A Novel Sensor to Measure the DC Bias in Distribution Power Transformers

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Abstract. With the advantages of long-distance transmission and correlation of the power system, HVDC project has become increasingly popular of implementation in China. When the HVDC system operated in monopole ground return mode, the DC bias occurred by the accumulated DC current at the point of common coupling of transformers and cause series bad influences to transformer itself. In order to reduce the DC bias phenomena in the secondary side of the transformer, it is of prime need to accurate and fast sense the DC bias. Firstly, this paper narrative the effect of DC bias to transformers. Then, a novel DC bias sensor is raised, which achieve the objective by measuring the DC voltage that across the resistance caused by the following of DC current. Last, simulations are taken to assess the accuracy and validity of the proposed DC bias sensor, and simulation results prove that the proposed sensor can accurately and quickly sense the DC bias.

1. Introduction
In the face of overhaul, commissioning and faults, HVDC transmission system or converter station are in need of maintaining monopolar operation [1-3]. When the HVDC transmission system operates in monopole earth mode, direct current will flow through the AC power transformer with grounded neutral, which will cause the ground potential of the substation around the DC grounding pole to rise. Due to the different degree of the potential rise of the substation at different locations, the potential difference will naturally occur and the current will form a DC circuit along the earth, transformer and line. At this time, the DC current flows into the transformer winding that grounded by neutral point and in high ground voltages, and flows back into the other transformer winding through the conductor, which saturates the transformer magnetism, and then generates a large number of harmonics in the excitation current, which makes the transformer produce DC bias that affects the normal operation of transformer, causing the adverse conditions such as vibration intensification, noise increase, loss increase, etc[4-9]. A schematic diagram of DC bias generation is showed in Fig.1.

With the rapid increase of electric load in recent years, the improvement of transmission voltage level and the increase capacity of power transformer, the phenomenon of DC bias becomes increasingly serious. The proportion of DC current in transformer excitation current is also high up. DC current will offset the operating point of the magnetization curve of iron core, resulting in the magnetic flux in AC transformer core half-saturated and more leakage magnetic flux presented. Since transformer noise and vibration are mainly caused by magnetostriction force in the cores and electromagnetic force in the windings, distorted magnetizing currents will induce numerous high-order harmonic frequency components in the vibration forces[10-11]. Consequently, local overheating, insulation damage, winding deformation, anomalous noise and vibration, which are generated in the transformers, endangering
potentially the safe operation of power systems.

As an important precondition to suppress DC bias in transformers, precise detection of DC bias has attracted many scholars at home and abroad. In high voltage transformers, DC voltage is too small to be detected by traditional detection methods, such as Hall element-based detection methods, which are difficult to identify weak DC voltage from AC voltage. Reference [12] Based on transfer function method, the state of transformer windings is monitored by known signals to detect the existence of DC current. In addition, in the detection method of DC current by measuring DC voltage, the difficulty of measuring DC voltage depends on the magnitude of DC current. Literature [13] detects DC voltage by measuring the whole voltage on the secondary side of the transformer and offsetting the AC component of the whole voltage with an equal and opposite AC voltage produced by the current transformer. However, the AC voltage is failed to completely offset by the current transformer for the current transformer itself is affected by the DC current and errors are existed in the measurement results. Another method is to use a small transformer that connected to the secondary side of the power transformer to extract the DC voltage information [14,15] from the excitation current in the transformer. However, this method is relatively more difficult to implement as the accuracy of DC voltage identification depends largely on how to obtain and process excitation current signals. In this paper, instead of using current transformer, the new DC bias sensor adopts AC cancellation technology based on RLC filter to substantially offset the AC voltage component. As shown in Figure 2, the DC bias can be detected indirectly by measuring the DC voltage, which is able to reflect the saturation degree of the power transformer and cannot affected by transformer rated power.

![Figure 1. The principle diagram of DC magnetics bias](image1)

![Figure 2. AC voltage component attenuation realized by the proposed sensor](image2)

2. DC Bias Sensor

2.1. Principle of DC bias sensor
In order to suppress DC bias in transformer and reduce DC current flowing into transformer, it is necessary to accurately detect the existence of DC bias. DC voltage, generated across the secondary winding when DC current flows into it, is more easily detected than the DC current itself, therefore, the sensor proposed in this paper detects DC bias through measuring the DC voltage across the windings within transformers, and the DC bias detection sensor mainly based on AC cancellation technology, which comprises a second-order RC frequency divider in the front part, a RLC filter in the middle, and an output gain stage in the terminal.

Fig.3 shows the arrangement of the DC bias sensor. The front end of the sensor is a two-stage RC-divider which attenuate the AC voltage component from 380V to 2V within 0.6 seconds under the condition that the DC current component remain unaffected. Although the resistance of the capacitor itself has an effect on the DC current but this is predictable and can be accommodated in the design. The residual AC voltage in the output signal of the two-stage divider is further eliminated by the AC cancellation circuit based on RLC low-pass filter. Finally, the separated DC voltage component is restored through the gain stage in the end. Meanwhile, the output signal of the two-stage divider has been backed up before passing it on to the AC cancellation circuit, which avoids the signal distortion due to load effect, and also plays an important role of protecting hardware.

Fig.4 illustrates the principle of the DC bias sensor. After the measured voltage signal is output from the two-stage RC divider, the AC cancellation circuit takes the input signal along two paths. One path contains an RLC filter to eliminate the DC component from the mixed voltage signal and offer a gain of -1 to the remaining signal. Another path allows mixed voltage signals to flow without a change, at last two paths are added together. Therefore, it is known that the output signal only contains DC voltage component. Positive gain stage at the end of the sensor restores the amplitude of the DC voltage to facilitate comparison with the initial input signal.

2.2. Transfer function of DC bias sensor
Assuming ideal capacitance is used, the transfer function of RC-divider stage is:
Modified transfer function when leakage resistance \( R \) is taken into consideration, is expressed as follows:

\[
\frac{V_i}{V_{in}} = \frac{1}{S^2C_1C_2R_1R_2 + S(C_1R_1 + C_2R_2 + C_2R_1) + 1} \quad (1)
\]

Where:

\[
G_i(s) = \frac{V_i}{V_{in}} = \frac{1}{A + B + C} \quad (2)
\]

\[
A = s^2C_1C_2R_1R_2 \quad (3)
\]

\[
B = s(C_1R_1 + C_2R_2 + C_2R_1 + \frac{R_1R_2}{r}(C_1 + C_2)) \quad (4)
\]

\[
C = (1 + \frac{2R_1}{r} + \frac{R_2}{r} + \frac{R_1R_2}{r^2}) \quad (5)
\]

Transfer function of RLC filter in AC cancellation loop is expressed as follows:

\[
G_2(s) = \frac{v_{out}}{v_i} = \frac{1 + \frac{R_1}{R_3}s^2}{s^2 + \frac{s}{RC} + \frac{1}{LC}} \quad (6)
\]

Hence, the total transfer function of the DC bias sensor is obtained as:

\[
G(s) = \frac{V_o}{V_{in}} = \left(1 + \frac{R_1}{R_3}\right)\left(1 + \frac{G_i(s)}{2}\right)G_2(s) \quad (7)
\]

Gain of the path contains RLC filter in AC cancellation circuit is given by the value of \( G_2(s) \). Its value gives the DC gain at \( S = 0 \) while give the 50Hz gain at \( S = j2\pi \times 50 \) rad/s, that is, \( G_1(0) = 0 \) and \( G_2(j2\pi \times 50) = (-1.00 + j0.00) \). Therefore, the DC bias sensor meets the need of zero gain for DC voltage signal and -1 gain for AC voltage signal, that is, under the condition that in steady state, the 50 Hz AC voltage on the secondary side of the transformer has no effect on the output of the DC bias sensor.

3. Simulation experiments and results

AC voltage on the secondary side remains stable in normal operation of transformer while the DC voltage experiences slight change, which depends on the voltage difference caused by the different potential rise between substations when the HVDC transmission system operates in monopole earth return mode. These changes can be found in the output signal of the DC bias sensor in the form of transient change. Figure 5 shows the response of the transfer function when the DC voltage is 1.25V and the AC component is not included as the step function input. It is observed that the steady state reaches 1.25V at 0.6 seconds. Figure 6 shows the response of the transfer function that the input of step function is a mixture of 1.25V DC voltage and 380V AC voltage, which also reaches 1.25V instantaneously. In the latter case, the peak value is several times of the steady-state value, but the step change of 380V occurs only when the circuit is switched on. By using a signal limiter at the output of the sensor, the peak value can be eliminated without affecting the subsequent output signal.
In order to evaluate the performance of the DC bias sensor, simulations of DC bias detection of transformer are carried out in MATLAB. It is assumed that the capacitance of capacitor C1 and C2 in the RC-divider of the DC bias sensor are both 3μF and the leakage resistance are 53 kΩ, which are effectively regulating the gain setting of the sensor in the final stage. Figure 7 shows the output of the DC bias sensor with the 1.25V(DC) without AC voltage component as step test input, which is founded in consistence with the output of the transfer function. Similarly, Figure 8 shows the output of the DC bias sensor with the DC voltage of 1.25V combined with 380V AC voltage as step test input, which is also consistent with that of the transfer function. As can be seen from Fig. 8, there is an initial inrush peak in the output of the DC bias sensor, which is caused by the 380V AC voltage in the input signal of the sensor, while it is observed from Fig. 7 that there is no such peak. It is known that the peak response can be eliminated by a signal limiter. Therefore, a signal limiter is installed at the output end of the DC bias sensor. Fig. 9 shows the voltage output of the DC sensor with the step input of 1.25V(DC) and without the AC voltage component, and it can be observed from the figure that the output decreased from 1.25V to 0V at 3s.
4. Conclusion
This paper introduces an accurate and fast method for detecting DC bias in transformer. Instead by measuring DC current directly, the DC bias sensor measures DC bias through the detection of the DC bias voltage across the secondary winding of the transformer. The voltage signal is used as input of the two-stage RC-divider, and then the AC cancellation circuit take the voltage signal output from the two-stage RC-divider into two paths. The output signal from the AC cancellation circuit is only the DC voltage signal, and finally the DC voltage signal is restored by the gain stage. In simulations, two kinds
of voltage signals are used as the input of DC bias sensor. One is a step input consisting of only 1.25V DC voltage, the other is a step input consisting of 1.25V DC voltage and 380V AC voltage. The simulation results show that the new DC bias sensor can detect transformer precisely and quickly. Besides, an additional signal limiter at the end of the sensor can effectively remove the initial inrush peak caused by 380V AC voltage.

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