Low frequency vibration test on the loosening performance of bolts for towers of power grids

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Abstract. This paper deals with loosening performance of bolts of transmission towers under low frequency vibration. To evaluate the loosening performance, 30 transverse tests for bolted joint are issued, whose frequency ranges from 1 Hz to 3Hz. The results show that double-nut bolts feature better loosening performance than single-nut bolts, and the loosening performance decreases along with the incensement of vibration frequency.

1. Introduction
Many bolts are used in the towers and fittings of overhead transmission lines. Along with the long time operation of power grids, bolts may become loose, which can lead to the clasps of towers and breakage of conductors [1-2]. For instance, conductor galloping may result in tower clasps, and normally we can find some damaged bolts on the ground. If the bolts joints work successfully, the towers could become more stable.

With the aim of evaluating the loosening performance of bolts, many researcher have done a lot of research [3-8]. However, the loosening performance under low frequency is lack of research. In this paper, we focus on the low frequency vibration test to achieve the influence exerted by vibration frequency and nut type on the loosening performance of bolted joints. The results can be utilized for improving the safety and stability of power grids.

2. Transverse vibration test of bolts for towers

2.1 Test Methods
In order to check the loosening performance of bolts, experiments have been conducted, according to the transverse vibration testing method for fasteners. The bolts are fastened to the equipment by specific pretention. Through alternating transversal displacement, the tested bolts can become loose. By checking the change of the residual pretention, we can evaluate the self-loosening performance for vibration frequency, single or double nuts. Figure 1 shows the equipment for the vibration test of bolt and Figure 2 depicts the adjustment of pretentions for bolts.
2.2 Test Conditions

The frequency of conductor galloping ranges from 0.5Hz to 3Hz. Considering the characteristics of the test equipment, the conditions are listed in Table 1, in particular the vibration frequency is 1 Hz, 2Hz, and 3 Hz, respectively. Every test case includes 5 samples, and the vibration takes 4 minutes. The standard torque value is 80N•m and the amplitude is ±1.6mm. For double-nut bolts, the pretention of each nut is same, which is 80N•m too.

| Case No. | Nut type      | Torque value/N•m | Amplitude/mm | Frequency/Hz |
|----------|---------------|------------------|--------------|--------------|
| 1-1      | Single-nut    | 80               | ±1.6         | 1            |
| 1-2      | Single-nut    | 80               | ±1.6         | 2            |
| 1-3      | Single-nut    | 80               | ±1.6         | 3            |
| 2-1      | Double-nut    | 80               | ±1.6         | 1            |
| 2-2      | Double-nut    | 80               | ±1.6         | 2            |
| 2-3      | Double-nut    | 80               | ±1.6         | 3            |

3. Test Results

During the test for each sample, the residual pretentions are measured. The pretentions for samples are different. As a result, we utilize the percentage between the residual pretention at 240m to the pretention as the loosening performance, which is computed as follows.

$$\alpha_F = \frac{\text{residual pretension}}{\text{pretention}} \times 100\% \quad (1)$$
3.1 Test Results of Single-nut

For single-nut bolts, 15 samples test have been conducted, and the experimental pretensions are listed in Table 2, including the residual pretension at 60s, 120s, 180, and 240s, respectively. Figure 3 depicts the time histories of the pretension and the residual pretention percentages of single-nut bolted joint under 2 Hz vibration. It is not difficult to see that along with the increment of vibration frequency, the residual pretention percentages decrease. The highest percentage is 74.8% under 1 Hz vibration, the lowest percentage is 21.4% under 3Hz vibration.

Table 2. Experimental pretentions of single-nut bolted joints.

| Sample No. | Pretention/ kN | Residual pretension/kN | αp/% |
|------------|----------------|------------------------|------|
|            | t=60s | t=120s | t=180s | t=240s | Ave. |
| 1-1-1      | 15.9  | 11.5  | 10.9  | 10.7  | 10.5 | 66.4  |
| 1-1-2      | 18.5  | 14.2  | 14    | 13.8  | 13.8 | 74.8  |
| 1-1-3      | 20.3  | 14.3  | 14.1  | 14.5  | 11.2 | 55.3  |
| 1-1-4      | 21.9  | 13.7  | 12.4  | 11.8  | 11.4 | 52.0  |
| 1-1-5      | 18.8  | 12.3  | 10.1  | 9.0   | 8.4  | 44.9  |
| 1-1-Ave.   | 19.1  | 13.2  | 12.3  | 12.0  | 11.1 | 58.7  |
| 1-2-1      | 17.2  | 13.5  | 11.5  | 10.5  | 9.9  | 57.6  |
| 1-2-2      | 17.7  | 11.1  | 9.1   | 7.5   | 5.8  | 32.8  |
| 1-2-3      | 17.7  | 13.4  | 12.3  | 11.6  | 11.1 | 62.9  |
| 1-2-4      | 20.5  | 14    | 13    | 12.2  | 11.3 | 55.2  |
| 1-2-5      | 21.9  | 15    | 14.3  | 13.7  | 13.1 | 59.6  |
| 1-2-Ave.   | 19.0  | 13.4  | 12.0  | 11.1  | 10.2 | 53.6  |
| 1-3-1      | 19.1  | 6.3   | 2.6   | 2.2   | 2.1  | 10.9  |
| 1-3-2      | 16.9  | 11.7  | 10.9  | 10.5  | 10.1 | 59.9  |
| 1-3-3      | 19.1  | 15    | 14.6  | 14.3  | 13.9 | 73.1  |
| 1-3-4      | 16.3  | 11.4  | 10.0  | 9.2   | 7.7  | 47.1  |
| 1-3-5      | 19.6  | 7.3   | 5.7   | 4.6   | 4.2  | 21.4  |
| 1-3-Ave.   | 18.2  | 10.3  | 8.8   | 8.2   | 7.6  | 42.58 |

(a) Residual preload
Figure 3. Time histories of the pretention and the residual pretention percentages of single-nut bolted joints under the 2 Hz vibration.

3.2 Results of Double-nuts

For double-nut bolts, 15 samples test have been conducted, and the experimental pretensions are listed in Table 3, including the residual pretention at 60s, 120s, 180, and 240s, respectively. Figure 4 depicts the time histories of the pretention and the residual pretention percentages of single-nut bolted joint under 3Hz vibration. It is not difficult to see that along with the increment of vibration frequency, the residual pretention percentages decrease too. The highest percentage is 76.8% under 1Hz vibration, and the lowest percentage is 48.2% under 3Hz vibration, which is similar to the single-nut bolts.

Table 3. Experimental pretentions of double-nut bolted joints.

| Sample No. | Pretention/kN | Residual pretension/kN | α_f / % |
|------------|---------------|------------------------|---------|
| 2-1-1      | 23.3          | 18.8                   | 17.9    | 17.4 | 16.1 | 69.0 |
| 2-1-2      | 19.2          | 15.1                   | 14.7    | 14.5 | 14.4 | 74.6 |
| 2-1-3      | 23.8          | 19.7                   | 18.9    | 18.5 | 18.2 | 76.5 |
| 2-1-4      | 17.7          | 14.3                   | 14.2    | 13.7 | 13.6 | 76.8 |
| 2-1-5      | 18.6          | 14.7                   | 13.9    | 13.3 | 12.9 | 69.2 |
| 2-1-Ave.   | 20.5          | 16.5                   | 15.9    | 15.5 | 15.0 | 73.2 |
| 2-2-1      | 18.7          | 15.4                   | 14.0    | 13.7 | 13.5 | 72.0 |
| 2-2-2      | 24.0          | 18.1                   | 17.4    | 16.9 | 16.6 | 69.3 |
| 2-2-3      | 21.9          | 17.3                   | 17      | 16.9 | 16.8 | 76.7 |
| 2-2-4      | 19.0          | 15.9                   | 15.9    | 15.8 | 14.5 | 76.5 |
| 2-2-5      | 22.0          | 15.5                   | 14.7    | 14.4 | 14.1 | 64.1 |
| 2-2-Ave.   | 21.1          | 16.4                   | 15.8    | 15.5 | 15.1 | 71.7 |
| 2-3-1      | 20.3          | 15.3                   | 14.9    | 14.7 | 14.4 | 71.0 |
| 2-3-2      | 22.1          | 17.2                   | 16.8    | 16.6 | 16.6 | 74.9 |
| 2-3-3      | 12.9          | 9.7                    | 9.4     | 9.1  | 8.9  | 69.1 |
| 2-3-4      | 22.0          | 14.6                   | 12.8    | 12   | 11.3 | 51.2 |
| 2-3-5      | 21.5          | 13.2                   | 11.4    | 10.6 | 10.4 | 48.2 |
| 2-3-Ave.   | 19.8          | 14.0                   | 13.1    | 12.6 | 12.3 | 62.9 |
Figure 4. Time histories of the pretention and the residual pretention percentages of double-nut bolted joints under the 3 Hz vibration.

4. Discussions
In order to check the influence of vibration frequency and the type of nuts, we summarize the average pretention, average residual pretension for each case, and the results are listed in Table 4. Figure 5 depicts the time histories of the average pretention and the average residual pretention percentages for bolted joints.

For single-nut bolts, the highest percentage is 58.7% under 1Hz vibration, and the lowest percentage is 42.5% under 3Hz vibration. For double-nut bolts, the highest percentage is 73.2% under 1Hz vibration, and the lowest percentage is 62.9% under 3Hz vibration.

It is not difficult to see that, the lowest percentage for double-nut bolts is bigger than the highest percentage for single-nut bolts, meaning that double-nut bolts feature better loosening performance than single-nut.

Table 4. Average pretention and residual pretentions.

| Case No. | Pretention/kN | Residual pretension/kN | $\alpha_r$ /% |
|----------|---------------|------------------------|---------------|
|          | t=60s | t=120s | t=180s | t=240s |
| 1-1-Ave  | 19.1   | 13.2   | 12.3   | 12.0   | 11.1   | 58.7  |
| 1-2-Ave  | 19.0   | 13.4   | 12.1   | 11.1   | 10.2   | 53.6  |
| 1-3-Ave  | 18.2   | 10.3   | 8.8    | 8.2    | 7.6    | 42.5  |
| 2-1-Ave  | 20.5   | 16.5   | 15.9   | 15.5   | 15.0   | 73.2  |
| 2-2-Ave  | 21.1   | 16.4   | 15.8   | 15.5   | 15.1   | 71.7  |
| 2-2-Ave  | 19.8   | 14.0   | 13.1   | 12.6   | 12.3   | 62.9  |
Figure 5. Time histories of the average pretention and the residual pretention percentages of bolted joints.

5. Conclusions
In this paper, low frequency vibration test on the loosening performance of bolts for towers of power grids is issued, and the main conclusions are as follows.

(1) For the vibration with low frequency, double-nut bolts feature better loosening performance than single-nut bolts, regardless of the specific vibration frequency.
(2) For the vibration with low frequency, the loosening performance decreases, along with the incensement of vibration frequency.

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