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Project Summary of Three Gorges' 840MVA Hydro-generator with Close-Loop-Self-Circulating Evaporative Cooling System

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Abstract – In December 2011 and July 2012, two sets of 840MVA hydro-generator of Three Gorges on Yangtze River with Close-loop-self-circulating evaporative cooling (CLSCEC) system were put into commercial operation. In this paper, we make engineering summary of these two generators with CLSCEC system. We also make a comparison between the internal water cooling (IWC) hydro-generator and the CLSCEC hydro-generator used in Three Gorges power plant in fields of their operating characteristics, working performances, technical features, working safety and reliability. In addition, engineering structures, type tests' results and systematic emulating calculation of CLSCEC schemes are analyzed.

Keywords: Evaporative cooling, Close-loop-self-circulation, Internal water cooling, Temperature rise, Hydro-generator, Three Gorges

1. Introduction

With the hydro-generator's unit-capacity becoming larger and larger, heat loading and stator coils' temperature rise increase rapidly. Finding a way to decrease the temperature rise and to reform temperature distribution has become quite important to the development of hydro-generators. Commonly used cooling methods especially in large capacity generators are air cooling, internal water cooling (IWC) as while as close-loop-self-circulation evaporative cooling (CLSCEC) method.

The CLSCEC tech is an effective way to decrease the temperature rise and to reform temperature distribution. Dislodging IWC system's inherent shortcomings such as high operation pressure (0.6~1MPa), pump forced circulation, oxide damming and water leaking, CLSCEC plans are put forward. The CLSCEC system, a kind of electric machines' inner-cooling mode, adopts high insulating performance coolants with excellent thermal conductance, and especially by using their excellent latent heat of vaporization, heat produced by stator bars can be totally taken away, and its working performance are more excellent than IWC mode, while working in a comparatively much lower working pressure (only 10% of IWC method as less than 0.06MPa) circumstances without applied force than IWC method with.

For more than forty years' concentration research and long-term cooperation with Dongfang Electrical Machinery Co., based on large amount of researches and experimentations, CLSCEC tech has formed a proprietary cooling technology with patented independent intellectual property rights. Since 1980s, in china, this tech has put into practice in two 10MW hydro-generators in Dazhai of Yunnan province, a 52.5MW hydro-generator in Ankang of Shanxi province and a 400MW hydro-generator in Lijiaxia of Qinghai province.

In 2006, we carried out the research of 840MVA hydro-generators with CLSCEC system of Three Gorges on Yangtze River. This research is a project of National Key Technology R&D Program in the 11th Five-year Plan of china.

In December 2011 and July 2012, two sets of 840MVA Hydro-generator of Three Gorges on Yangtze River with Close-Loop-Self-Circulating Evaporative Cooling System were put into commercial operation in succession. The fulfill of these two generators symbols that the use of this cooling tech has been in an industry application period.

2. Operating Principle of Self Circulation Evaporative Cooling System of Hydro-generator

When the evaporative cooling hydro-generator works at a certain load, all stator bars change under the same law as follows:

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The temperature of stator bars increases due to absorbing heat generated by winding copper losses, while by absorbing the heat through specific heat capacity, the coolant inside the hollow conductors of stator bars is gradually raising its temperature along the length of the hollow conductor.

When it reaches the coolant's saturation temperature, in accordance with the local pressure and boiling results, the temperature point at which the major coolant start to boiling is called evaporative point.

Along with the increase of heat absorption of coolant, gas contents increases and gas quality rises. Therefore, gas quality at the exit of stator bar is of an important indicator of thermal load capability. According to boiling heat exchange mechanism, temperature of gas-liquid mixture will no longer rise after the evaporative point and it declines slightly along with decreasing of pressure till to the outlet of bar. Accordingly, temperature of stator bar has the similar typical feature in both change way and distribution so as that temperature of all bars is restricted within the same value and distribution scope by the mode of boiling heat exchange. The components and the working schematic diagram of evaporative cooling system are shown in Fig. 1 and Fig. 2.

Fig. 1. Schematic diagram of evaporative cooling system of a hydro-generator

3. General Designing Plan of the CLSCEC System of Three Gorges' 840MVA Hydro-generator

In electromagnetism design of generators adopting CLSCEC tech, working parameters, structure dimensions and collocation fields and stator coils' temperature are almost the same as generators with IWC method in Three Gorges Power Plant.

In addition, the working pressure of the stator windings' cooling system decreases obviously. So the CLSCEC generator operates in a safe and stable mode from zero to its maximum capacity, especially in accident operating modes.

In structure design, added CLSCEC facilities are assembled at the existing conditions without any large changes, and can be easily maintained, examined and repaired.

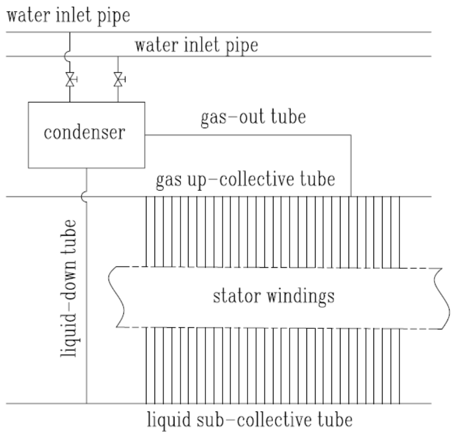

Fig. 2. Sketch of CLSCEC system's structure

In field of cooling circuit of IWC hydro-generators in left and right bank of Three Gorges Power Plant, stator winds are connected in series in parts. While in CLSCEC's design, they are in parallel individually to guarantee these inner-cooling elements can be cooled sufficiently (shown in Fig.2.).

The main differences between IWC and CLSCEC mode in Three Gorges' hydro-generators are shown as in Table 1.

Table 1. Comparisons between IWC and CLSCEC scheme

	CLSCEC Scheme	IWC Scheme
Stator windings' cooling method	Evaporative-cooling	Inner water cooling
Collector rings' cooling method	Air cooling	Inner water cooling
Cooling apparatus including pipes	Condenser	Pure water cooler
Pure water processing system including pipes	No	Yes
Evaporative cooling circulation pipes	Yes	No

The structure of CLSCEC scheme contains seven parts: stator windings' evaporative-cooling system, condenser, pressure-sharing and gas exhaust pipe system, coolant's supply & release system, cooling water supply & release system and CLSCEC system's monitored control system (shown in Fig.3.).

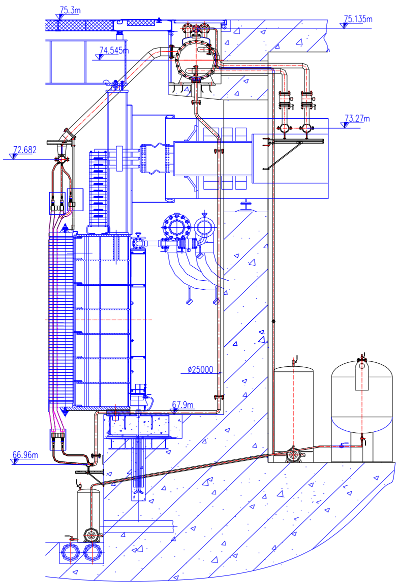

Fig. 3. General engineering assembling drawing of 840MVA evaporative cooling hydro-generator of Three Gorges on Yangtze River

Stator windings' evaporative cooling system contains stator bars, liquid-down pipe, sub&up-annular pipe, sub&up-insulating tube, gas-out tube and condenser (shown in Fig.2). The main differences between IWC and CLSCEC mode in Three Gorges' hydro-generators are shown as in Table 2.

Table 2. Comparisons between IWC and CLSCEC scheme

	CLSCEC Scheme	IWC Scheme
The number of cooling branches	1080 All stator bars are connected in a parallel cooling way	171 168 branches with 6 stator bars connected in series each, and 3 branches with 3 series stator bars each
Working Pressure of inner cooling system (MPa)	Less than 0.08	0.6~1
Driving Mode	No-pump and self-circulation	Pump drive

4. Emulation Calculation and Type Tests Results of the Engineering Design of CLSC Evaporative Cooling Hydro-generator

In order to consummate the engineering scheme, we establish an experimental set: with 18 real Three Gorges' CLSCEC hydro-generator's stator bars and stator core to systematically testify the CLSCEC system. All these structures are the same in physical dimensions as those in real Three Gorges hydro-generators.

Combined with simulating calculation and model experiments, CLSCEC system's liquid level, allowable pressure, stator windings' temperature limit and reasonable cooling-water flux, temperature levels of stator bars in different loads, and the other system parameters are confirmed.

When evaporative cooling hydro-generators are established, a series of type tests are carried out. The error percentage between emulation calculation and type tests results is less than 10%.

4.1 Temperature Limit of Stator Bars

Based on more than 200 teams of testing data of different loads and simulating calculation results, when in evaporative cooling mode, the conductor's temperature of generator stator coils' is less than 65℃ using the coolant complied with environmental requirements. Other kinds of effects such as accident conditions are considered, we deem that the reasonable stator coils' setting alarming temperature is 68℃ (10K higher than the coolant's boiling point).

4.2 Selection of Original Liquid Level of CLSCEC System

The original liquid level of a hydro-generator with CLSCEC system is a very important guideline to decide the cooling ability of the cooling system. Based on the simulation experiments and calculation, we treat some different liquid levels, and finally confirm 4.3m (90% liquid level), the best approximation values between the experiments and calculation, as this cooling system's best liquid level. The testing values, stimulating working conditions of 840MVA, are shown in Fig.4., the highest conductor's temperature along a generator stator coil is only 62.0℃. The simulation calculation results of temperature difference between stator bar and stator core are shown in Table 3.

From these figures in Fig. 4, we can see that the temperature of the hollow and solid conductors is no more than 65℃ when the original liquid level is from 3.9m to 4.3m. These liquid levels are satisfied with the demand of a generator's long term operation. But when the original liquid level is from 3.9m to 4.1m, the temperature of stator bars' upper part could be a little higher than the other parts, while when the original liquid level is from 3.55m to 3.7m, the temperature of stator bars' upper part could be more than 80℃. This is the main reason why we choose 4.3m as the original liquid level of CLSCEC system.

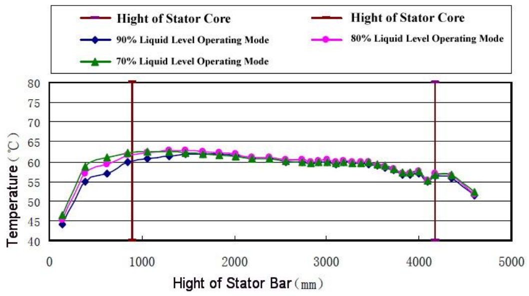

Fig. 4. Temperature distribution curve of stator bars' hollow conductor along vertical length in different static state liquid level (840MVA)

Table 3. Emulating calculation of temperature difference between stator core and stator bar at different generator load

Generator load	840MVA		778MVA		444MVA	
Segment Position	Stator core	Stator bar	Stator core	Stator bar	Stator core	Stator bar
Temperature difference/ K	6.89	8.11	7.73	8.75	7.99	8.44

4.3 Emulating Calculation Results of CLSCEC System

According to evaporative cooling system design scheme, loop emulation calculation of evaporative cooling system at typical generator working load is analyzed. Combined with generator stator windings' evaporative cooling system and stator core air cooling system, the simulation result covers the temperature distribution of stator core and bars, as well as the axial temperature difference distribution between the two.

Then considered the ventilation system design, according to the result of air flow and temperature values of these typical conditions, coupling analysis is conducted.

Selecting the hydro-generator with CLSCEC system at 550MVA, 778MVA and 840MVA working loads to simulate the generator running at low load, rated load and maximum load, operation temperature distribution of stator is calculated. With the match of air cooling system and evaporative cooling system, according to the design scheme of the total air volume, we calculated as followed.

Firstly, use the thermal network method to calculate the air-cooling system in all aspects of the air flow distribution and temperature rise.

Secondly, the impact of air-cooled heat transfer coefficient is mainly reflected in the calculation, and so are the boundary conditions of air temperature and wind values. Therefore the temperature of air gap and air cooler can be given.

Finally, with these calculating results and combined with the simulation results of evaporative cooling system as the boundary condition, the three-dimensional temperature distribution in the stator calculation is carried out. The calculating result of emulating 840MVA working load is shown in Fig.5. ~ Fig.6. and Table 4.

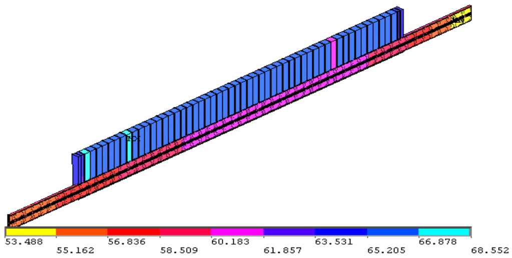

Fig. 5. Emulation calculation result of stator temperature distribution along stator bar in 3D (840MVA)

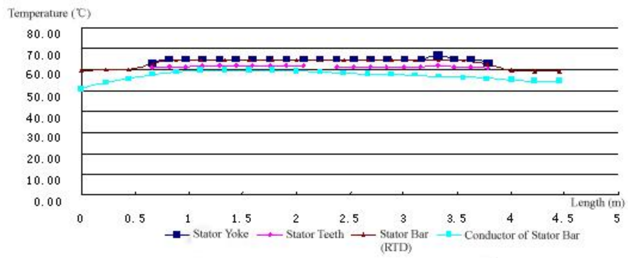

Fig. 6. Emulation calculation result of axial temperature distribution along the hydro-generator (840MVA)

Table 4. Temperature summery of calculating result in 840MVA working load

	Temperature (℃)		
Segment Position	Stator Teeth	Stator Yoke	Stator Bar (RTD)
Max	62.90	68.16	65.58
Avg	62.28	65.87	63.68
	Temperature Difference (K)		
Segment Position	Stator Bar to Stator Teeth	Stator Bar to Stator Yoke	Axial Temperature difference along Stator bar
Max	2.69	2.58	5.31

Also have the experimental solutions (shown in Fig.4. and Table 3) supported these simulation calculation results.

Through analysis and computation, we can see that the evaporative cooling system has almost the same cooling effect compared with the IWC system. Simultaneously, the evaporative cooling system has more even temperature distribution along the circumferential direction than the IWC system, which has at least 4K temperature differences.

5. Operational State & Type Tests Results of the Engineering Design of CLSC Evaporative Cooling Hydro-generator

In December 2011 and July 2012, two sets of the Three Gorges underground power station 840MVA evaporative cooling hydro-generator (shown in Fig.7.) were put into commercial operation on schedule.

Fig. 7. 840MVA CLSC evaporative cooling hydro-generator

As of now, these two units running in good condition, the indicators meet the contract requirements, and the actual cooling effect of the evaporative cooling system has been fully than the capacity of air cooling and IWC generator sets in the same power station. Working temperature of the three kinds of cooling mode hydro-generators are shown in Table 5.

Table 5. Stator windings' operating temperature comparison of three kinds of cooling mode hydro-generator in Three Gorges Power Plant

Generator No.	28F	31F	18F
Cooling Mode	CLSCEC	Air Cooling	IWC
Working Load (MW)	700	682	698
Average Temperature of Stator Core (℃)	56.2	58.1	54.5
Working Temperature of Stator Bar (℃)	56.6~62.2	64.4~71.4	44.8~53.2
Temperature Difference along a Stator Bar (K)	5.6	7	8.4

In May 2012, type tests of 840MVA CLSCEC hydro-generator were carried out and the total number of type tests is 31. These type tests involved maximum load temperature rise test, short-circuit heat-stable at rated load temperature rise test (including two air coolers and a condenser to exit, two air cooler and two condenser to exit running 15 minutes, condensers with no cooling water for three minutes), rated load temperature rise test and other tests associated with cooling mode.

From the type tests results, the superiority of evaporative cooling system's cooling effect has been proved. In all these type tests, the pressure of the evaporative cooling system does not exceed 0.032MPa, and the average temperature of stator windings does not exceed 60℃.

Some typical testing results are chosen as shown in Table 6. The deviation between systematic theoretical calculation and type tests or modeling tests is less than 10%.

Table 6. Thermal stability test results of type tests

		Load Test		840MVA Short Circuit Test
Active Load (MW)		641	701.3	
Reactive Load (MVar)		309.5	342.2	
Current (A)		19.9	21.7	24.4
Temperature of Stator Bars	Max (℃)	61.1	62.2	58.7
	Min (℃)	56.3	56.6	51.9
	Avg (℃)	58.15	58.94	55.87
	Temperature Rise (K)	36.6	37.11	35.82
Temperature Difference of Stator Bars (K)		4.0	4.3	5.2

6. Conclusion

Up till now, two sets of the world's largest evaporative cooling hydro-generator with a capacity of 840MVA of Three Gorges on Yangtze River have been no fault working safely and stably. Especially one of these two sets has been put to use for more than one year and a half.

From the design, simulation calculation and the process of production, installation and commissioning, the use of CLSCEC tech has been in an industry application period.

Furthermore, in terms of the demand for manufacture and maintenance, evaporative cooling system can be designed in a more concise way than water-cooling system.

From type tests results and routine operation records, it shows that CLSCEC tech has its advantages over traditional air cooling and IWC technology, especially in fields of cooling efficient. When working in rated load, the max temperature of stator bars is less than 63℃, and the working pressure of CLSCEC system is normally less than 0.01MPa.

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