

Research on Harmonic Features of High-Power Doubly-fed Hydro-generator

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Abstract: In order to accurately calculate the generator loss, point out the distribution of generator loss and reveal the effect of harmonic magnetic field and other factors to generator loss. In this paper, a 6.5 MW doubly-fed hydro-generator was taken as an example. Time-stepping finite element method was adopted for the numerical simulation of electromagnetic field in generator, and Matlab was used for the Fourier analysis of electromagnetic field in the generator. This paper gave the distribution characteristics of generator loss in different structures, and pointed out the key factor of affecting generator loss. Based on the numerical study results, the generator electromagnetic fields were compared and analyzed when generator used skewed slot, magnetic slot wedge and both skewed slot and magnetic slot wedge. The result that both skewed slot and magnetic slot wedge structure has most benefit to the generator was got. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Doubly-fed hydro-generator, Time-stepping finite element, Iron loss, Harmonic analysis, Structure optimization.

1. Introduction

Doubly-fed hydro-generator power system is a new power generation system. By the combined control of doubly-fed hydro-generator excitation and hydraulic turbine regulation system, the hydro-generator always running in the near unit speed. It improves the efficiency of generator, reduces the hydro-generator damage what is caused by cavitation and increases the stability of power system [1-2]. Therefore, doubly-fed hydro-generator has incomparable superiority and wide application prospect. So it is necessary to analysis and research.

Experts and scholars at home and abroad mainly study working principle and control strategy of doubly-fed hydro-generator at present. For example, reference [3] detailed describes working principle and characteristic of doubly-fed hydro-generator, and provide equivalent circuit and basic equations of doubly-fed hydro-generator. Reference [4] puts forward a self-adaption control strategy using Cerebellar Model Articulation Controller (CMAC), and this control strategy contrasted with conventional PID control to prove feasibility and effectiveness of the control strategy. Reference [5] studies the relationship between static stability and control

feedback factor of adjustable speed doubly-fed hydro-generator power system. The analysis proves that static stability and control feedback factor of the adjustable speed doubly-fed hydro-generator power system are closely related. In recent years, with doubly-fed hydro-generator unit capacity rising, the generator electromagnetic load and thermal load also have significantly increased. Because the generator loss leads to the generator heating, so the generator performance will be influenced. When the phenomenon is serious, the generator will be damaged [6].

Therefore, we need to study electromagnetic loss in the doubly-fed hydro-generator. In order to seek electromagnetic distribution in the generator, and reveal influence of the relevant factor to generator loss. Then the key technology that inhibits generator loss is found. At the same time, doubly-fed hydro-generator output force is promoted, and doubly-fed hydro-generator thermal load is reduced. The paper established a 6.5 MW doubly-fed hydro-generator model, and finite element method was used for simulating to electromagnetic field within the generator. The paper also used Matlab to decompose electromagnetic field within the generator for further analyzing loss variation of the generator, and pointed out the key factors of affecting the generator loss. Based on the results, the generator structure was improved, and some useful conclusions were got. These conclusions have reference value to improve the generator structure and reduce the generator loss.

2. Finite Element Simulation of Doubly-fed Hydro-generator

2.1. Mathematical Model

2.1.1. Boundary Conditions Mathematical Model

In the 2D electromagnetic field, when displacement current is ignored and Maxwell equation is satisfied, the generator electromagnetic field boundary problem can be expressed as follow:

$$\begin{cases} \Omega : \frac{\partial}{\partial x} \left(\frac{1}{\mu} \frac{\partial A_z}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{1}{\mu} \frac{\partial A_z}{\partial y} \right) = -J_z \\ \Gamma_1 : A = 0 \\ \Gamma_2 : A = 0 \\ \Gamma_3 : A_{I1} = -A_{I2} \end{cases} \quad (1)$$

where Ω is the solution area, Γ_1 is the stator outer boundary, Γ_2 is the stator inner boundary, Γ_3 is the model both sides boundary, A_z is the vector magnetic potential on the generator axial direction, A_{I1} , A_{I2} are the vector magnetic potential on both sides of model border, J_z is the current density component on the generator axial direction, μ is the permeability of the medium.

2.1.2. Iron Loss Calculation Mathematical Model Base on Finite Element Method

Previous scholars have proposed many calculating generator iron loss methods. This paper uses an extensive calculating iron loss method. The method is Bertotti constant coefficient trinomial method. The equation can be expressed as follow [7-11]:

$$P_{fe} = k_h f B^2 + k_e f^2 B^2 + k_a f^{1.5} B^{1.5} \quad (2)$$

$$k_e = \frac{\pi^2 \gamma d^2}{6\rho}, \quad (3)$$

where γ is the conductivity, d is the thickness of steel sheet, ρ is the density of ferromagnetic material, k_h and k_a can be acquired by fitting silicon steel sheet measured loss data.

2.2. Fundamental Assumption

To simplify the analysis, the doubly-fed hydro-generator makes some assumptions as follow [12]:

1) We assume that generator magnetic field hasn't change along axial direction, and end inductance is constant. So we will 3D electromagnetic field problem of generator simplify into 2D electromagnetic field problem of generator;

2) External magnetic field of generator is very little, so we ignore it;

3) We ignore temperature effect of conductivity and permeability;

4) Iron core laminations are same character on all directions, and magnetizing curve is single value;

5) We ignore the effect of high harmonic and displacement current in the power grid, and the skin effect that eddy current generate in the winding;

6) We ignore the change of load resistance and inductance in the power grid. We only analyze generator electromagnetic properties with rated load.

2.3. Physical Model

In this paper, 6.5 MW doubly-fed hydro-generator electromagnetic performances were analyzed. The generator stator and rotor windings are star connected. The generator rated voltage, rated frequency and power factor and so on are shown as follow:

Table 1. 6.5 MW doubly-fed hydro-generator main parameters.

Power	Frequency	Voltage	Stator slot number	Rotor slot number
6.5 MW	50 Hz	6300 V	216	144

Based on the above assumptions, the stator and rotor end inductances are constant, and 3D actual model will be simplified into 2D model. Because the generator poles, size and mesh number are all very large. At the same time, calculation is very large and slow. So generator model was simplified using generator periodicity. The simplified model is shown in Fig. 1. As the model is two poles of the generator, so the model is one-twelfth of the entire model.

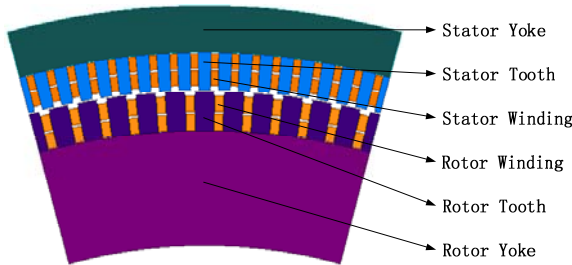


Fig. 1. Doubly-fed hydro-generator model.

2.4. Model Mesh

For considering high harmonic magnetic field and improving the simulation accuracy, the generator stator, rotor and air gap mesh generations were more intensive. So the generator mesh generation is shown in Fig. 2.

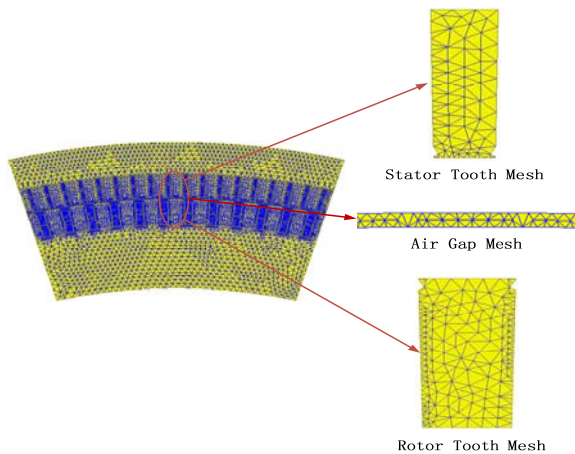


Fig. 2. Model mesh generation.

3. Finite Element Simulation Results and Analysis of Doubly-fed Hydro-generator

3.1. Finite Element Simulation Results

Flux density is the main parameter of generator. That flux density is too high will cause generator saturation, iron loss and harmonic increase and so on. So flux density distribution and air gap flux density

waveform were analyzed with rated load. Flux density distribution with rated load is shown in Fig. 3.

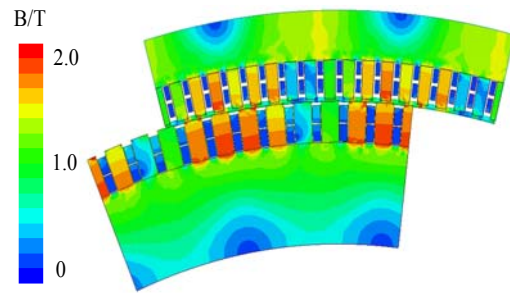


Fig. 3. Flux density distribution with rated load.

As the stator and rotor are parallel grooves, so the tooth is trapezoidal tooth. Therefore, the average flux density at 2/3 of the stator and rotor tooth. So the average flux density is 1.86 T with rated load at the maximum flux density tooth by post-processing. The flux density is slightly saturated.

Fourier decomposition of air gap flux density with rated load is shown in Fig. 4. Fig. 4 shows that the air gap flux density harmonic content is very large. This harmonic can be divided into stator phase harmonic magnetic field, stator and rotor tooth harmonic magnetic field, but the tooth harmonic magnetic field has great influence on the generator. In the high harmonic, $2mq \pm 1$ harmonic is known as the tooth harmonic.

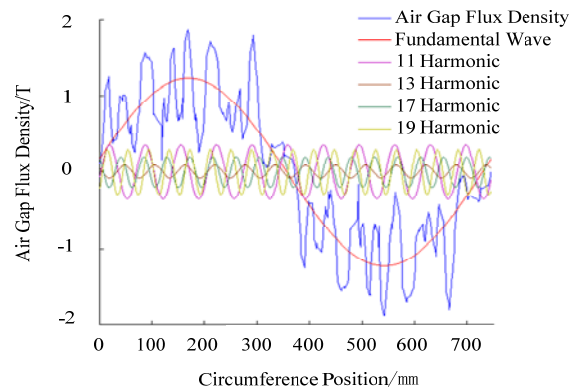


Fig. 4. Fourier decomposition of air gap flux density.

Harmonic amplitude of air gap flux density is shown in Fig. 5. As other harmonic content is very low, so they aren't shown in Fig. 5. Fig. 5 shows that 11 harmonic, 13 harmonic, 17 harmonic and 19 harmonic are larger. These harmonics are tooth harmonic. Because stator and rotor use open slot, and lead to that air gap permeance is nonuniform. So the tooth harmonic is generated. Theoretical and experimental prove that harmonic magnetomotive force will result in many adverse effects. For

example, harmonic magnetomotive force lead loss to increase, then loss increasing makes generator temperature and additional torque increasing and generator efficiency reducing. So tooth harmonic content can't be neglected [13-14].

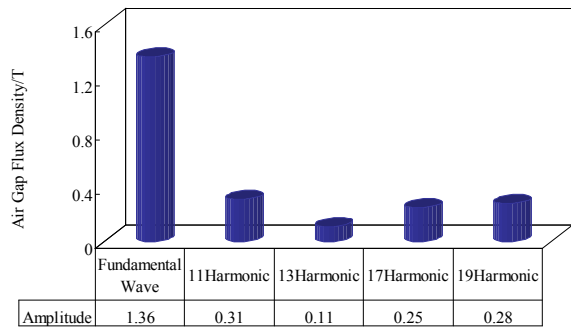


Fig. 5. Harmonic amplitude of air gap flux density.

3.2. The Generator Harmonic Analysis

Iron loss has great impact to generator efficiency and temperature, so the generator iron loss is an important parameter. This paper uses the time-stepping finite element method to calculate the generator iron loss. Equation (2) shows that the generator iron loss and flux density are closely related. The generator iron loss curve is usually a dynamic curve with time change. Previously, we do Fourier decomposition to air gap flux density, then the flux density harmonic is got by the Fourier decomposition. But the flux density harmonic is only a steady state analysis at a moment. Although the flux density harmonic at a moment can also explain the flux density and harmonic distribution in the generator, but if dynamic loss is analyzed by the flux density harmonic at a moment is inadequate. So this paper extracted flux density with time change curves on the generator stator, rotor yoke and tooth, then these curves were Fourier decomposed. The flux density with time change curve showed that 0.96 s- 0.98 s is a period. For making analyzed result more clear, this paper analyzed Fourier decomposed flux density curve at 0.96 s- 0.98 s, and only showed 11 harmonic, 13 harmonic, 17 harmonic and 19 harmonic in the flux density harmonic decomposition figure. Then other harmonic decomposition will be shown in Table 2. The flux density with time change curve and the flux density Fourier decomposition curve on the generator stator, rotor yoke and tooth are shown in Fig. 6-Fig. 9.

Each of flux density harmonic amplitudes on the generator stator, rotor yoke and tooth is shown in Table 2.

The Table 2 shows that flux density of the generator stator and rotor tooth is larger, flux density of the generator stator and rotor yoke is smaller. While a lot of high harmonics in the generator stator and rotor. These harmonics will cause loss on the generator. This paper used the finite element method

and accorded to flux density of the various parts of the generator to calculate the generator loss. The calculation results are shown in Fig. 10 - Fig. 13.

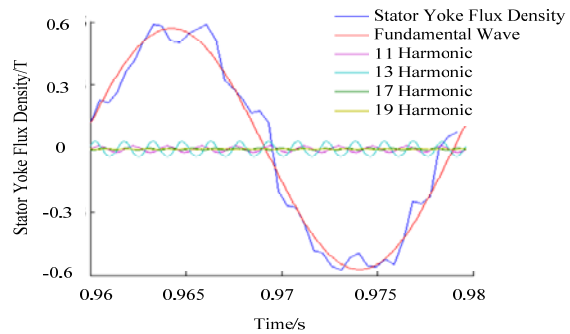


Fig. 6. Fourier decomposition of the stator yoke flux density.

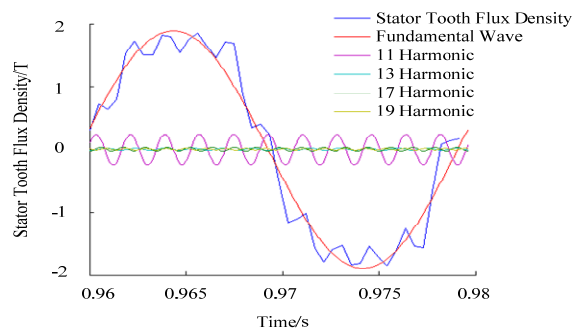


Fig. 7. Fourier decomposition of the stator tooth flux density.

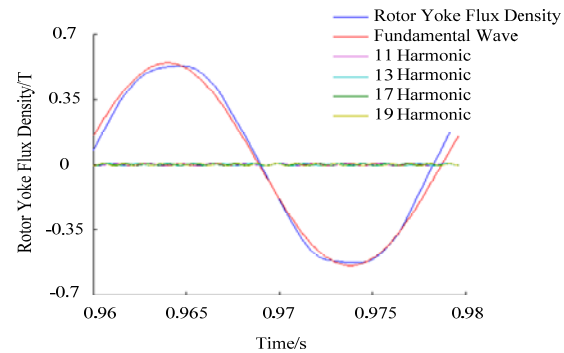


Fig. 8. Fourier decomposition of the rotor yoke flux density.

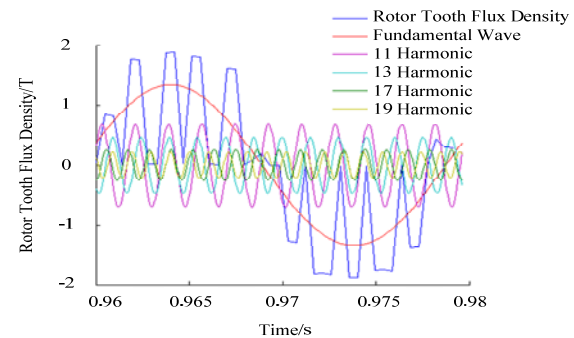


Fig. 9. Fourier decomposition of the rotor tooth flux density.

Table 2. Harmonic amplitude of the various parts of the generator.

	Stator yoke	Stator tooth	Rotor yoke	Rotor tooth
Fundamental wave amplitude/T	0.5699	1.8866	0.6222	1.3313
3 harmonic/T	0.0100	0.1641	0.0159	0.1227
5 harmonic /T	0.0215	0.1010	0.0234	0.0599
7 harmonic/T	0.0038	0.0739	0.0096	0.2086
9 harmonic/T	0.0024	0.0883	0.0073	0.1070
11 harmonic/T	0.0145	0.2440	0.0074	0.6902
13 harmonic/T	0.0364	0.0167	0.0066	0.4696
15 harmonic/T	0.0093	0.0251	0.0041	0.0555
17 harmonic/T	0.0049	0.0297	0.0053	0.2575
19 harmonic/T	0.0028	0.0133	0.0063	0.2210

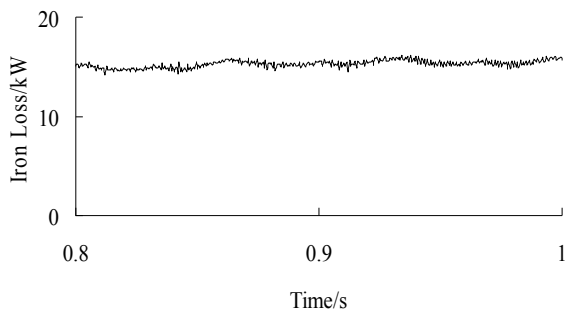


Fig. 10. Stator yoke iron loss.

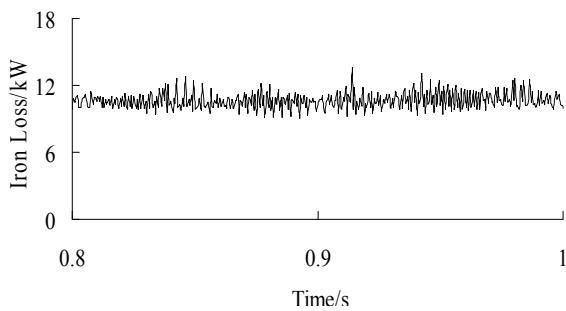


Fig. 11. Stator tooth iron loss.

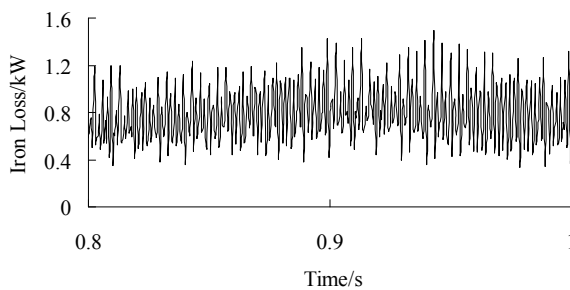


Fig. 12. Rotor yoke iron loss.

Flux density of the various parts of the generator compared with iron loss shows that the relationship between flux density and iron loss is nonlinearity. Iron loss has related with flux density, material property and analyzed region size. So the large flux

density region may have small iron loss. The iron loss curves show that the curves are stable fluctuation at 0.8 s- 1 s. So this paper got the average iron loss on the various parts of the generator. The average iron losses with rated load on the various parts of the generator are shown in Table 3.

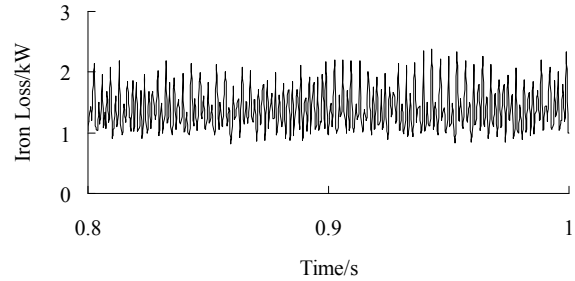


Fig. 13. Rotor tooth iron loss.

Table 3. Iron losses on the various parts of the generator.

	Yoke	Tooth
Stator	15.32 kW	10.64 kW
Rotor	0.80 kW	1.38 kW

Harmonic analysis of the generator stator, rotor and air gap shows that a large of harmonics exists in flux density. These harmonics are mainly $2mq\pm 1$ harmonic. The $2mq\pm 1$ harmonic is called as tooth harmonic. The tooth harmonic cause no-load additional loss to increase, so lead iron loss to increase [15].

4. The Generator Improved Structure Analysis

As tooth harmonic will produce harmonic electromotive force, then increase the generator loss. So weakening tooth harmonic is an important method to improve the generator performance. The tooth harmonic has a characteristic that harmonic winding factor is equal to fundamental wave winding factor. So distributed winding can't weaken tooth harmonic, but skewed slot, semi-closed slot or magnetic slot wedge can weaken tooth harmonic. This paper mainly used skewed slot structure (a rotor tooth skewed), magnetic slot wedge put into stator and rotor rabbet (relative permeability of magnetic slot wedge is 8) and both to improve the generator structure, so that weakened situation of the tooth harmonic was observed. As flux density on the generator air gap can better reflect the generator harmonic situation. So this paper mainly extracted flux density on the generator air gap to observe, and compared three improved structures on the influence of the tooth harmonic. Fourier decomposition of three structures on the generator air gap are shown in Fig. 14 - Fig. 16.

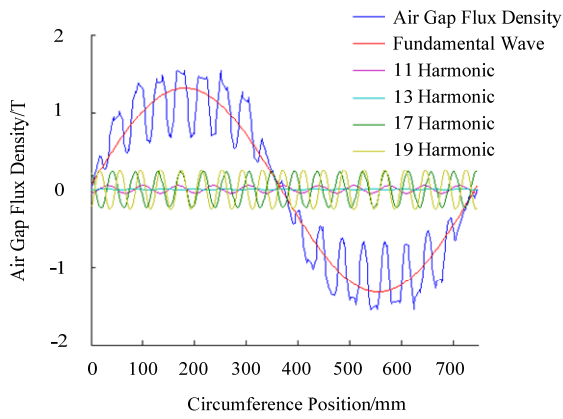


Fig. 14. Fourier decomposition of flux density using skewed slot on the generator air gap.

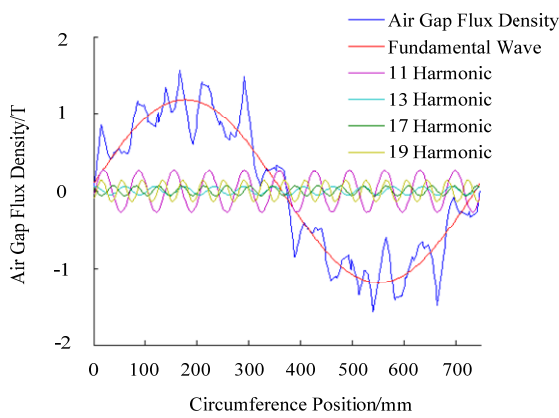


Fig. 15. Fourier decomposition of flux density using magnetic slot wedge on the generator air gap.

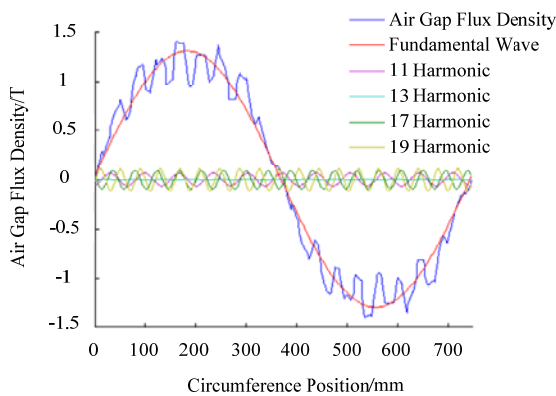


Fig. 16. Fourier decomposition of flux density using both skewed slot and magnetic slot wedge on the generator air gap.

Fig. 14 - Fig. 16 shows that flux density and harmonic content of three improved structures are significantly reduced. Now three improved structures are compared with the original structure. The compare result is shown in Table 4. The project 1 is skewed slot structure, the project 2 is magnetic slot

wedge structure and the project 3 is both skewed slot and magnetic slot wedge structure.

Table 4. Harmonic amplitude of three improved structures compare with harmonic amplitude of original structure.

	Original project	Improved project		
		Project 1	Project 2	Project 3
Fundamental wave amplitude /T	1.3600	1.3157	1.1814	1.3002
Weakened proportion/%		3.26	13.13	4.40
11 harmonic/T	0.3100	0.0483	0.2696	0.0638
Weakened proportion /%		84.42	13.03	79.42
13 harmonic/T	0.1100	0.0108	0.0542	0.0055
Weakened proportion /%		90.18	50.73	95.00
17 harmonic/T	0.2500	0.2286	0.0612	0.0907
Weakened proportion /%		8.56	75.52	63.72
19 harmonic/T	0.2800	0.2492	0.1353	0.1108
Weakened proportion /%		11.00	51.68	60.43

In order to observe the tooth harmonic weakened situation of three improved structure. The harmonic amplitude histogram based on Table 4 is shown in Fig. 17.

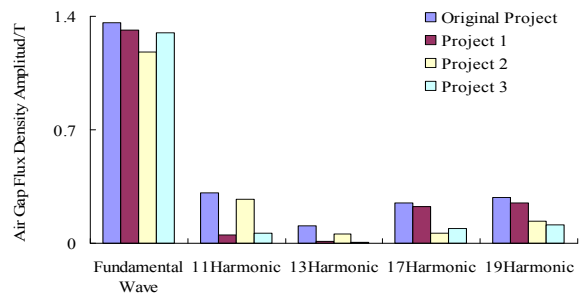


Fig. 17. Harmonic amplitude compare histogram of three improved structure and original structure.

Table 4 and Fig. 17 show that three improved structures weaken tooth harmonic, but also impact fundamental wave. The project 2 has most effect on fundamental wave among three improved projects. The effect can be related with permeability of material. So the study should be done in future. Four projects show that the project 3 most weaken tooth harmonic, and least impact fundamental wave. So the project three is most reasonable and reliable.

5. Conclusion

In this paper, 6.5 MW doubly-fed hydro-generator was taken as an example. This paper used time-stepping finite element method, and analyzed the

generator loss and flux density. Then some conclusions are got.

1) The generator stator and rotor harmonic analysis show that the generator stator and rotor tooth flux density is larger than the generator stator and rotor yoke flux density. But amplitude of each harmonic of flux density on the generator stator and rotor tooth isn't always larger than amplitude of each harmonic of flux density on the generator stator and rotor yoke.

2) The generator loss analysis shows that tooth harmonic cause no-load additional loss to increase, then lead iron loss to increase.

3) Three improved project compared with original project shows that both skewed slot and magnetic slot wedge structure most weaken tooth harmonic, and least impact fundamental wave. So this project is most reasonable and reliable.

This paper analyzed the reason of causing tooth harmonic, and studied the influence on tooth harmonic to the generator. Then this paper proposed three improved projects. The study results have reference value to improve the generator structure and reduce the generator loss.

Acknowledgements

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