

Simulation study on the frequency response curve of the winding in different kinds of failure

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Abstract. The equivalent circuit model is established to reflect the physical characteristics of the inner winding of the transformer, and then the parameters of the equivalent circuit model are calculated by using the finite element simulation software Maxwell ANSYS. Based on the establishment of the transformer winding equivalent circuit model and the distribution of resistance, capacitance, inductance calculation results, the variation of the distribution parameters of different winding faults is obtained. Use circuit analysis software PSpice and data analysis software MATLAB to simulate and set up the deformation of different types and degrees of transformer winding, such as winding axis shift, winding radial deformation, change of pitch of winding. According to the variation of the distribution parameters, the variation of the frequency response curve of the transformer winding is obtained.

Keywords: transformer winding; finite element modeling; simulation calculation; frequency response curve.

1 Introduction

Transformer is one of the most important electrical equipment in power system, its safe and stable operation is of great significance to ensure the safe operation of the entire power grid [1-2]. In recent years, the transformer fault arises along with the increase of the power system capacity and load. The statistical data shows that winding deformation is one of the leading cause of transformer fault. At the beginning of winding deformation, transformer operation would not be influenced obviously, as well as transformer operation need to be online for a long time. Thus, it is hard to detect winding deformation in time when it begins. Therefore, it is important to detect the winding deformation fault and prevent the accident of the transformer [3].

There is a variety of methods to detect the winding deformation developed at home and abroad[2], divided into non electric measurement such as vibration analysis method [3], ultrasonic method[4], divergent coefficient method and electrometric method such as short circuit impedance method[5]and frequency response analysis[6].

Among those methods, the frequency response analysis has the characteristics of high stability, efficiency, non destruction, economy, simplicity and so on, it is widely applied in transformer testing project.

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And it contains two methods that are Sweep Frequency Response Analysis (SFRA) and Impulse Frequency Response Analysis (IFRA). SFRA is applied widely in China, and China power industry which method has promulgated the standards and IEC standards for it[8-9]. While IFRA is researched and reported abroad frequently, Tom De Rybel who came from The University of Columbia, did a research that the high frequency pulse signal is injected from the end of the casing to the winding, and made the laboratory prototype[10]; and Eduardo Gómez-Luna from The University of Columbia, has been devoted to the study of the frequency response of the transient signal obtained from the transient signal and carried out the verification of simulation and experimental[11-12], May Wang from PowerTech Labs in Canada, proposed the view of using power system transient over-voltage signal to carry out online monitoring of transformer winding deformation, and also conducted a lot of tests[13].

In this paper, the SFRA method is used to detect the winding faults. We used circuit analysis software PSpice and data analysis software MATLAB to simulate and set up the deformation of different types and degrees of transformer winding, such as winding axis offset, winding radial deformation, change of distance between the winding discs. According to the variation of the distribution parameters, the variation of the frequency response curve of the transformer winding is obtained.

2 Equivalent circuit model establishment and simulation of parameters

2.1 Establishment of equivalent circuit model

The magnetic permeability of the core is almost the same as the air under a high voltage frequency (usually above 1kHz). The winding can be regarded as a passive linear distributed parameter network composed of linear resistance, inductance, capacitance. In order to facilitate the calculation, the commonly used centralized parameters instead of the distribution parameters. Because the effect of resistance on the potential distribution is poor, the resistance can be ignored. The simplified equivalent circuit model is a lumped parameter chain network with capacitance and inductance. The equivalent circuit model of the transformer winding is established in the PSpice software. The model is shown in Figure 1 which is a distribution parameter network with 14 discs and 7 stages.

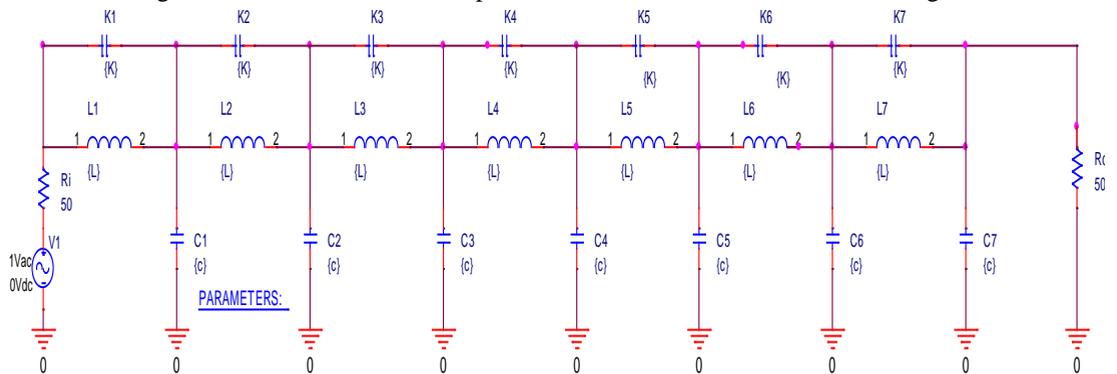


Figure 1. Equivalent circuit model of transformer winding

2.2 Simulation of parameters

The winding model is established by ANSYS software which is shown in Figure 2, then the equivalent circuit parameters of the transformer winding are calculated by the Maxwell ANSYS finite element software as shown in Table 1.

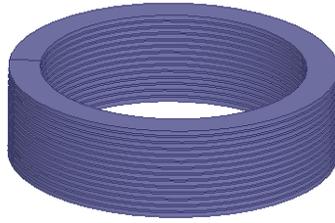


Figure 2. Continuous winding discs model

Table 1. Equivalent circuit parameters of transformer winding

Equivalent longitudinal capacitance K/pF	Ground capacitance/pF	Inductance/ μ H
1089.78	76.18	1045.60

3 Simulation of frequency response characteristic of normal winding

The equivalent circuit model of transformer winding is established by PSpice circuit simulation software. We substitute equivalent circuit distribution parameters into circuit model of winding, then exerting swept-frequency signal at one end of the winding, finally the frequency response curve of the normal winding is obtained which is shown in Figure 3.

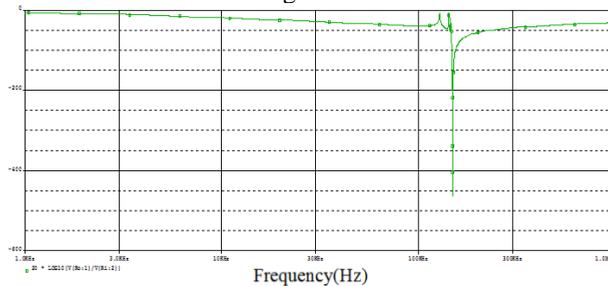


Figure 3. The frequency response curve of normal winding

From Figure 3 we can see that, the frequency response curve of the transformer winding contains resonant and anti resonant points. The frequency response characteristic of the transformer winding is caused by the geometric parameters of the winding. Because the winding is composed of a number of inductance and capacitance parameters, there will be a phenomenon of multi frequency resonance in the transformer. If the series resonance occurs in the winding, the frequency response curve generating peak; on the contrary, if the parallel resonance occurs in the winding, the frequency response curve generating trough. For a fixed transformer winding, its equivalent circuit parameters are determined, so the frequency response curve is uniquely determined. When the winding deformation occurred, the equivalent circuit parameters will change, peaks and troughs of the frequency response curve will also change, that is the resonance point will change. We can analysis the deformation of windings through the change of frequency response curve.

4 Simulation and research on frequency response characteristics of deformed winding

The model of the winding axis deviation, the axial deformation of the winding and the change of the distance between the windings are established by finite element software, and the capacitance and inductance parameters are obtained by simulation. On the basis of this, and then the winding deformation is simulated. By simulating the frequency response curves of the winding deformation

using PSPICE simulation software and exploring winding deformation parameter change frequency response curve change rules, we can get the variation of frequency response curve of the winding in different deformation types and deformation degree as shown in the figure 4.

4.1 High voltage winding axis offset

At present, the transformers are mainly three-phases and three-pillars structure, but the three-phase windings are not symmetrically arranged. Especially for the A phase and C phase winding, it is easy to cause the uneven distribution of the magnetic field on both sides of the core column under the action of the magnetic field of the B phase winding, it will cause the winding to be subjected to one side force which leads to the axis offset of the winding.

The model of the transformer's axis deviation is established by the finite element software Maxwell ANSYS. The top view of high voltage winding axis offset for 35 mm are shown in Figure 4.

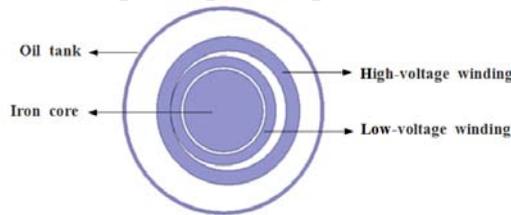


Figure 4. Transformer top view of the winding axis offset for 35mm

The capacitance of the high voltage winding axis offset for 35 mm is shown in Table 2.

Table 2. The ground capacitance of the winding axis offset for 35 mm

Ground capacitance	Before offset/pF	After offset/pF	variation /%
High voltage - low voltage	58.26	156.2	+166.68
High voltage - oil tank	17.92	18.28	+4.00
Total capacitance	76.18	174.48	+126.41

The ground capacitance increased by 126.97% after the high voltage winding axis offset and the capacitance between the high and low voltage windings varies greatly.

The different axis offset from 5mm to 35mm of the high voltage winding are set up, and the corresponding trend of the radial capacitance of the power supply is obtained which is shown in Figure 5.

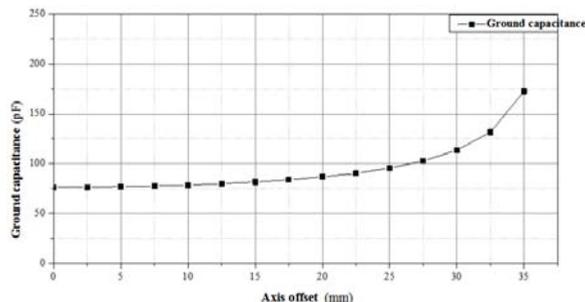


Figure 5. The influence of winding axis offset on the ground capacitance

It can be concluded from Figure 5 that with the increase of the axial offset, the radial capacitance increases, and the growth rate is accelerating.

In order to get the influence of axial offset on the frequency response curve of high voltage winding, the frequency response curves of 15mm and 35mm in two cases were compared and analyzed. And they were compared with the frequency response curve of the normal winding as

shown in Figure 6. The frequency and the amplitude frequency response curve of the resonant peaks and troughs with the change of axial offset are shown in Table 4 and table 3.

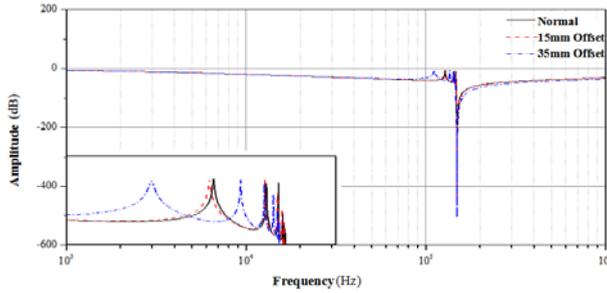


Figure 6. The influence of winding axis offset on frequency response curve

Table 3. The influence of winding axis offset on the crest of frequency response curve

Crest	Characteristic quantity	Normal	Offset	
			15 mm	35 mm
First	Frequency /kHz	128.26	127.70	111.28
	amplitude	-6.03	-6.04	-6.02
Second	Frequency /kHz	144.76	144.56	135.68
	amplitude	-9.84	-7.64	-6.27
Third	Frequency /kHz	145.98	145.88	144.17
	amplitude	-9.27	-7.14	-9.10
Fourth	Frequency /kHz	147.13	147.10	146.64
	amplitude	-35.18	-34.57	-18.09

Table 4. The influence of winding axis offset on the trough of frequency response curve

Trough	Characteristic quantity	Normal	Offset	
			15 mm	35 mm
First	Frequency /kHz	105.03	106.04	78.87
	amplitude	-40.10	-39.89	-35.21
Second	Frequency /kHz	139.25	138.96	128.97
	amplitude	-46.63	-46.40	-40.22
Third	Frequency /kHz	146.98	146.84	140.06
	amplitude	-51.26	-50.97	-46.49
Fourth	Frequency /kHz	146.72	146.66	145.78
	amplitude	-55.16	-56.98	-48.28

In order to research the influence of high voltage winding axis offset unit number on the frequency response curve, we plotted the the frequency response curve of the high voltage winding of which with 3 units and 7 units 35 mm axis offset and the curve of normal winding, they are shown in figure 7. It can be seen from the figure that the movement amount of resonant point to low frequency direction will increase with the aggrandizement of the unit numbers of axis offset.

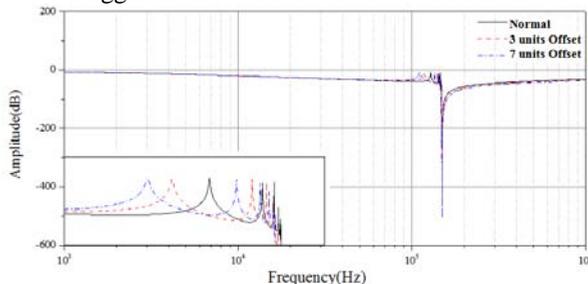


Figure 7. The influence of different elements of winding on frequency response characteristic

4.2 Radial deformation of winding

Because the distribution of magnetic field is different on each point of the discs. Every point of a winding disc can be subjected to different electromagnetic stress, thus the discs may be subjected to different values of the expansion and contraction force. If the force exceeds the yield point of the coil, it will lead to the permanent deformation of the linear cake, such as the winding deformation of plum blossom shape or bulge shape .

The radial deformation model of the transformer which is established based on the finite element simulation software Maxwell ANSYS is shown in Figure 8. We set up four different degrees of radial deformation winding model.



Figure 8. Top view of four kinds of different radial deformation of high voltage winding

The ground capacitance, the equivalent longitudinal capacitance and inductance will change after radial deformation of high voltage winding occurred. The variation curves of the ground capacitance with the radial deformation of the high voltage winding are shown in Figure 9.

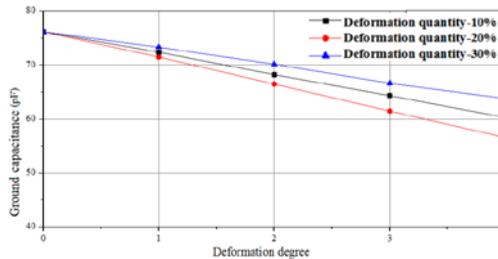


Figure 9. The influence of winding radial deformation on ground capacitance

We can see from Figure 9, Figure 10 and Figure 11 that the ground capacitance decreases with the increase of the degree of deformation, but the equivalent longitudinal capacitance and inductance value increase with the aggrandizement of the degree of deformation and deformation.

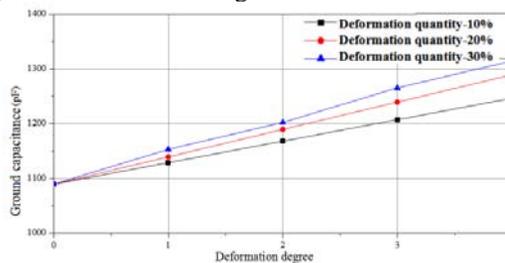


Figure 10. The influence of winding radial deformation on equivalent longitudinal capacitance

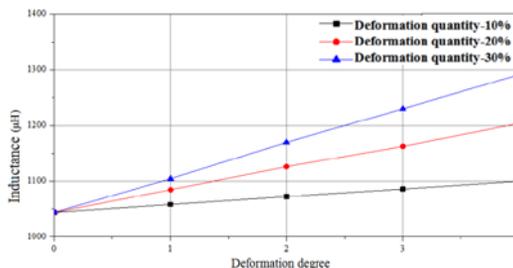


Figure 11. The influence of winding radial deformation on the inductance

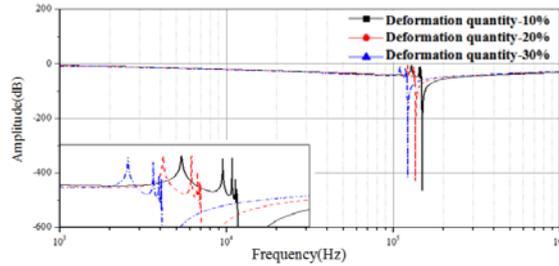


Figure 12. The influence of winding radial deformation on the frequency response curve

The frequency response characteristics of the high voltage winding with different radial deformation (10%, 30%) are compared with that of the normal state which is shown in Figure 12. The frequency response curve shifted to the low frequency due to the high voltage winding radial deformation, and the movement amount increase with the aggrandizement of the deformation quantity. The frequency and the amplitude frequency response curve changes of the resonant and anti resonant point with the degree of deformation are shown in Table 5 and table 6.

Table 5. The influence of winding radial deformation on the resonant crest

Crest	Characteristic quantity	Normal	Deformation quantity	
			10%	30%
First	Frequency /kHz	128.26	121.84	109.45
	amplitude	-6.03	-6.05	-6.16
Second	Frequency /kHz	144.76	131.73	118.39
	amplitude	-9.84	-6.23	-14.06
Third	Frequency /kHz	145.98	135.84	120.28
	amplitude	-9.27	-26.16	-28.40
Fourth	Frequency /kHz	147.13	136.59	120.95
	amplitude	-35.18	-36.50	-39.07

Table 6. The influence of winding radial deformation on the the resonant trough

Trough	Characteristic quantity	Normal	Deformation quantity	
			10%	30%
First	Frequency /kHz	105.03	105.01	96.41
	amplitude	-40.10	-44.24	-44.68
Second	Frequency /kHz	139.25	129.45	116.31
	amplitude	-46.63	-49.33	-49.77
Third	Frequency /kHz	146.98	135.17	119.67
	amplitude	-51.26	-56.05	-56.49
Fourth	Frequency /kHz	146.72	136.31	120.70
	amplitude	-55.16	-57.99	-58.43

In order to research the influence of different element numbers of radial deformation of high voltage winding on the frequency response curve, we plotted the frequency response curve of the high voltage winding which with 30% radial deformation on 3 units and 7 units and the curve of normal winding, they are shown in figure 13. It can be seen from the figure that the movement amount of resonant point to low frequency direction increased with the aggrandizement of the element numbers of radial deformation.

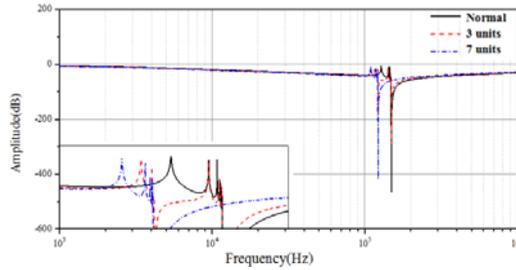


Figure 13. The influence of winding radial deformation with different units on the frequency response curve

4.3 The change of the distance between the high voltage winding discs

The winding discs will not only be subjected to electromagnetic force perpendicular to the axial direction of the core. But also the axial electromagnetic force, if the force is larger than the mechanical deformation stress of the winding, the discs will move. It will cause the change of the distance between the winding discs. When the deformation is more serious, two adjacent discs are likely to fit together, it will cause the damage of external insulation paper and short circuit in two adjacent discs, in a result the transformer ratio will be changed directly, and the normal operation of the transformer will be affected seriously. At the same time, the insulation gasket between the discs will fall off and damage under the action of winding extrusion and friction, seriously affecting the structural stability of the winding.

The model of the variation of the distance between the cakes of the transformer is established by using the finite element simulation software Maxwell ANSYS, it is shown in Figure 14.

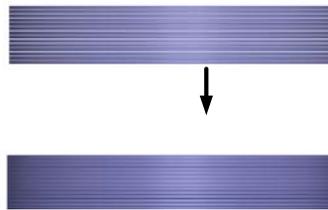


Figure 14. Schematic diagram of the change of the distance between the winding discs

The decrease of the distance between the high voltage windings will lead to the change of the parameters in the equivalent circuit model of the transformer, which is mainly due to the change of the equivalent longitudinal capacitance caused by the capacitance of the discs, as shown in Figure 15. Compared with the normal winding, the decrease of the distance between the discs will lead to the increase of the capacitance, and then lead to the increase of the equivalent longitudinal capacitance.

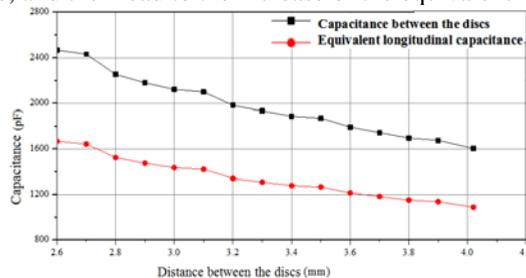


Figure 15. Capacitance between the high voltage winding discs and the equivalent longitudinal capacitance

The influence of different distance of discs on frequency response characteristic is shown in Figure 16.

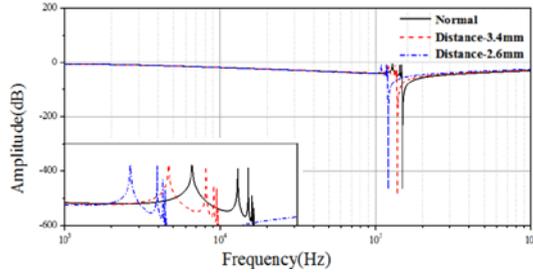


Figure 16. The influence of distance between the winding discs on the frequency response curve

The frequency response curve shifted to the low frequency direction due to the decrease of the distance between the high voltage winding discs, and the movement amount increase with the decrease of the distance between the discs. The frequency and the amplitude frequency response curve changes of the resonant and anti resonant point with the between the discs are shown in Table 7 and Table 8.

Table 7. The influence of distance between the winding discs on the the resonant crest

Crest	Characteristic quantity	Normal	Distance	
			5.4 mm	4.6 mm
First	Frequency /kHz	128.26	120.78	108.79
	amplitude	-6.03	-6.03	-6.02
Second	Frequency /kHz	144.76	134.62	117.19
	amplitude	-9.84	-7.58	-6.80
Third	Frequency /kHz	145.98	135.18	118.96
	amplitude	-9.27	-26.19	-18.86
Fourth	Frequency /kHz	147.13	136.11	119.59
	amplitude	-35.18	-26.97	-28.10

Table 8. The influence of distance between the winding discs on the the resonant crest trough

Trough	Characteristic quantity	Normal	Distance	
			5.4 mm	4.6 mm
First	Frequency /kHz	105.03	101.34	96.41
	amplitude	-40.10	-40.48	-41.14
Second	Frequency /kHz	139.25	129.81	115.27
	amplitude	-46.63	-47.27	-48.30
Third	Frequency /kHz	146.98	136.37	118.41
	amplitude	-51.26	-51.94	-55.04
Fourth	Frequency /kHz	146.72	135.80	119.37
	amplitude	-55.16	-55.86	-56.99

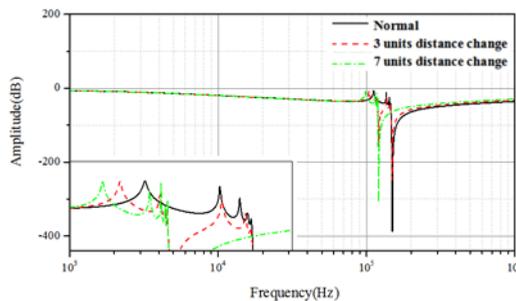


Figure 17. The influence of distance between the winding discs with different number of units on the frequency response curve

The influence of different number of elements on frequency response characteristic of the high-voltage winding is shown in Figure 17. We can know that the more the number of units, the trend of the frequency response curve moving towards the low frequency band is more obvious.

5 Conclusion

The simulation of transformer winding deformation based on the frequency response analysis method has been carried out in this paper and the simulation results are discussed and analyzed. The frequency response curves of three kinds of important winding faults can be obtained through the simulation analysis.

(1) Winding axis offset

The frequency response curve shifted to the low frequency direction due to the winding axis offset, and the movement amount increase with the aggrandizement of the winding axis offset and the number of units. The frequency of resonant peak and trough decrease with the increase of the winding axis offset. The winding axis offset has a great influence on the amplitude of the high frequency resonance point and the frequency of low frequency resonance point.

(2) Radial deformation of winding

The frequency response curve shifted to the low frequency due to the radial deformation of winding, and the movement amount increase with the aggrandizement of the deformation quantity. The frequency of resonant peak and trough decrease with the increase of the deformation quantity. The radial deformation of winding has the same influence on the amplitude and the frequency of the resonance point in all frequency bands.

(3) The change of the distance between the winding discs

The frequency response curve shifted to the low frequency direction due to the decrease of the distance between the high voltage winding discs, and the movement amount increase with the decrease of the distance between the discs. The frequency of resonant peak and trough decrease with the reduce of the distance between the winding discs, but the amplitude of resonant trough is not affected by the deformation.

References

1. M. Bagheri, M. S. Naderi, and T. Blackburn, "Advanced transformer winding deformation diagnosis: Moving from off-line to on-line," *IEEE Trans. Dielectr. Electr. Insul.*, vol. 19, no. 6, pp. 1860–1870, Dec. 2012.
2. Vandermaar A J, Wang M, Srivastava K D. Review of condition assessment of power transformers in service [J]. *IEEE Electrical Insulation Magazine*, **18** 6:12-25, (2002)
3. González C, Pleite J, Valdivia V, et al. An overview of the on line application of frequency response analysis (FRA) [C]. *IEEE International Symposium on Industrial Electronics (ISIE)*, Vigo, Spain, (2007)
4. Bagheri M, Naderi M S, Blackburn T, et al. Advanced transformer winding deformation diagnosis: moving from off-line to on-line [J]. *IEEE Transactions on Dielectrics and Electrical Insulation*, **19** 6: 1860-1870,(2012)
5. Ma H Z, Geng Z H, Chen K, et al. A New Fault Diagnosis Method for Power Transformer Winding Deformation Based on Vibration [J]. *Automation of Electric Power Systems*, **4** 25: 89-95, (2013)
6. Xu D K, Ji S C, Li Y M. A Theoretical Research on On-Line Monitoring of Winding Deformation of Power Transformer [J]. *High Voltage Engineering*, **26** 3: 16-18.(2000)
7. He P, Wen X S. Survey of Frequency Response Analysis on Winding Deformation of Transformers [J]. *High Voltage Engineering*, **32** 5: 37-41, (2006)
8. Gomez-Luna E, Mayor G A, Gonzalez-Garcia C, et al. Current status and future trends in frequency-response analysis with a transformer in service [J]. *IEEE Transactions on Power Delivery*, **28** 2: 1024-1031, (2013)

9. China Electricity Council. DL/T911-2004 Frequency response analysis on winding deformation of power transformers[S].Beijing: China Electric Power Press, (2005)
10. International Electrotechnical Commission. IEC 60076-18 Ed. 1.0 Power transformers - Part 18: Measurement of frequency response[S], (2012)
11. Rybel T D, Singh A, Vandermaar J A, et al. Apparatus for online power transformer winding monitoring using bushing tap injection[J]. IEEE Transactions on Power Delivery, **24** 3: 996-1003, (2009)
12. Gomez-Luna E, Mayor G A, et al. Application of wavelet transform to obtain the frequency response of a transformer from transient signals—Part 1: theoretical analysis [J]. IEEE Transactions on Power Delivery, **28** 3: 1709-1714, (2013)
13. Gomez-Luna E, Mayor G A, et al. Application of wavelet transform to obtain the frequency response of a transformer from transient signals—Part II: practical assessment and validation [J]. IEEE Transactions on Power Delivery, **29** 5: 2231-2238, (2014)
14. Wang M. Winding movement and condition monitoring of power transformers in service [D]. Canada: The University of British Columbia, (2003)