No-load voltage and damper winding loss and heat analysis of the pole shoe and damper winding centre line shifted structure of tubular hydro-generators

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Introduction: In recent years, the pole shoe and damper winding centre line shifted structure (as shown in Figure 1) has been applied to optimize the no-load voltage waveform of hydro-generators [1]. However, there is a need to further understand the applicability of this structure, its influence on the loss and heat of damper winding, and whether it can be further promoted and applied. Therefore, it is necessary to implement in-depth analysis of the influence of such a structure on the no-load voltage waveform and damper bar loss and heat.

For the pole shoe and damper winding centre line shifted structure that has been gradually applied in hydro-generator in recent years, this letter selects one real integer and one fractional slot large tubular hydro-generator as examples. Then revealed the influence trends of different shift degrees on the no-load voltage waveform quality and the damper winding loss and heat under rated load conditions. Also, it compared these trends with those of the traditional stator skew 1 slot structure. The results show that for integer slot generator, this kind of shift structure can obtain high-quality no-load voltage waveform close to the traditional stator skewed 1 slot scheme, and the damper winding loss and heat is significantly smaller than the latter. For fractional slot generators, this kind of shift structure will lead to the deterioration of the no-load voltage waveform.

Table 1. Basic parameters of the two generators

| Generator type | SFWG34-44/6020 | SFWG18-68/5700 |
|----------------|----------------|----------------|
| Rated power $P_N$ (MW) | 34 | 18 |
| Rated voltage $U_N$ (kV) | 10.5 | 6.3 |
| Rated power factor $\cos \varphi_N$ | 0.95 | 0.95 |
| Number of magnetic poles $2p$ | 44 | 68 |
| Number of slot per pole per phase $q$ | 2 | $1^{1/2}$ |

Table 2. Structural design scheme

| Structural design scheme | Scheme content |
|-------------------------|----------------|
| Shift pole shoe and damper winding centre line | The shift range of pole shoe and damper winding centre line is 0–0.5$t_1$, the interval step size $\Delta t = 0.025$t_1, no skew stator slot |
| Traditional stator skew 1 slot | Stator skew 1 slot, pole shoe and damper bar centre line no shift |

Necessary explanation before the results discussion: As an important factor that affects the safe operation of generators and electric power communication, the quality of the no-load voltage waveform was defined using the following two parameters as per the Chinese national standard 1029-2005 GB/T [5]. The first parameter is the deviation of the actual waveform from the sinusoidal waveforms of the line voltage, which are defined by the harmonic distortion factor (HDF):

$$HDF = \sqrt{\frac{U_2^2 + U_3^2 + \ldots + U_n^2}{U_1^2}} \times 100\%$$  \hspace{1cm} (1)

The second parameter is the telephone harmonic factor (THF), which quantifies the disturbance of the voltage waveform harmonics in telecommunications:

$$THF = \sqrt{\frac{U_2^2\lambda_2^2 + U_3^2\lambda_3^2 + \ldots + U_n^2\lambda_n^2}{U^2}} \times 100\%$$ \hspace{1cm} (2)
Results and analysis of no-load voltage waveform: Some no-load voltage waveform calculation results are shown in Figures 2–4 and Table 3.

![Fig. 2](image1)  
**Fig. 2** Generator no-load voltage waveform quality (a) SFWG34-44/6020 generator (**q** = 2), (b) SFWG18-68/5700 generator (**q** = 11/2)

![Fig. 3](image2)  
**Fig. 3** No-load voltage waveform (FWG34-44/6020, **q** = 2): (a) Skew 1 slot, (b) shift 0.2 **t**1

![Fig. 4](image3)  
**Fig. 4** No-load voltage waveform (SFWG18-68/5700, **q** = 11/2): (a) Skew 1 slot, (b) shift 0.2 **t**1

![Fig. 5](image4)  
**Fig. 5** Influence of the shift degree on the total loss of the damper winding in a pair of magnetic poles (rated condition): (a) SFWG34-44/6020 generator (**q** = 2), (b) SFWG18-68/5700 generator (**q** = 11/2)

![Fig. 6](image5)  
**Fig. 6** Integer slot generator damper bar temperature distribution (SFWG34-44/6020, **q** = 2, rated condition): (a) Shift 0.2 **t**1, (b) skew 1 slot

Table 3. Comparison of the waveform quality parameters between the integral and fractional slot generators

| Scheme        | SFWG34-44/6020, **q** = 2 | SFWG18-68/5700, **q** = 11/2 |
|---------------|---------------------------|-------------------------------|
|               | HDF (%)       | THF (%)       | HDF (%)       | THF (%)       |
| Shift 0       | 1.89          | 1.17          | 1.65          | 1.25          |
| Shift 0.2**t**1 | 0.85          | 0.67          | 13.05         | 5.45          |
| Shift 0.4**t**1 | 1.18          | 1.04          | 4.09          | 2.17          |
| Stator skew 1 slot | 0.69          | 0.88          | 0.77          | 0.44          |

where **U** is the actual line voltage, **U**i (**i** = 1, 2, 3 ... **n**; **n** is the highest order considered) is the line voltage of the **k**th harmonic, and **λ**_**k** is the weighted coefficient of the **k**th harmonic.

For large generators, the 1029–2005 GB/T regulates HDF ≤ 5%, THF ≤ 1.5% [5].

In the damper winding loss and heat analysis of this letter, Σ**P** is the total loss of the damper winding in the pair of the magnetic pole regions during the rated operation of the generator, and **T**_max and **T**_min are the maximum and minimum temperatures of the damper winding in the above region during the generator’s rated operation, respectively.

Results and analysis of no-load voltage waveform: Some no-load voltage waveform calculation results are shown in Figures 2–4 and Table 3.

In general, regarding the integer slot generator SFWG34-44/6020 (**q** = 2), it can be seen from Figure 2 that with the increase in the shift degree of the pole shoe and damper winding centre line, the HDF and the THF show a trend of first decreasing then increasing, and then decreasing again. When the shift degree is near 0.2**t**1, the waveform quality is the best. As for the fractional slot generator SFWG18-68/5700 with **q** = 11/2, the change in the above two parameters is the exact opposite. When the shift degree is near 0.2**t**1, the waveform quality is the worst.

Based on this, combined with Table 3, more specific situations can be observed.

1. For the integer slot generator SFWG34-44/6020 (**q** = 2), when the pole shoe and damper winding centre line were shifted by 0.2**t**1, the waveform quality was great, where its HDF and THF were only 17% and 44.6%, respectively, of the upper limit required by the Chinese national standard 1029-2005 GB/T. In this case, the waveform quality is not only significantly better than most of the other structural schemes, but it is also very close to the traditional stator skew 1 slot scheme, as shown in Figure 3.

2. For the fractional slot generator SFWG18-68/5700 with **q** = 11/2, when the above shifted structure was adopted, the no-load waveform became worse. And when it was shifted by 0.2**t**1, the waveform quality was worst. The HDF and THF exceeded 161% and 263% of the upper limit required by Chinese national standard 1029-2005 GB/T, respectively. Also, the waveform quality was far inferior to the traditional stator skew 1 slot scheme, as shown in Figure 4.

Some calculation results of damper winding loss and heat underrated condition are shown in Figures 5–7 and Tables 4 and 5.

1. Whether for the integer slot generator SFWG34-44/6020 (**q** = 2) or for the fractional slot generator SFWG18-68/5700 (**q** = 11/2), when
1. Whether it is an integer slot or a fractional slot tubular hydro-generator, when the pole shoes and damper winding centre line shifted structure is adopted, the total loss of the damper winding and the maximum temperature show a rising fluctuation trend with the increase in the shift degree. However, it is worth noting that their value does not change much and that it is significantly smaller than that of the traditional stator skew 1 slot structure.

2. For the integer slot tubular hydro-generator, a better no-load voltage waveform can be realized when the pole shoe and damper winding centre line are reasonably shifted, where the voltage waveform quality almost reaches that of the stator skewed 1 slot structure. However, for the fractional slot tubular hydro-generator, this type of shifted structure can lead to deteriorating the no-load voltage waveform quality. Therefore, for fractional slot hydro-generator, it is still recommended to adopt a stator skewed slot scheme in design and manufacture.

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