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24kV 蒸发冷却汽轮发电机定子绝缘结构的可行性研究

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FEASIBLE RESEARCH ON STATOR INSULATION STRUCTURE OF 24kV RATED EVAPORATIVE COOLING GENERATOR

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ABSTRACT: It is very difficult for 24kV rated voltage large turbo-generator to be manufactured in China. Because under high voltage, the technology to improve electric field distribution of stator coil in slot and to against corona in slot is hard to finish. By calculative and experimental simulation, this paper analyzed in detail the three-state insulative system consisted of gas, liquid, and solid formed by evaporative cooling mode, including the reliability of its anti-corona and anti-breakdown . This paper offers a new kind of stator insulation structure that is suitable to evaporative cooling mode and can be applied to high voltage level. After a series of researches on insulative characters and laws of the new structure, a conclusion that the new insulative system is feasible to 24kV rated voltage is arrived.

KEY WORDS: Electric machinery; Evaporative cooling; Anti-corona; Stator; Insulation

摘要：国产大型汽轮发电机，很难做到 24kV 电压等级。电压高，定子绕组槽内电场分布的改善及耐电晕等技术处理难度大。该文采用理论计算与模型实验两方面的仿真手段，详尽地分析了蒸发冷却方式下形成的气、液、固三态绝缘体系的耐电晕、耐击穿的可靠性，提出一种适合于该冷却方式的、应用于高电压等级的新型定子绝缘结构，系统地研究了结构的绝缘特点及规律，并得出这一新型绝缘体系对 24kV 电压等级是可行的结论。

关键词：电机；蒸发冷却；耐电晕；定子；绝缘

1 INTRODUCTION

To traditional cooling mode (air-cooled, hydrogen- cooled, water-cooled), there are two bad factors. Firstly the stator insulation can’t be immersed into an insulating medium, so it is difficult to avoid corona problems caused by high electric intensity of air[1]. Statistical datum of world wide show that turbo-generators whose rated voltages are over 18kV brought accidents as their stator insulation have been damaged by corona, and the number of them is about one –third of the whole number of stopping-generator accidents. If the rated voltage is higher than 22kV, it is quite difficult to prevent corona discharge from happening in stator insulation. Secondly, the size of a stator core slot is very small. If the rated voltage is increased, the insulation thickness in a slot is certainly added. That of couse leads to the copper section in slot being decreased, while the heat-transfer from copper getting more and more difficult.

Evaporative cooling is a new advanced method used in large power equipments. Comparing with traditional cooling methods, the superiorities of evaporative cooling are the characters of its cooling medium, which are high insulation performance, low boiling point, and incombustibility. An evaporative cooling medium immerses the whole stator. When the generator is running, part of it will become gas. The admixture of gas and liquid cooling medium will fill all the clearance in slot and stator insulation, so the admixture and the stator coil main insulation form a three-state insulating system consisting of solid, liquid and gas, which offers a precondition for decreasing the thickness of stator coil main insulation[2].

Because the problems of stator coil insulation structure, electric fields and corona presenting in slot and endings and so on haven't been completely solved rightly, up to now, generators of 24kV rated voltage can't be made in China. So this paper, aiming at the actuality, regards the evaporative cooling system as a study object and gives feasible researches on stator insulation of 24kV rated voltage in two facets—calculative simulations and experiments.

2 DESIGN STATOR INSULATION STRUCTURE OF 24kV

An evaporative cooling medium is liquid under natural temperature. If it is purified, its breakdown voltage is a little higher than transformer oil's. Lots of experiments have proved that after a liquid or the mixture of gas and liquid evaporative cooling medium is broken down, it can naturally recover its insulative ability if the breakdown voltage is lowed slightly. Except that the medium has been broken down for so many times in very high voltage that part of it has become charcoal, its breakdown voltage begins to depress gradually[3]. Table 1 lists electric characters of four kinds of evaporative cooling medium. Institute of Electrical Engineering, Chinese Academy of Sciences has accumulated various experimental researches on evaporative cooling system for more than forty years. Their results show that 1. evaporative cooling mediums could bear a part of stator main insulation, furthermore their insulative ability can reach 11kV level under appropriate liquid pressure and insulative space[4]. 2. the anti-corona performance of a stator coil without corona-protective coating into a evaporative cooling medium excels that of a stator coil placed in air with corona-protective coating.

Discharges of stator coils in slots are caused by partial high electric field reaching the breakdown level of air because the dielectric coefficient ε of air is so small compared with that of solid insulative materials, that air electric-fields in the interspaces of solid insulative materials are too high. But air breakdown voltage is much lower than that of solid insulative materials. While to stator coils immersed into an evaporative cooling medium which has high insulative level and relatively high dielectric coefficient ε, all the interspaces in solid insulative materials have been filled by the medium, as a result partial electric fields' focus can be avoided, so the corona can be eliminated to a great degree. Basing on this point, decreasing the thickness of a stator's main insulation immersed into an evaporative cooling medium is completely feasible, meanwhile the cooling effect is also considered. All in all, a new stator insulation structure in the three states insulative system of gas, liquid, and solid material should be design as below: Stator loaders are solid conductors. a) According to rated voltage level, a layer of proper solid insulative material, whose thickness is decreased, is wrapped around a loader, so as to bear part of main insulation action and to avoid impurities in evaporative cooling medium and burrs of stator core from toughing the high voltage copper. Remainder of the main insulation is put on an evaporative cooling medium b) A layer of subsection insulation that is wrapped outside the layer of solid main insulation is used to fix the coil into the stator slot firmly, as shown in figure 1. c) Stator coils have no corona-protective coating. The cross section sketch of the new insulation structure in slot is shown in figure 2. The aim of subsection insulation layer is to put apart spaces in slots for the evaporative cooling medium flowing inside slots circularly, so that the insulating and cooling effects are best. Epoxy glass-cloth reinforced mica-paper tape has been tested in engineering practicing for a long time, and it is very suitable to high voltage level generators. Its manufacture technical is mature, so it is used for the thinner layer of solid main insulation and the subsection layer of fixing insulation. For 24kV rated voltage, we calculate that the thickness of the main insulation layer is 4mm; while the thickness of the subsection insulation layer is 2.5mm, to evaporative cooling mode.

表 1 蒸发冷却介质的电气参数

Tab.1 Electric parameters of evaporative cooling mediums

Electricparameters	Cooling medium			
	R-113	FF31-A	FF31-L	FLa
Breakdownvoltage /kV	37	55	44	40
ε	2.4	1.87	1.711	1.9
tgδ	0.006	0.002	0.0005	0.0001

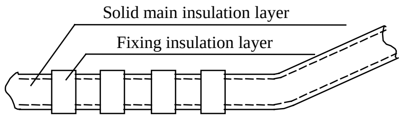

图 1 浸在蒸发冷却介质中的定子绝缘新结构

Fig 1 New stator insulation structure in evaporative cooling medium

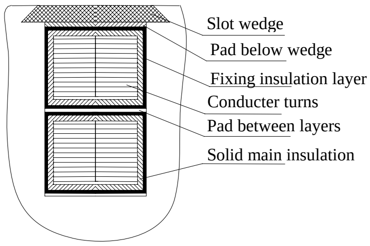

图 2 新型绝缘结构槽内横截面示意图

Fig.2 Cross section sketch of the new insulation structure in slot

3 EXPERIMENTATION RESEARCH ON THE NEW STATOR INSULATION STRUCTURE

As shown in figure 3, the high voltage experimental coil was a flat double fiberglass copper winding with the section size of 12.5mm ×1.45mm wrapped by a 4mm-thick epoxy glass-cloth reinforced mica-paper tape as the solid main insulation layer. Then outside the line section of the main insulation layer, the same insulative material that was 25mm in width was wrapped every other 25mm wide distance, until it was 2.5mm thick, which was regarded as the fixing layer. The winding was placed into a transformer core in E type. They were called the stator model. Then they were put in a high voltage experimental container. Being closed firmly, the container was poured by an evaporative cooling medium— R-113(because it is the cheapest in all the evaporative cooling mediums), until the stator model was immersed completely. The winding was connected with a high A-C experimental transformer through a screw conductor in the container. A grounded point was derived from the core by another screw conductor. Then it was connected to the input of measuring partial discharge equipments through a attenuator.

The experimental processes and phenomena are described below.

(1) Complexion of corona: To the experimental winding marinated in coolant R-113, the DST-2 type equipment of measuring partial discharge was used to measure its maximal discharge quantities q for various levels of voltage[5-9]. When the experiment voltage was raised gradually from 0 to about 12kV, a corona signal emerged but was too weak to be examined and the maximal discharge *q* was 5~10pC. When the voltage was fallen from 12kV to 6kV, the corona signal disappeared. After this phenomenon has been repeated for a few times, the voltage of beginning corona and the one of extinguishing corona almost were the same. When the voltage was raised gradually from 12kV to 40kV, we measured every maximal discharge *q* in the stator model. Now the relationship between *q* and the experiment voltage is drew in figure 5.

(2) Complexion of flashover: When the voltage was raised to be 47kV(last five minutes), no flashover was found. While the voltage continued to rise until it reached 48kV, some flashover signals appeared but were not distinct. When the voltage was fallen back to 47kV, they disappeared. This phenomenon was repeated for several times. The results were also consistent

(3) Complexion of breakdown: When the voltage was raised to be 62kV, the whole insulation system of the model was not broken down. Because the experiment was limited by its capacity, the experimental voltage was only raised to be 62kV.

图 3 实验中的定子模型

Fig. 3 The stator model used in experimentation

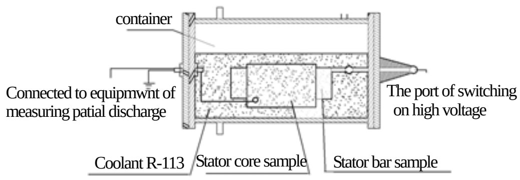

图 4 高压实验装置

Fig. 4　Experiment equipments

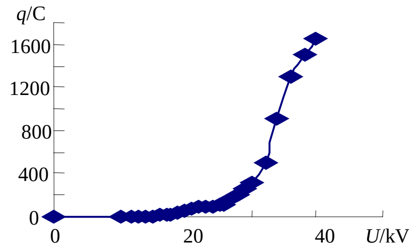

图 5 最大放电量与实验电压的关系图
Fig. 5 The relationship between *q* and voltages

4 CALCULATIVE SIMULATION FOR THE NEW STATOR INSULATION STRUCTURE

4.1 General Review

In order to explain all the phenomena described above, this paper carefully analyzed the electrical fields distribution in stator slot by an engineering software EMAS using finite element method in a workstation computer. We researched the anti-corona property of a high-voltage generator stator in a slot according to electrostatic theories[10-13].

An electrostatic problem of some solution region may be expressed as:

$$\begin{cases} \nabla^2\varphi = -\rho_f/\varepsilon ------(\forall\varphi\in\Omega) \\ \varphi=\varphi_s ----------(\forall\varphi\in\Gamma_1) \\ \partial\varphi/\partial n = 0 --------(\forall\varphi\in\Gamma_2) \end{cases} \quad (1)$$

where ρ_f is the symbol of freedom-charge bulk density in the solution region, ε is the dielectric coefficient symbol, φ_s is the known potential symbol, Ω is the symbol of solution region with a kind of dielectric medium, Γ_1, Γ_2 is respectively the first and the second kind of boundary face or line.

As in our problem, there is no bulk charge, and the finite element method automatically satisfies the second kind of boundary condition, the problem can be simplified as:

$$\begin{cases} \nabla^2\varphi = 0 ------(\forall\varphi\in\Omega) \\ \varphi=\varphi_s -------(\forall\varphi\in\Gamma_1) \end{cases} \quad (2)$$

4.2 CALCULATIVE MODEL OF THE ELECTRIC FIELD IN A SLOT

The electric field distribution of a stator coil in a slot for an evaporative cooling turbo generator was relatively complex. So, basing on actual situations of the generator[2] , this paper made some reasonable hypotheses and boundary-handling described below to the difficult problem:

(1) As shown above, the length of a stator coil in an evaporative cooling generator consists of some groups of a fixing insulation -layer turn width and a space between two of fixing insulation -layer turns. Because of effectively being exchanged their place in slot, all sections of copper coils may be considered to have the same potential namely phase voltage of the stator coil. Therefore we assume that the electric field distributions in every group of fixing layer and the space between layers are independent and the same. As a result, we chose a turn width of the fixing insulation layer and a length of evaporative cooling medium filling in the space between two fixing-layer turns as axis direction of the solution region.

(2) Since the shape of cross section of a stator coil in slot is symmetry, the electric field distribution in it is also symmetry. Then we chose one forth cross section of the solid main insulation of a stator coil in a slot as radial direction of the solution region.

Combining (1),(2) two hypotheses, we put forward the solution region composed by copper surface, solid main insulation layer, cooling medium R-113, fixing insulation layer, and slot wall, which is three dimension. The solution region is shown clearly in figure 6.

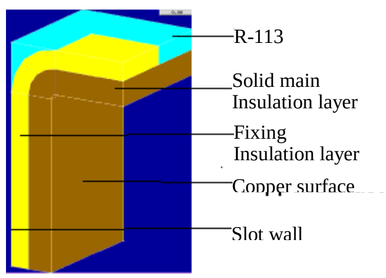

图 6 槽内电场的求解域
Fig. 6 Solution region of electric field in slot

(3) In figure 6, the copper surface is considered as the first kind of boundary condition, its potential is the phase voltage of stator coil; while the slot wall is also such, but its potential is stator core's potential, namely zero 0. Leaving two faces are both electric field symmetry faces, satisfying the second kind of boundary condition, $\partial\varphi/\partial n=0$.

4.3 DISTRIBUTION LAWS OF THE ELECTRIC FIELD IN AN EVAPORATIVE COOLING STATOR SLOT

In order to let the calculative simulation results correspond with the experimental results, this paper calculated every electric field of the solution region for five phase-voltage levels exerting on the stator coil. They were: the voltage of beginning corona 12kV; rated phase voltage 13.9kV, rated voltage 24kV, the voltage of beginning flashover 48kV, and at last the highest experimental voltage 62kV. Now here three important electric field distributions are given in figure7-9.

Tab.2 is the calculative values of the biggest electric field intensity in three medium regions, which are R-113, solid main insulation layer, and fixing insulation layer. From these electric field distributions in an evaporative cooling stator slot, we can see that the focus region of electric field lies in the evaporative cooling medium, while in the solid main insulation layer and the fixing insulation layer the electric field intensity is comparatively much lower and no very high electric field intensities.

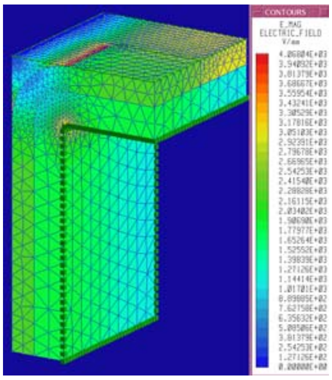

图 7 12kV 电压等级下的电场分布
Fig. 7　Electric field distribution under 12kV

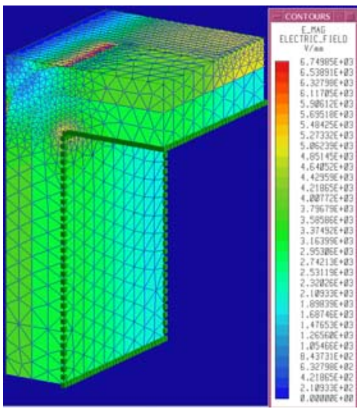

图 8　24kV 电压等级下的电场分布
Fig. 8 Electric field distribution under 24kV

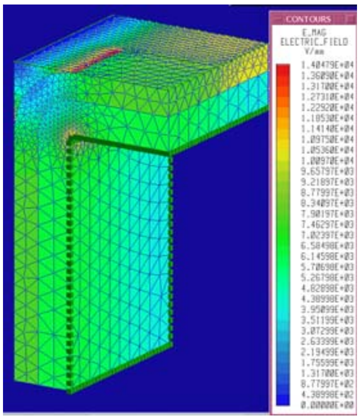

图 9　48kV 电压等级下的电场分布
Fig. 9　Electric field distribution under 48kV

表 2 三个介质区域内最大电场强度的比较
Tab. 2 Comparison among the biggest electric field intensities in three medium regions

High voltage Level /kV	Biggest electric field intensity /(kV/mm)		
	R-113	Solid main insulation layer	Fixing insulation layer
12	4.0680	3.3564	2.2883
24	6.7499	5.2733	3.7969
48	14.0479	10.5364	6.1459

Because an evaporative cooling medium has high ability to against corona and high breakdown voltage level, and furthermore if it is broken down for a not very long time, later it can recover its own insulation character at once, we are certain that the focus region of electric field existing in an evaporative cooling medium don’t affect the whole stator insulation, whereas the corona possibility occurring in all solid main insulations is fallen to the lowest degree. This is the reason why the stator coil immersed into an evaporative cooling medium is cancelled its corona protective coating, and is decreased its insulation thickness more than one third of the original one (The insulation thickness of a 24kV- stator coil is at least 6mm). As for the reason that in the stator model experiment, at 12kV voltage level there was a rather weak corona signal appearing in the evaporative cooling medium, we checked the experimental medium R-113 carefully, and found a little fibers, it might cause small leader channels in a high voltage such as 12kV, and then brought partial discharges in the evaporative cooling medium[11-13]. So, if an evaporative cooling medium is used in a high voltage generator, it should be strictly purified.

5 CONCLUSION

This paper relatively successfully resolves the anti-corona problem in a 24kV rated voltage stator coil in a slot for the evaporative cooling mode, by experimental and calculative two facets simulation. Offering a new kind of stator insulation structure for evaporative cooling turbo-generators, this paper has proved that it is feasible as a 24kV stator insulation structure. The research conclusions can be regarded as a technical project for making the 24kV rated voltage large turbo-generator in China. Also, this paper offers credible research ways for three-state insulation system consisting of gas, liquid, and solid.

REFERENCES

[1] Meek J M, Craggs I D. Electrical breakdown of gases[M]. Oxford University Press, 1978.

[2] Gu Guobiao, Research and development about the application of evaporative cooling technology to 50 MW turbo-generator[J]. Bulletin of Institute of Electrical Engineering, Academia Sinica, July, 1992, 23(5)：1-15.

[3] Luan Ru, Gu Guobiao. Simulating experimentation and analysis of the stator insulation structure for evaporative cooling turbo-generation[J]. Large Electric Machine and Hydraulic Turbine, November, 2002, 165(6)：23-26.

[4] Fu Deping. Feasibility test of insulation structure of 20kV generator with evaporative cooling[J]. Bulletin of Institute of Electrical Engineering, Academia Sinica, June, 1999,32(12)：32-25.

[5] 王建生，邱毓昌，吴向华，等. 用于 GIS 局部检测的超高频传感器频率响应特性[J].中国电机工程学报，2000, 20(8)：42-44.
Wang Jiansheng, Qiu Yuchang, Wu Xianghua *et al*. Frequency response charaterristic of UFH sensor used for PD detection in GIS[J]. Proceedings of the CSEE, 2000, 20(8)：42-44.

[6] Wood J, Hindmarsh R T, Hogg W K. The use of loaded resins for controlling electrical stress in turbo generator insulation[C]. IEEE Conf. Publication 1979,177：144-148.

[7] Laurenceau P, Dreyfus G, Lewiner J. New principle for the determination of potential distribution in dielectrics[J]. Physical Review Letters. 1977, 3(1)：46-49.

[8] 张明超，王建生，邱毓昌. GIS 中局部放电测量用超高频传感器[J]. 电网技术，1998, 22(8)：42-44.
Zhang Mingchao, Wang Jiansheng, Qiu Yuchang. UHF sensors for PD measurements in GIS[J]. Power System Tehnology, 1998, 22(8)：42-44.

[9] Maeno T, Futami T, Kushibe H *et al*. Measurement of spatial charge distribution in thick dielectrics using the P.E method[J]. IEEE Transaction on Electrical Insulation. 1988,5(3)：433-439.

[10] Provos R L. Dielectric stress along insulation surface[C]. 7th BEMA International Electrical Insulation Conference, Brighton, England, 1993：104-110.

[11] Lutz Niemeyer. A generalized approach to partial discharge modeling[J]. IEEE Transaction on Dielectrics and Electrical Insulation, 1995, 2(4)：510-527.

[12] Edward Gulski. Digital analysis of partial discharge[J]. IEEE Transaction on Dielectrics and Insulation, 1995, 2(5)：822-835.

[13] 栾茹，傅德平，唐龙尧. 新型浸润式蒸发冷却电机定子三维温度场的研究[J]. 中国电机工程学报，2003, 24(8)：205-209.
Luan Ru, Fu Deping, Tang Longyao. Study on 3D temperature distribution in new evaperative cooling asynchronous generator[J]. Proceedings of the CSEE, 2004, 24(8)：205-209.

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