Development of Large-capacity Indirect Hydrogen-cooled Turbine Generator and Latest Technologies Applied to After Sales Service

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In terms of environmental problems and power generation costs, an increase of the capacity of indirect hydrogen-cooled turbine generators with high efficiency and good maintainability are required. Mitsubishi Hitachi Power Systems Co., Ltd. (MHPS) developed High Heat Transmission®, which improves the heat transmission rate of the stator coil insulation by approximately three times higher compared to conventional one produced with existing technology, and the feasibility of a 900 MVA class indirect hydrogen-cooled turbine generator, the basic design of which has been completed by actual equipment verification using a 600 MVA class generator, was confirmed. High Heat Transmission® can be applied not only to new generators, but also to existing generators, and it can be expected to contribute to an increase of output and the resolution of problems with generators experiencing overheating of stator coils. We are also promoting the application of newly developed technologies to the generator service field, such as inspection and monitoring technologies of generators.

1. Introduction

In recent years, the reduction of CO2 emissions and the stable and low-cost supply of electric power are required to suppress global warming. MHPS is promoting development for an increase of the capacity of indirect hydrogen-cooled turbine generators with high efficiency and good maintainability.[1] For this development, we implemented higher cooling, lower losses, and lower vibration design using various design tools such as fluid analysis on the scale of hundreds of millions of elements and through vibration analysis with electromagnetic field analysis. We have also developed High Heat Transmission®, which improved the cooling performance of the stator coil, and have currently completed factory rotation performance testing using a 600 MVA class generator equipped with High Heat Transmission®, where good test results were obtained. In addition, this paper presents an example case where High Heat Transmission® is applied to an existing generator. Furthermore, this paper introduces the latest technology lineup in servicing for existing generators such as insulation diagnosis technology and stator wedge looseness diagnosis technology.

2. Technology for increase of capacity of indirect hydrogen-cooled turbine generator

MHPS selects a cooling system suitable for the capacity band of the generator. Conventionally, we have used an air cooling system for the small-capacity band (up to 300 MVA), an indirect hydrogen cooling system for the medium-capacity band (200 to 500 MVA), and a direct water cooling system for the large-capacity band (500 to 1600 MVA).[1] Compared with the direct water cooling system, the indirect hydrogen cooling system has advantages in terms of operational performance and maintainability because of the elimination of the need for a stator cooling water system and its piping. It also has the advantage of better efficiency resulting from lower losses due to the increased conductor area because hollow conductors for cooling stator coils with water are not used. MHPS is working on increasing the capacity of indirect hydrogen-cooled turbine generators through higher cooling, lower losses, and lower vibration design using large scale analysis and design tools for which the calculation accuracy has been verified[1], as well as the development of High Heat Transmission®, which enhances the cooling performance of stator coils.

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Figure 1 shows the fluid analysis from the ventilation fan to the periphery of the stator coil end basket using hundreds of millions of elements as an example of large scale analysis. The analysis results are used for the design study to optimize the structure and to reflect the parameters of the design. Due to the increased generator capacity, the electromagnetic force at the stator coil end increases, so it is necessary to strengthen the support of the stator coil end. For the design of the support structure, frequency response analysis with electromagnetic force analysis at the stator coil end is applied.

Figure 2 shows an example of frequency response analysis with electromagnetic force analysis. The electromagnetic force analysis is intended for the connection ring side consisting of the stator coil end and the connection ring, and can simulate various operating conditions of the generator because the analysis model includes the stator core and the rotor. Figure 2 shows the analysis results at the rated load (results of a certain moment) and the electromagnetic forces of the stator coil end and the connection rings are calculated for one cycle and input as a load to the frequency response analysis. Using these analysis results, the support structure of the stator coil end is designed so that the vibration value and the stress value of each part are suppressed below the design limit.

In the repair or part replacement of generators manufactured by other companies, the design data of which are difficult to obtain completely, these analysis and design tools estimate detailed design specifications by comparing the obtained data with the analysis results. In addition, these tools are used for designing performance improvements based on this estimation.

Actual equipment verification of High Heat Transmission® is described in detail in the next chapter.

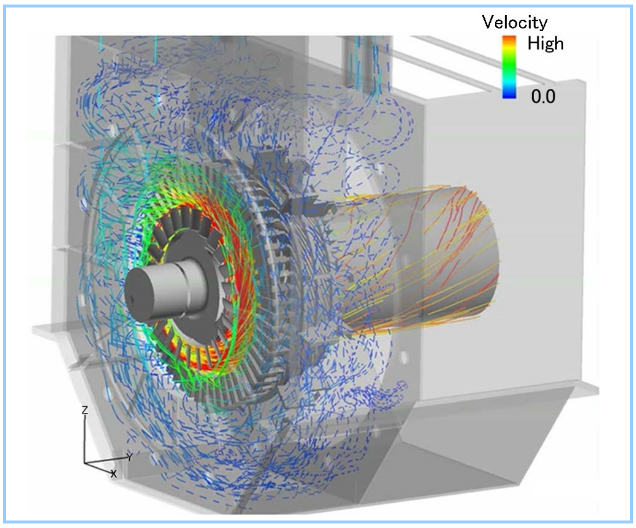

Figure 1 Fluid analysis from ventilation fan to periphery of stator coil end (flow line distribution)

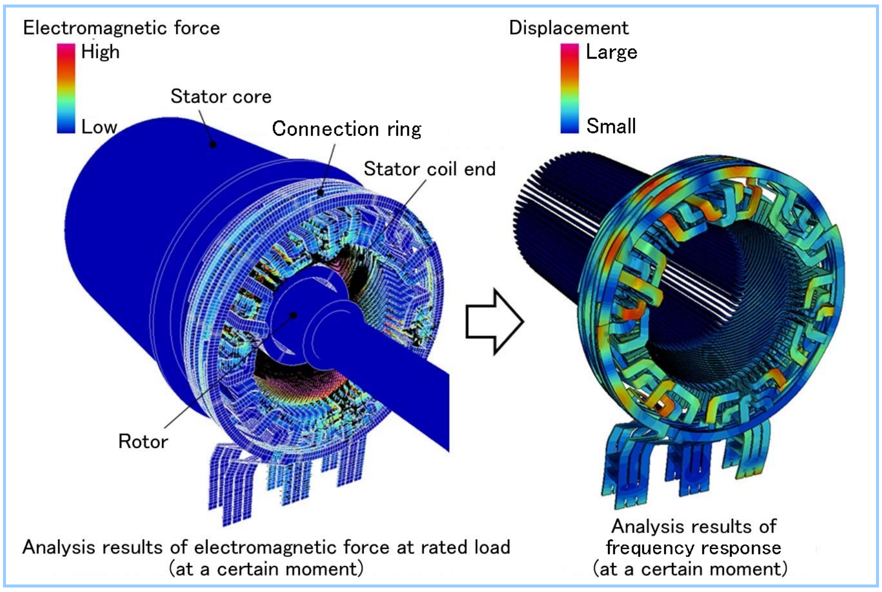

Figure 2 Frequency response analysis with electromagnetic force analysis at stator coil end

3. Actual equipment verification of High Heat Transmission® on 600 MVA class generator

High Heat Transmission®, which improves the stator coil cooling performance, is a key technology among the technologies for increasing the capacity of indirect hydrogen-cooled turbine generators. Here are shown the results of verification of the cooling performance using actual equipment rotation tests performed with a 600 MVA class turbine generator equipped with MHPS's proprietary High Heat Transmission®.

The stator coil has a high voltage of several tens of kV and the coil is protected with an insulation layer. As shown in **Figure 3**, the heat generated in the strand conductor of the stator coil of the indirect hydrogen-cooled turbine generator is cooled with hydrogen gas through the insulation layer. The thermal conductivity of the insulation layer is about one-thousandth of that of the strand conductor, and therefore the improvement of the thermal conductivity of the insulation layer enhances the cooling performance of the stator coil. High Heat Transmission® improves the heat transmission rate of the insulation layer by about three times higher by adding high thermal conductive micro filler to the insulation layer. To date, the evaluation of the thermal, electrical, and mechanical basic characteristics and long-term reliability of High Heat Transmission® has been completed[2], and now High Heat Transmission® is in the phase of application to actual equipment. The heat transmission rate is a parameter indicating the cooling performance obtained by dividing the thermal conductivity by the insulation thickness of the stator coil. Because the cooling performance is enhanced not only by the improvement of the thermal conductivity of the insulation, but also further through the reduction of the insulation thickness due to the improvement of the electrical insulation characteristics, it is evaluated not by the thermal conductivity, but also by the heat transmission rate which includes the effect of both thermal conductivity and the thickness of the insulation layer.

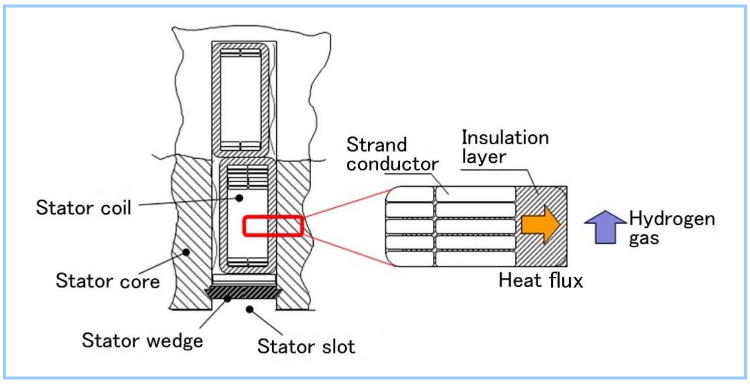

Figure 3 Cross section of stator coil

Figure 4 Actual equipment verification test of High Heat Transmission®

To verify the cooling performance when High Heat Transmission® is applied to a large-capacity indirect hydrogen-cooled generator, an actual equipment verification test was carried out using a 600 MVA class turbine generator equipped with High Heat Transmission® (**Figure 4**). Before the actual equipment verification test, the improvement of the cooling performance of High Heat Transmission® was predicted by network analysis[3] (analysis that models the ventilation and the heat transfer path in a generator using a network). The analysis results are indicated by the solid line and the dotted line in Figure 5. With this design, it is expected that the strand temperature rise of the stator coil of High Heat Transmission® can be reduced by about 40% in comparison with that of conventional insulation. The actual measurement values of the strand temperature rise of the stator coil obtained by the actual equipment verification test are indicated by the circles in **Figure 5**. The measured values of the temperature rise roughly correspond to the analysis values at both the inside of the stator slot and the stator coil end, and it was verified that the stator coil of High Heat Transmission® has cooling performance as predicted by the design.

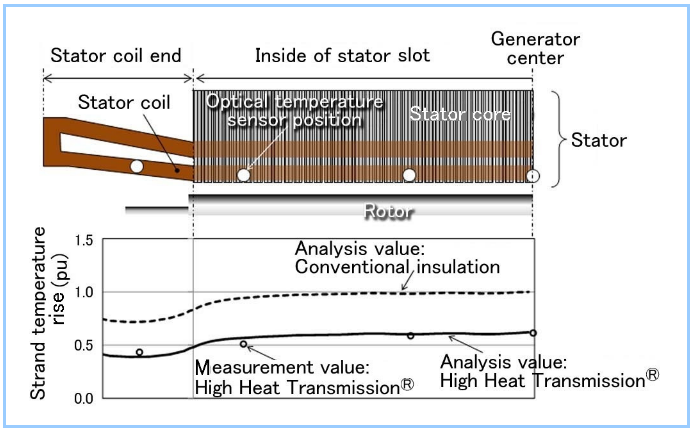

Figure 5 Analysis of stator coil strand temperature and measurement results

From the above, the feasibility of the 900 MVA class indirect hydrogen-cooled turbine generator[1] was confirmed and the improvement of the cooling performance due to High Heat Transmission® was verified.

4. Application of technologies to service field

MHPS has been actively applying the latest technologies developed for new generators to the generator service field, and has developed inspection and monitoring technologies unique to the service field. **Table 1** shows the latest technologies applicable to the generator service field. This section presents the items marked with an asterisk in Table 1, including an example in which the developed High Heat Transmission® was applied to an existing generator to reduce the stator coil temperature.

Table 1 Latest technologies for generator service

No.	Kind of technology	Item
1	Temperature reduction and reliability enhancement of stator coil	*High Heat Transmission®
		*Optimization of stator strand arrangement
		Inner corona shield (enhancement of insulation characteristics)
2	Quantitative evaluation of remaining insulation life, Optimization of part replacement timing	*Diagnosis of stator coil insulation and quantitative evaluation of remaining insulation life
		*Digital Wedge Tapper® (Diagnosis of stator wedge looseness)
3	Increase of generator capacity	Stator coil end elbow made of stainless steel
		Structure for enhancement of generator terminal cooling
		Structure for reduction of stator coil end vibration
4	Repair of generators manufactured by other companies	*Check of interference and fitting of parts using 3D scans and 3D CAD

4.1 Technologies for temperature reduction and reliability enhancement of stator coil

By reducing the temperature of the stator coil of an existing generator, advantages such as an extension of the insulation life and enhancement of the generator output are expected. Therefore, even in existing generators, stator coil rewinding has been performed using the stator coil to which High Heat Transmission® and/or the optimization of the strand arrangement are applied, aiming at temperature reduction. For example, we expect an indirect hydrogen-cooled generator of 160 MVA to reduce the strand temperature of the stator coil by about 40% through the use of High Heat Transmission® and the optimization of strand arrangement. Technologies for optimizing the strand arrangement include the reduction of the circulating current by improving the strand transposition angle in the slot from 360° to 540° [4] and the reduction of the eddy current by reducing the strand thickness.

The effect of High Heat Transmission® is more significant for indirect hydrogen-cooled turbine generators in comparison with air-cooled turbine generators. This is because the gas temperature rise of an indirect hydrogen-cooled turbine generator is smaller than that of an air-cooled turbine generator, and the thermal resistance of the main insulation is dominant over the stator coil temperature rise. For some existing generators, it is estimated that their strand temperature may exceed the limit temperature according to re-engineering results. In this example case of the replacement of the stator coil in an existing turbine generator, the strand temperature rise is estimated to be reduced by 25% due to the application of High Heat Transmission® and the strand arrangement optimization technology, even though the generator is air-cooled, and the temperature is expected to be within the limit value. The results of the temperature study using network analysis are shown in **Figure 6**.

With this technology, it becomes possible to improve the performance including the reduction of the temperature, the enhancement of reliability, and the increase of the output simply by replacing parts such as stator coils without significantly modifying the generator. High Heat Transmission® has been applied not only to various air-cooled and indirect hydrogen-cooled equipment for thermal power generation, but also to equipment for hydraulic power generation.

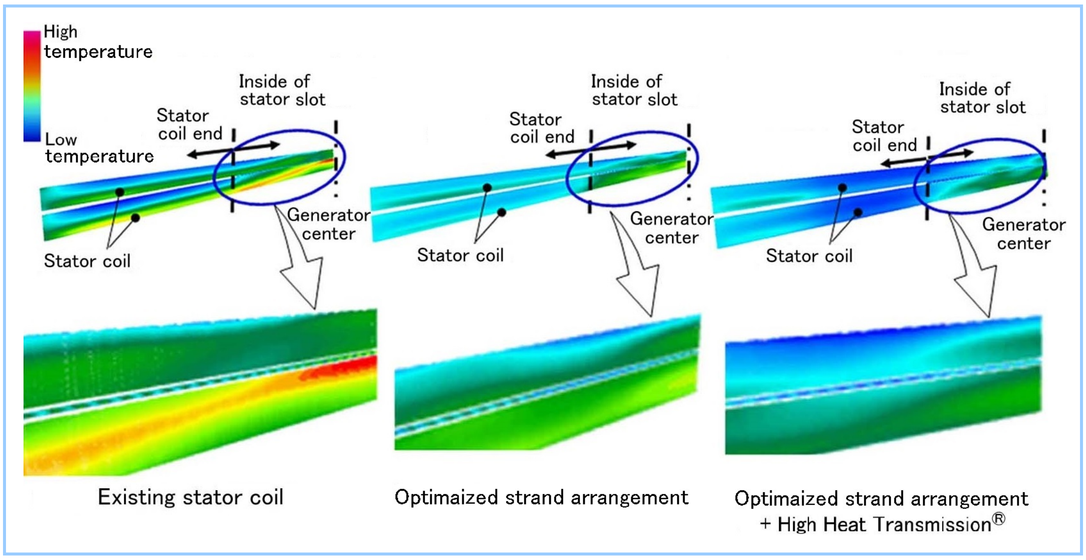

Figure 6 Analysis results of stator coil temperature

4.2 Diagnostic technology of stator coil insulation

The insulation layer of the stator coil of the generator is used in an environment where high voltage, high temperature, and vibrations such as electromagnetic force of the coil are applied. The insulation layer is one of the main components that determine the reliability of the generator, because if the insulation layer deteriorates and a ground fault occurs, the generator is tripped. In addition, the deterioration diagnosis and the remaining life evaluation are important technologies for the evaluation of the reliability of the generator. The stator wedge is used to firmly fix the stator coil within the stator slot. Loosening of the stator wedge may cause wear of the insulation layer and result in insulation breakdown, so the diagnosis of the looseness of the stator wedge in the insulation layer of the stator coil is important. This section introduces the remaining insulation life evaluation method and the stator wedge looseness diagnosis technology.

To accurately evaluate the remaining life of the stator coil insulation, the test results of accelerated deterioration model bars and actual machine sampling bars were compiled in a database and a new quantitative evaluation method of remaining life based on this database was developed.[5] As shown in **Figure 7**, it was confirmed by a comparison between the values of the remaining insulation strength estimated using this quantitative evaluation method and the actual values measured by the test that the accuracy was sufficient to evaluate the remaining insulation life. In addition, the remaining insulation life of the developed High Heat Transmission® can be evaluated using this method. The remaining insulation life evaluation method has already been applied to actual generators.

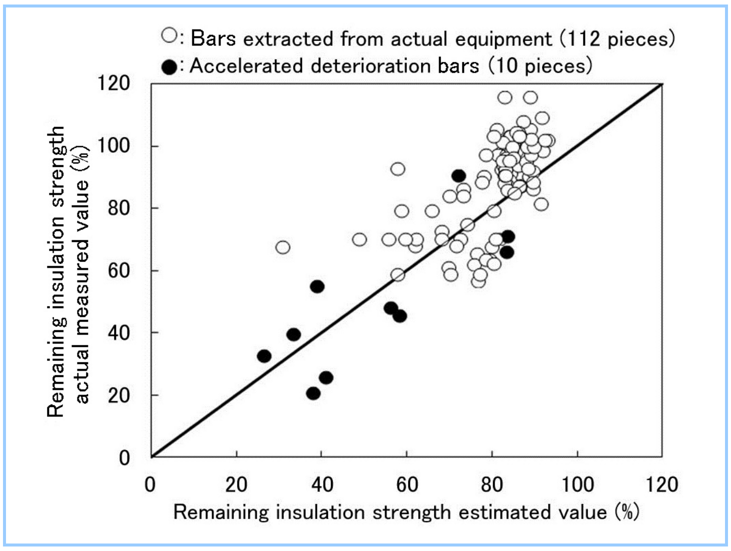

Figure 7 Comparison between values estimated by remaining insulation life evaluation method and measured values

The state of looseness, etc., of the stator wedge is normally evaluated by a sensory test (hammering sound test) performed by a specialist. Because this is a sensory test, however, a subtle difference in judgment between specialists may occur, and it was difficult to create a database of the inspection results without personnel differences. As such, we developed a wedge looseness diagnostic device (Digital Wedge Tapper®) that mechanizes the hammering sound test. **Figure 8** shows the stator wedge looseness diagnosis using Digital Wedge Tapper® and the inspection results. By performing quantitative evaluation of wedge looseness diagnosis using this device, variations in judgment between specialists can be eliminated, and the creation of a database has become easy. Therefore, it is now possible to accurately evaluate the replacement timing of stator wedges.

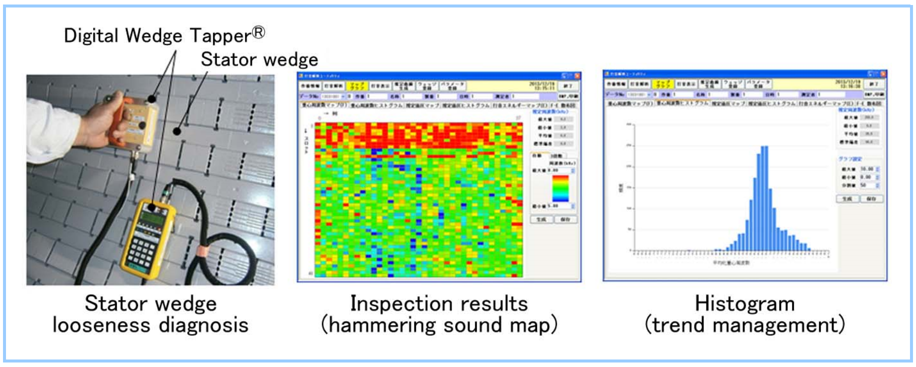

Figure 8 Stator wedge looseness diagnosis (Digital Wedge Tapper®)

4.3 Technology for repair of generators manufactured by other companies

MHPS is working on the development of technologies for the repair of generators manufactured by other companies to meet the repair needs of customers, who possess generators manufactured by other companies that have technical issues. In most cases, design drawings and information on such generators that are necessary for repair work cannot be obtained, and fitting to existing equipment is particularly important. Therefore, we perform 3D measurement using 3D scans on site, and create a 3D model using 3D CAD in the design process to check for interference. As target parts, those with complicated shapes such as connection rings and stator coil end supports, as well as stator coils, can be designed with high accuracy by using three-dimensional models. We have already delivered and installed such parts at sites. **Figure 9** shows an example case of renewing the stator coil of a generator manufactured by other companies. MHPS does not simply repeat the existing design even for a component such as stator coil. We perform comprehensive evaluation based on the electrical design, ventilation and temperature design, as well as the strength and vibration design of the entire generator, and then design, manufacture and supply parts suitable for the generator.

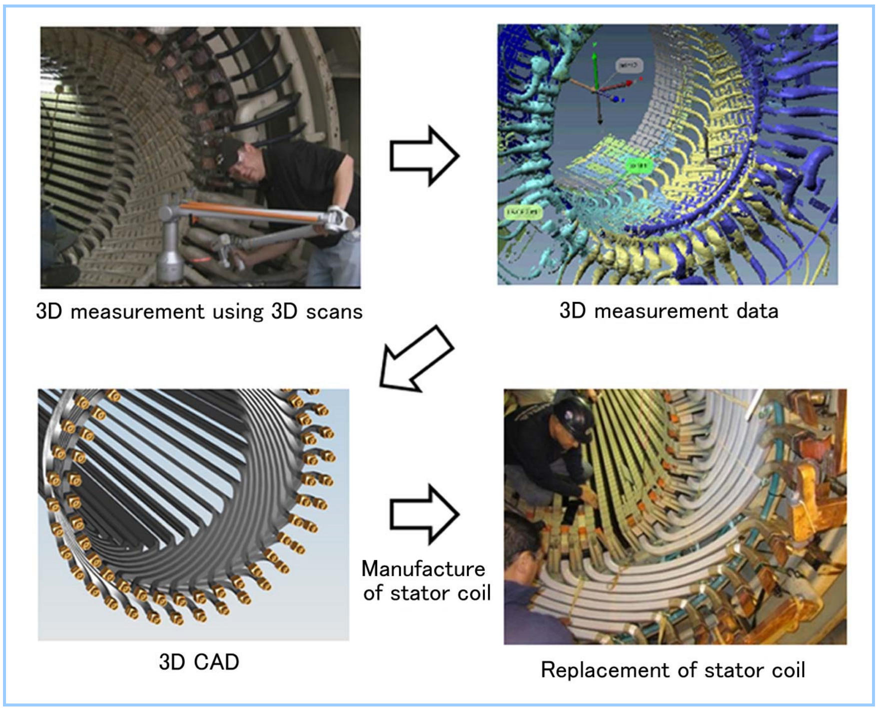

Figure 9 Replacement of stator coil of generator manufactured by other companies

5. Conclusion

MHPS confirmed the feasibility of 900 MVA class indirect hydrogen-cooled turbine generators in a temperature verification test using a 600 MVA class generator equipped with High Heat Transmission®. In addition, we also promote the application of the developed technologies such as High Heat Transmission® to existing generators, and the improvement of the performance characteristics such as temperature reduction, the enhancement of reliability and an increase of the output are made possible by the replacement of parts including the stator coil, etc. In addition, MHPS's other latest technologies for the service field have been applied to actual generators and contribute to the enhancement of reliability.

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