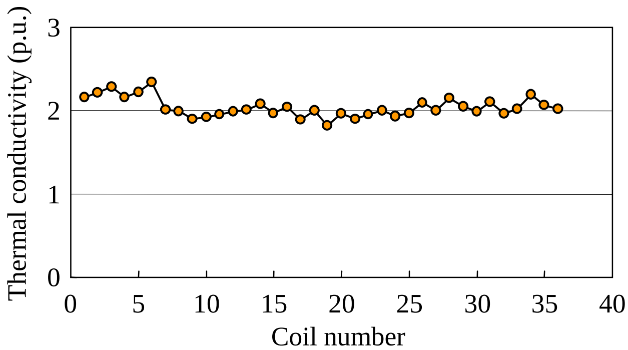

Fig.6 Thermal conductivity of HTC insulation coils

To test the ductility of insulation with filler added, the surface strain at bending rupture of the insulation layers was measured. The results showed no change from conventional insulation system and enough ductility against excessive electromagnetic forces at the instance of line faults (Fig.7).

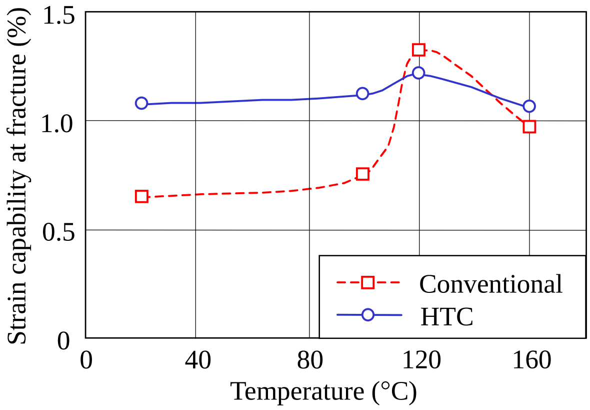

Fig.7 Surface strain at bending rupture test

Furthermore, the mechanical strength of HTC insulation was equivalent to that of the conventional insulation at working temperature.

4.2 Evaluation tests on HTC insulation coils

HTC insulation coils were assembled into 600 MVA class model slots, and heated by AC current to conduct thermal cycling at 40-155 °C for evaluating long-term reliability as shown in Fig.8. The tanδ change of HTC insulation coils after 1,000 thermal cycles was small comparing with initial figures, and the resistance against repeated thermal cycling was evaluated successfully as shown in Fig.9.

Fig.8 Thermal cycling test of HTC insulation coils

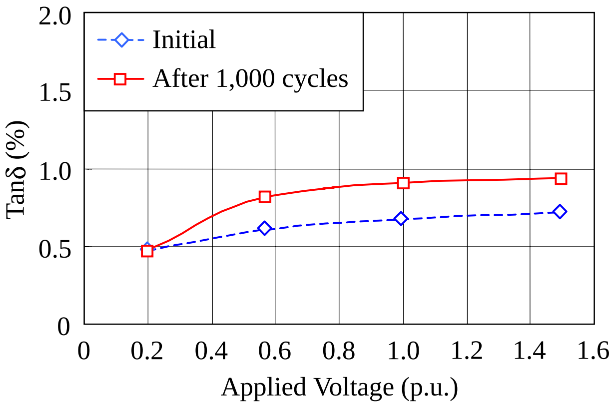

Fig.9 Tanδ change due to thermal cycling

Furthermore, in order to evaluate dielectric characteristics after adding filler, voltage endurance tests were conducted on industrial use coils including large size coils exposed to the thermal cycling discussed above. The test results showed the same or better characteristics compared with conventional insulation over a wide range of electrical stress, and met with the basic concept (Fig.10).

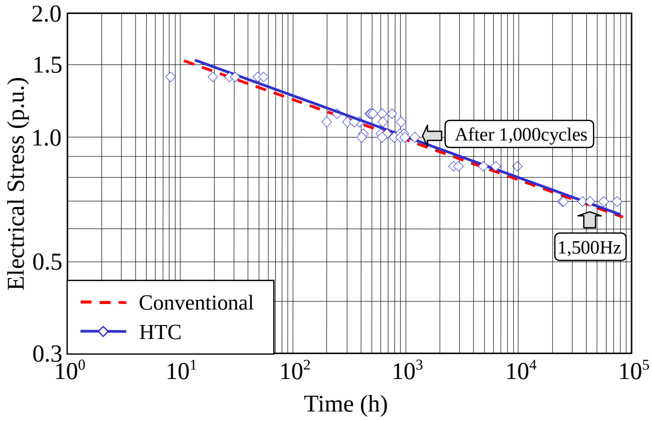

Fig.10 Voltage endurance test

4.3 Evaluation tests on HTC insulation generator

Temperature measurements were conducted on a 350 MVA class hydrogen-cooled turbine generator with HTC insulation coils at shop tests. In comparison with a conventional insulation generator of the same frame size, HTC insulation generator showed a remarkable reduction in coil temperature.

Not only was the coil surface temperature lower, but also the conductor temperature measured by a special method was much lower in comparison with the conventional generator. Furthermore, the temperature difference between the internal and the external surfaces of HTC insulation was found to be smaller as shown in Fig.11.

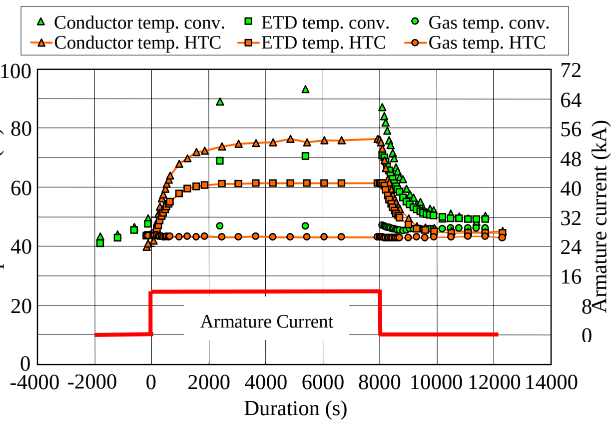

Fig.11 Temperature tests at rated stator current three phase short circuit

In addition, sudden three phase short-circuit tests were conducted to evaluate the resistance against excessive electromagnetic forces. Detailed inspections on the end winding insulation surface after the tests showed no abnormality.

5. ADVANTAGES OF HTC INSULATION GENERATORS

The newly developed HTC insulation can improve thermal conductivity of insulation while maintaining electrical stresses and coil temperatures at the same level as conventional insulation generators. By appropriate combination of HTC insulation technology with an improved generator ventilation system and optimized frame structure, the maximum unit capacity of indirect-cooled generators is remarkably increased as shown in Fig.12.

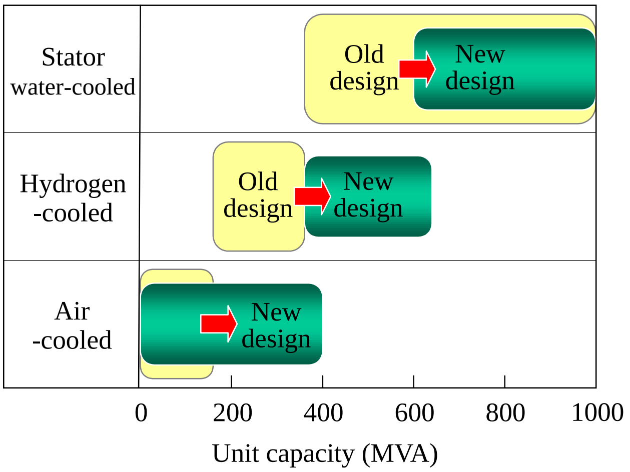

Fig.12 Enlarged capacity range for indirect-cooled generators

The power density and efficiency of the generators could be attained at a level comparable with those of water-cooled generators. The increased power density of HTC insulation generators is shown in Fig.13, and is found to be equivalent to that of water-cooled generators.

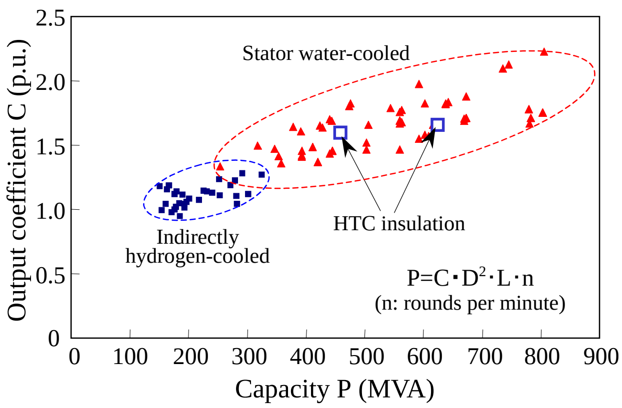

Fig.13 Generator output coefficient

HTC insulation generators with indirect-cooled coils do not need to provide cooling hydrogen gas or water passages in the coils, thus contributing to high reliability because of the simplified coil structure. Moreover, no necessity of auxiliary equipment such as a stator water-cooling unit will be profitable from the viewpoint of economy.

6. DESIGN IMPACTS WITH HTC INSULATION

HTC insulation is found to reduce the temperature difference between the internal and the external surfaces of the insulation wall without any change of insulation thickness and coil structure. Therefore, stator current can be increased, resulting in uprating of the generator. For the same generator capacity, reduction in coil losses and windage loss accompanied by reduced quantity of cooling gas will improve generator efficiency.
Furthermore, during operations at peak load specified to the output characteristics of gas turbines, coil conductor temperatures are higher than at base load operations. With some applicable standards, the peak output of a generator is restricted with the estimated maximum permissible temperature of the conductors. Because the difference between the maximum conductor temperature and ETD coil temperature in HTC insulation generator is decreased, its peak capacity can be increased more than that of conventional insulation generators.
In the case of increasing unit capacity with the same frame size, HTC insulation generators offer high reliability because they can be designed for the same electrical stress and the same temperature as conventional generators.
The fact that mechanical deterioration caused by rapidly increasing requirements for frequent start/stop and various load operations for load adjustment is now generally recognized as the critical insulation deterioration factor. This learnt to be resulted in insulation deterioration accompanied by high coil temperature, high electrical stress and rigid coil assembling in slots. It is also clear that the basic concept of HTC insulation generators ensures long-term reliability under these operations.
The various advantages achieved by HTC insulation technology are not limited to newly designed generators, but also apply to operating generators at rewinding of stator coils as listed below:

- For the same generator capacity in kW
  - Larger apparent capacity (larger reactive power)
  - Improved generator efficiency
- For increasing generator capacity
  - Increased generator capacity with minimum design change (10-15%)
  - Simplified cooling system (from direct-cooling to indirect-cooling)
  - Reduced electricity power supplied to auxiliary equipment by eliminating of coil coolant and its cooling unit

Furthermore, site rewinding by using half-turn coils with VPI process allows shortened rewinding period for whole winding, applicable partial rewinding, easy removal of existing coils and no transportation of a heavy stator to the factory.

7. CONCLUSION

The newly developed HTC insulation is compatible with well-established coil manufacturing processes, and also applicable to proven design at the same electrical stress and coil temperatures as much experienced conventional insulation generators. Furthermore, the applications of such advanced HTC insulation remarkably increase the maximum unit capacity of indirect-cooled turbine generators, providing high total cost merits from the viewpoints of design, manufacturing and efficiency.

Stator rewinding of operating generators enables increased generator capacity and improved efficiency without any change of coil design, except for the insulation system.

The newly developed HTC insulation system can minimize design limitations as discussed above, and provide distinguished flexibility in the design stage. Various requirements from customers could be surely responded because of the improved aspects of this technology. This advanced technology would guarantee much profit to customers.

8. REFFERENCES

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