Experiments and simulation analysis of 500kV single-phase three-column transformer in No-load under DC bias

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Abstract. The DC-bias experiments were carried out on two identical single-phase autotransformers which parameters are 250MVA/500kV. The aim of the experiments was to test the ability of transformers for withstanding DC bias. The variation laws of the electrical quantity, the temperature rise, vibration with the increasing DC current under no-load are obtained. The effective value of the exciting current under DC bias is much higher than the normal no-load exciting current. The reference for the DC bias experiments of large transformers can be provided through this method.

1. Introduction
When HVDC (High Voltage Direct Current transmission) system is under the influence of geomagnetic storm or under the monopolar operation mode, there may be DC current flowing into the neutral point of the transformer, which may cause the DC bias problem of the transformer. It may lead to harmonic content, higher reactive power consumption, vibration, noise enhancement, local hot spots and other problems that affect the safe and stable operation of the transformer[1-5].The methods to avoid DC bias have been proposed [6], [7]. A method was proposed to analyze the ability to withstand dc bias in transformers and an experiment obtain the transformer over-excitation multiples[8].
In order to provide a reference for actual transformer under the influence of DC bias, a DC bias test system is established by two identical single-phase autotransformers with a parameter of 250MVA/500kV. The variation laws of electrical quantity, the temperature rise and vibration with the increasing of DC current are measured and analyzed.

2. Experiment setups
The basic parameters of the transformer are shown in Table.1.

| Type                  | ODFS-250000/500 |
|-----------------------|-----------------|
| Voltage/kV            | (536√3)/(230√3±2.5%)/63 |
| Capacity/kVA          | 250000/250000/80000 |
| Current/A             | 808/1883/1270    |
| Phase                 | Single phase     |
The measurement setups is shown in Figure.1. The low-voltage windings are connected to the AC voltage source in parallel, and the high-voltage windings are connected in series. Therefore, the electromotive force induced in high-voltage windings are counteracted owing to the series connection, so that the DC voltage source can be inserted into the circuit.

Figure.1 Experiment circuit diagram and setups.

The generator in the factory acts as the test power source via a step up transformer, and the capacity of the generator is 30000kVA. The Idc (DC bias current) of 1A, 2A and 3A is applied to the high-voltage series circuit respectively. When the Idc is added to 3A, the voltage waveform distortion rate of the generator reaches 10%, and the rate remains constant as the Idc increase.

3. Electrical quantities under DC bias

Voltage and current waveforms on the low-voltage side of T2 transformer were measured and harmonic analysis was conducted on the voltage and current waveforms, as shown in Figure.2. Figure. 2 shows that the voltage and current waveforms on the low-voltage side of T2 transformer are seriously distorted after DC bias. The current waveform distortion is partly due to the influence of DC bias and partly due to the voltage source waveform distortion.

It can be seen from the harmonic analysis results that the voltage source waveform mainly contains odd harmonic components, and the current waveform contains both odd and even harmonic components. And the higher the Idc., the better effective current value. The effective value of the exciting current under 3A DC bias reached 28A, which is 11.2 times of the normal no-load exciting current (2.5A).
Figure 2 Voltage and current at low voltage side of T2 transformer under different $I_{dc}$

As shown in Figure 3, reactive power increases approximately linearly with the increase of $I_{dc}$. The operating efficiency of transformer will be reduced when DC bias is applied.

Figure 3 Reactive power at low voltage side of T2 transformer

4. Temperature under DC bias
When the transformer reaches the rated voltage of 60% and the regulating coils of the two transformers are only staggered in 1 gear, the capacity of generator is close to full. At this time, the current of the medium-voltage winding is only 10% of the rated current. Due to insufficient generator capacity in the plant, it is impossible to conduct temperature rise test under rated voltage and simulated load.

Finally, 0A, 1A and 2A $I_{dc}$ are applied respectively at the rated no-load voltage, the temperature of top oil ($\theta_{o\_top}$) and cooler inlet ($\theta_{in\_cooler}$) and outlet ($\theta_{out\_cooler}$) of T2 transformer with the increasing of $I_{dc}$ was measured. Temperature data was recorded every 20 minutes.
The circuit of temperature rise test is shown in Figure.1. The loss of T2 transformer under the Idc of 0A, 1A and 2A are 72kW, 82kW and 86kW respectively as shown in Figure.4, which were measured using the power analyzer.

The applied DC current and duration are shown in Table.2. The temperature curves at each measuring point are shown in Figure.5. In addition, the temperature rise test interval between 0A Idc and 1A Idc is 12 hours, during which the transformer is naturally cooled. There is no time interval between 1A Idc and 2A Idc. Since the transformer was not sufficiently cooled at the beginning of the test, the initial temperature of each measuring point was different.

Figure.5 shows that the 0in_cooler is higher than others. Table.3 shows the temperature rise of the top oil relative to the ambient temperature at the moment of 370min. The main heat source in no-load under DC bias test is core loss. As can be seen from Table.3, compared with the case without DC bias, the top oil temperature rise δT_o_top at the 370min moment only increased 1.8℃.

Figure.6 shows the infrared thermal image of the oil tank surface of the transformer at a certain moment under the 2A DC bias. The temperature at the top of the transformer is higher, and the temperature difference between the top and bottom reaches approximately 20℃.

Table.2 Applied DC current and duration

| Idc/A | duration/hour |
|-------|---------------|
| 0A    | 6             |
| 1A    | 4             |

Table.3 Temperature rise of top oil at 370min

| Idc/A | Temperature rise/K | Increment/K |
|-------|--------------------|-------------|
| 0     | 16.4               | 0           |
| 2A    | 18.2               | 1.8         |

Figure.6 Infrared thermal image of T2 transformer at a time in 2A DC bias
5. Vibration acceleration under DC bias
The vibration acceleration was monitored in four typical positions as marked A, B, C, D shown in Figure.7. It shows that the vibration data collection is carried out with a hand-held vibration analyzer and a sensor attached to a mounting magnet based on the principle of piezoelectricity accelerometer. Those sensors can easily obtain the acceleration from the surface of the transformer tanks. The commercial PRUFTECHNIK VIBXPERT® II was selected, which has a frequency range from 10Hz to 10kHZ with a sensitivity of 100mv/g.

The peak value of acceleration waveform at typical positions with DC bias were shown in Figure.8. By comparing the peak acceleration of four positions, it shows the upper area vibrates more severely than lower area, middle area vibrates more severely than the corner, the front vibrates more severely than the side, and the peak value varied greatly from 1.5 m/s² to 19.0 m/s² when a Idc. of 3A added into the high voltage winding. The acceleration waveform of the most severely points A was presented in Figure.9. Then the FFT analysis was carried out to presents the frequency spectrum. Figure.10 shows that the main frequency are even harmonics and mostly concentrated in the first 500 Hz when there is no DC bias, it also summarizes the max magnitude of the harmonics occurred in 400Hz is 0.8 m/s². The FFT analysis shows odd harmonics and high-order harmonic occur and arise sharply under DC bias, the magnitude of biggest harmonic appeared at 450Hz is bigger than 3m/s².

6. Conclusion
The voltage and current on the low-voltage side are distorted under DC bias. The voltage waveform contains many even harmonic components. Both even and odd harmonic components appear in the current waveform. The effective value of the exciting current increases with Idc, the effective value of the exciting current under 3A DC bias reached 28A, which is 11.2 times of the normal no-load exciting current (2.5A).

The main heat source under no-load DC bias test is core loss. The temperature rise of top oil under 2A DC bias at 370min is 1.8°C higher than the case without DC bias.
The most severe vibration occurs in the upper and middle area. There are mainly even harmonics without DC bias current, whereas, the odd and high-order harmonics occur when DC bias current is inserted into the circuit. This research can provide reference for the operation and maintenance of transformers in service.

7. Reference

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