Online State Diagnosis of Transformer Windings Based on Time-frequency Analysis

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Abstract: - The power transformers are the key equipments in the power system. To keep the stable operation of the transformers, it's necessary to get their state information on a real-time basis. Therefore, the efficient online monitoring system is developed which obtain the state of the transformers by the accelerometers attached on the tank. The locations of these accelerometers can be determined by the method of varying current with constant frequency. The vibration intensity change is used to initially detect the windings' state by online monitoring the vibration signal of the shocks. Then the time-frequency analysis further processes these signals in order to detect the fault information contained. The short-circuit experiments have been done on the large power transformer of 50000KVA, which finds that the time-frequency analysis can be used to more precisely detect the fault characteristics of windings. Compared with traditional off line short circuit reactance method, the time-frequency analysis is more effective.

Key-Words: - Transformer winding, time-frequency analysis, Vibration intensity，Short-circuit reactance，Condition monitoring

1 Introduction

Power transformer functions as a node to connect two different voltage levels, which is one of the most essential and the most expensive components of electrical power plants. For example, the transformer with hundreds MVA capacity costs about several million US dollars. Its design life is usually 20 to 35 years[1]. If it is carefully maintained and diagnosed at the right time, it can extend its life. Therefore, it's feasible way to reduce the costs of exchanging transformers by prolonging their service life.

When it is new, the transformer has sufficient electrical and mechanical strength to withstand unusual system conditions. With the aging of the transformer, its insulation strength can degrade to such a degree that it cannot withstand system events such as short-circuit faults. This increases the risk of failures[1-4], which can result in serious power system issues. Thus it is important to maintain the transformer in good operating condition and to prevent these failures by monitoring their states on a real-time basis[5].

2 State of arts and our present work

The traditional routine detection methods include dissolved gas analysis, in-service partial discharge (PD), short-circuit reactance measurement, and FRA frequency response test. These methods are detailed as follows:

1) Dissolved gas analysis[1, 6-16]. Dissolved gas analysis is based on the principle that for any particular type of hydrocarbon gas, its production rate changes with different temperature. By means of dissolved gas analysis (DGA), it is possible to distinguish faults such as partial discharge, overheating, and arcing in a great variety of oil filled equipment. But this method is not sensitive.

2) In-service partial discharge testing[1, 17-35]. PD in transformers degrades the properties of the insulating materials and can result in eventual

failures. PD causes high-frequency low-amplitude disturbances on the applied voltage and current waveforms that can be detected electrically. Electrical PD signals can be measured at a number of different locations, including bushing tap current or voltage and neutral current.

3) Short-circuit reactance measurement[36]. Transformer short-circuit reactance measurement is one of the traditional methods to estimate the deformation of transformer windings. It measures the short-circuit reactance of windings which is compared with the original reactance values. The gap is used to estimate the winding deformation, which is also an important index to determine whether the transformer is qualified or not.

4) FRA frequency response test[4, 37]. The basic principle of FRA frequency response test is that the windings are assumed as the passive linear two-port network consisted of linear resistors, capacitors, inductors and other parameters. The deformation of the windings will lead to the change of the corresponding parameters in the equivalent network, which results in the change of the transfer function.

Based on the distributed parameter transfer model of transformer's windings, the last two methods identify the windings' deformation by the change of distributed parameter or leakage reactance. However, when the winding undergoes a small deformation, especially when the axial compaction force decreases, while the electrical parameter doesn't change, these methods are not effective in detecting the real status.

The looseness or deformation of windings essentially affects the mechanical characteristics of transformers' body[38], which can be identified and analyzed by measuring the related vibration signals. Nowadays, the research based on vibration methods is conducted on transformers condition monitoring. Sanz-Bobi et al.[39] study how to measure the vibration of windings with the accelerometer sensor located on the inner of transformers. Mechefske[40] reports an experiment about tank vibration monitoring over two twin units with the vibration signals recorded from outside the transformer tank, and finds that the frequency spectra changes obviously when the windings are loose. McDonald and MIT[5, 41] develop an inspection system based on artificial neural network. Xie poan et al.[42] build a finite-element model of a single winding. The clamping pressure is identified by estimating the 100-Hz vibration amplitude of the tank with simulation and experiment. García and Alonso[43, 44] develop a mathematical model with electrical current, voltage, and temperature as input. The state of transformer is identified by comparing the 100-Hz vibration amplitude of the tank.

The aforementioned researches mainly propose the methods of identifying the windings' state based on the 100-Hz vibration amplitude of the tank. The change of winding's state, for example clamping pressure, can be shown on the vibration amplitude of 100-Hz. The reason is that the natural frequency offsets because of the winding's structure characteristics change, which lead to the change of the 100-Hz vibration amplitude. Because of the nonlinear characteristics of the insulation cardboard, the change of the winding's natural frequency leads to the obvious increase in the amplitude of harmonic components, in addition to the change of 100-Hz vibration amplitude. It is characterized with the increase of vibration magnitude of the winding. Therefore, vibration intensity of the transformer can be used to monitor the change of the winding's states. Furthermore, the duration is very short when the transformer suffers from the short-circuit shock, with the results that the shock signals collected are non-stationary. Therefore, the time-frequency analysis is used to monitor the change of the winding's states by analyzing the change of 100-Hz and harmonic components amplitudes.

This paper focuses on the locations of these accelerometers attached on the tank of the transformer, and the vibration intensity and the time-frequency analysis with the aim to find out the faulted winding as soon as possible. The short-circuit shock experiments have been done on the large power transformer of 50000KVA. This study finds that these methods are more effective to monitor the state change of windings than the short circuit reactance method.

3 Short-circuit Shock Tests of Transformer Windings

3.1 The research on the choice of measuring point

The vibration of the transformers' windings is transferred to the tank through the structure parts and the cooling oil. The vibration can be detected by the accelerometers which are attached in the tank. How to identify the right locations of accelerometer is an important issue. The vibration response of windings is in proportion to the square of exciting current[43]. Therefore, the method of varying current with constant frequency is used to study the choice of measuring point. In this experiment, phase

C is chosen as the research objective. The detailed locations of measuring points can be shown in Fig. 1.

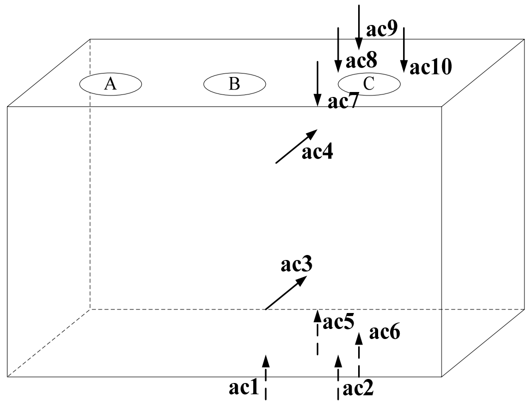
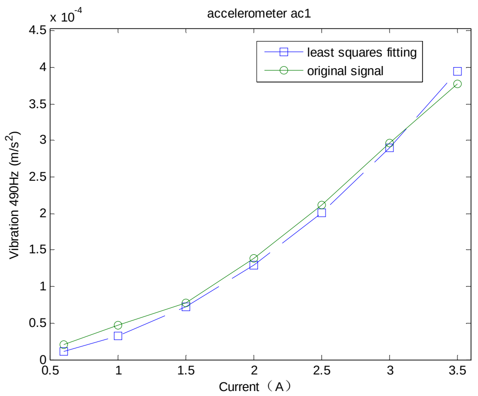
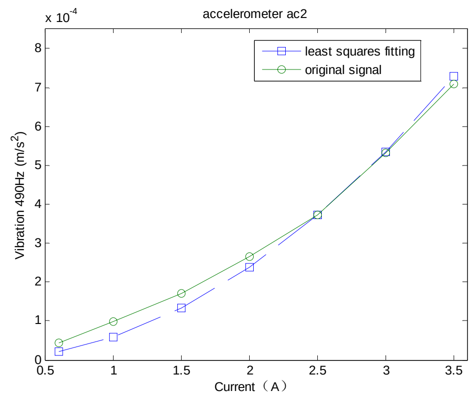
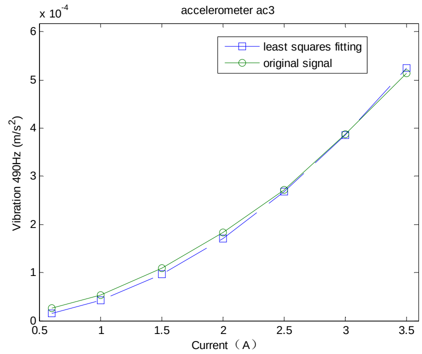


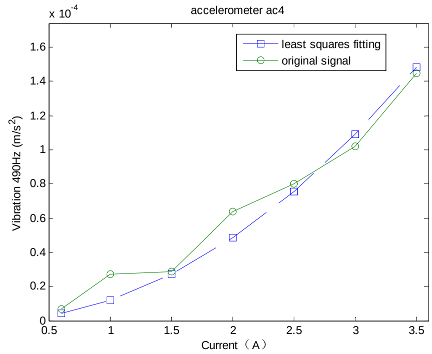
Fig. 1 The location of measuring points

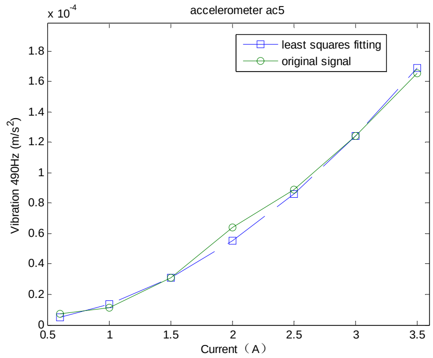
During the experiment, the exciting current of 245Hz is chosen in order to avoid the interference of low frequency and increase signal-to-noise ratio. Therefore, the response amplitude of 490Hz is chosen. Phase C is excited respectively by the current of 0.6A, 1.0A, 1.5A, 2.0A, 2.5A, 3.0A and 3.5A. With the test result of each measuring point, fitting curve is derived by least square method, which is the nearest to the original signal and proportional to the square of excited current. The detailed experimental results are compared as follows:

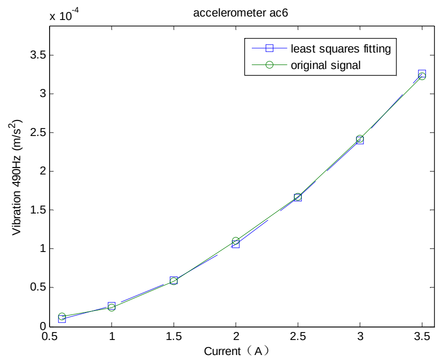


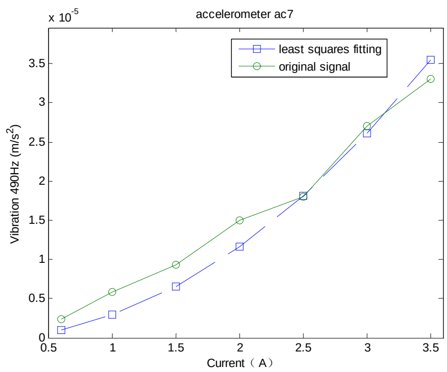












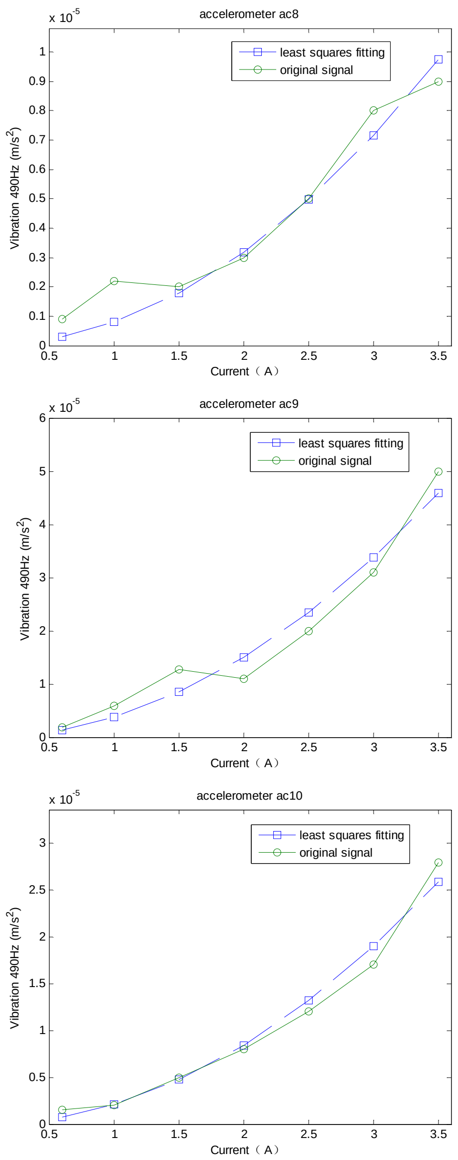


Fig. 2 The experimental results comparison with fixed frequency and varying current for each measuring point

To make sure whether the signal in every measuring point satisfies the relation between the vibration response amplitude and the square of exciting current, the deviation percentages of the response in every exciting current from the fitting curves are summed, as shown in Table 1. From this table, we can see that the most fitting accelerometers locate in the bottom and the side of the transformer, except for the one in the top. Besides, Table 2 shows the ranking of vibration amplitudes in every measuring point when the exciting current is 3.5A. From this table, it can be known that the vibration response amplitude of the bottom is more than that of the top, which means the vibration is transferred from bottom to top.

Table 1 The rank of deviation percentage in every measuring point

No.	Accumulated gap（%）
ac6	38.17
ac5	69.66
ac3	81.74
ac10	94.70
ac1	100.31
ac2	125.65
ac4	134.28
ac9	164.95
ac8	167.95
ac7	171.57

Table 2 The rank of vibration response of every measuring point with 3.5A exciting current

No.	Response under frequency doubling（m/s^2）
ac2	0.00071
ac3	0.000515
ac1	0.000378
ac6	0.000323
ac5	0.000165
ac4	0.000145
ac9	0.00005
ac7	0.000033
ac10	0.000028
ac8	0.000009

From this experiment, a conclusion can be reached that the measuring points should be located in the bottom and the side of the body. After knowing the location of measuring points, the next step is to do the experiments of short circuit shock for the large transformer with 50000 KVA.

3.2 Short circuit shock for power transformer with 50000KVA

The experimented transformer's rated capacity is 50000KVA and rated voltage is 110KV. The short-circuit shock tests have been conducted according to the standards[45] of GB 1094.5-85 or IEC 76-5: 1976. To begin with, the low-voltage side of the transformer is short-circuited. Then the short-circuit shock occurs three time separately for every phase A, B, and C windings. Every time, the exciting current keeps constant and the shock time lasts 0.25s. Meanwhile, the vibration signal caused by the shock is obtained by the accelerometers which are attached on the transformer tank of the low-voltage side. The measuring points are located as shown in Fig. 3.

Fig. 3 The location of measuring points

Taking measuring points ac3 for phase C as an example, Fig. 4 shows its time-domain signals under the three times shocks. From this figure, it can be seen that the vibration response keeps a rather large vibration magnitude during the load period of short-circuit current, while it gradually decays with the disappearance of the short-circuit current. However, it's difficult to tell the differences of the three times shocks from this figure. Therefore, the further signal analysis is needed.

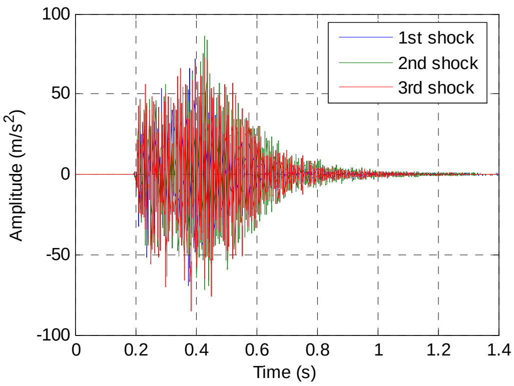


Fig 4. The time-domain comparison of measuring point ac3 of phase C under the three times shocks

4 Analysis of Experimental Data

4.1 Vibration intensity

When the winding is in normal state, its vibration responses have no big difference under the shock of the same short-circuit current. However, when there exists the clamping pressure looseness or distortion of the winding, the change of its structure characteristics would be shown in the vibration response[40]. Therefore, the changes of the winding's vibration level can be used to detect the state of the winding by the on-line monitoring of the winding.

To state the vibration of the transformer under the shock of short-circuit more clearly, we introduce vibration intensity as follows:

$$a_{id} = \sqrt{\left(\frac{\sum_{i=1}^{k} a_{Xrms_i}}{k}\right)^2 + \left(\frac{\sum_{i=1}^{m} a_{Yrms_i}}{m}\right)^2 + \left(\frac{\sum_{i=1}^{n} a_{Zrms_i}}{n}\right)^2}$$

Where,

a_{Xrms_i} , a_{Yrms_i} , a_{Zrms_i} —the vibration level of measuring point i in the direction of x, y, z

K, m, n — the number of measuring points in the direction of x, y, z

From the above formula, the vibration intensity could be derived, as shown in Fig. 5 and Table 3. These comparisons show that the vibration intensities of phase B change small under the three times short-circuited shock, which means the winding of phase B has sufficient mechanical strength to withstand the short-circuit shock. However, the vibration intensities of phase A and C change obviously. Especially when they suffer from the second shock, the vibration intensities increase more than 14%. It shows that the states of low-voltage windings of phase A and C change under the shock, with the increasing tendency.

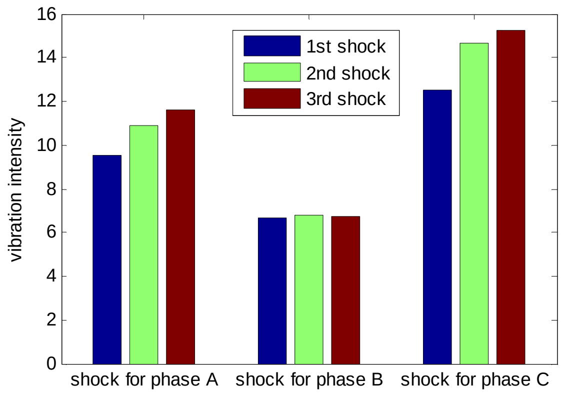


Fig. 5 The comparison of vibration intensity

Table 3 The comparison of vibration intensity

	Phase A	Increasin-g ratio	Phase B	Increasin-g ratio	Phase C	Increasin -g ratio
Shock 1	9.5566		6.6516		12.4995	
Shock 2	10.9223	14.29%	6.7752	1.86%	14.6642	17.32%
Shock 3	11.64	21.80%	6.7297	1.17%	15.2617	22.10%

According to the requirement of GB 1094.5-85 or IEC 76-5: 1976, the reactance of every winding is measured after every shock. The detailed results are as shown in Table 4.

Table 4 The comparison of reactance change

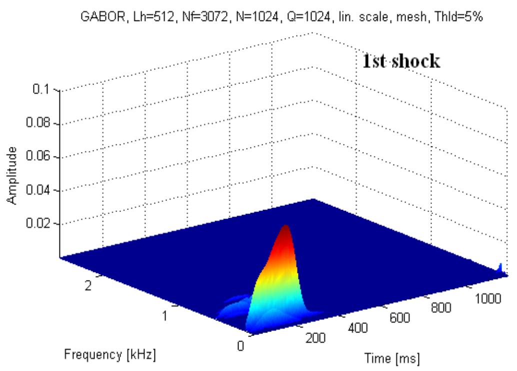
	Phase A		Phase B		Phase C	
	Reactance	Gap of Reactance	Reactance	Gap of Reactance	Reactance	Gap of Reactance
Before Experiment	46.94		37.08		28.8	
Shock 1	47.01	0.15%	37.09	0.03%	28.79	-0.03%
Shock 2	47.01	0.15%	37.09	0.03%	28.67	-0.45%
Shock 3	47.01	0.15%	37.09	0.03%	28.56	-0.83%

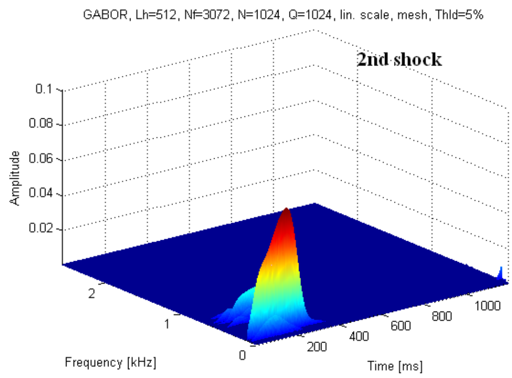
Note: The gap of reactance is the deviation percentage of the reactance after shock from the value before the shock.

The comparison of reactance shows that the reactance of phase C decreases gradually after the three times shocks and the gap approaches -1%, which means the state of the winding of phase C changes after the shocks. However, the reactance of windings of phase A and B doesn't change after the shocks. From the opinion of the short-circuit reactance method, these two windings are normal. The short-circuit Reactance method and vibration intensity method have reached the same conclusion on the states of phase B and C, not on phase A. Therefore, the time-frequency analysis is used to analyze the vibration signal of phase A, phase B and C, in order to study the reason of the difference and the winding's fault characteristics.

4.2 Time-frequency analysis for the short-circuit shock signal

Because the insulation cardboard of the winding is nonlinear material, the vibration response caused by the exciting current of 50Hz is mainly consisted of harmonic components of 100Hz and 50Hz. Therefore, the requirement for the frequency resolution precision is not high during the time-frequency analysis. Then Gabor transform is employed for the signal process. Fig. 6~8 show the time-frequency diagrams of phase A, phase B and C.





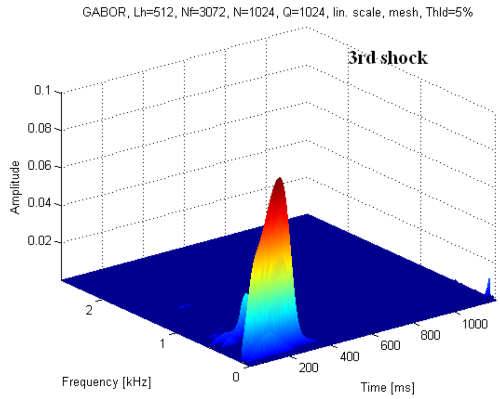
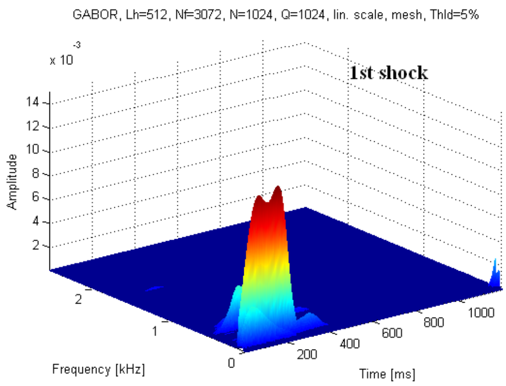


Fig 6 The time-frequency diagrams of Measuring point ac1 of phase A for the short-circuit shocks



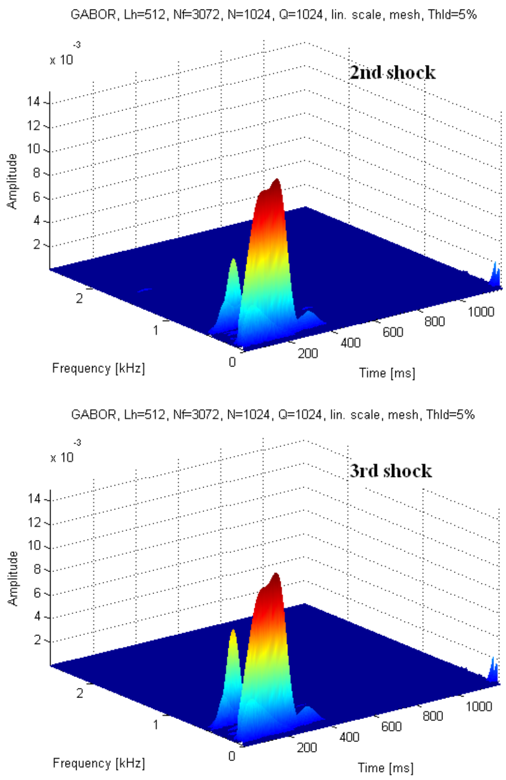
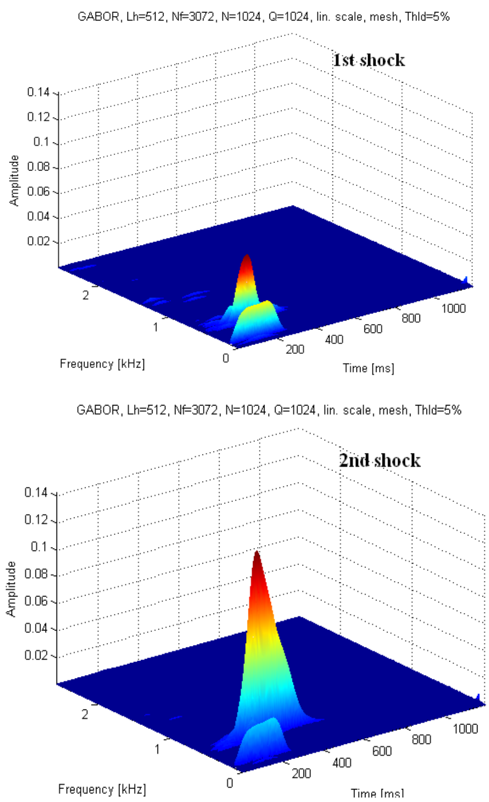


Fig 7 The time-frequency diagrams of Measuring point ac2 of phase B for the short-circuit shocks



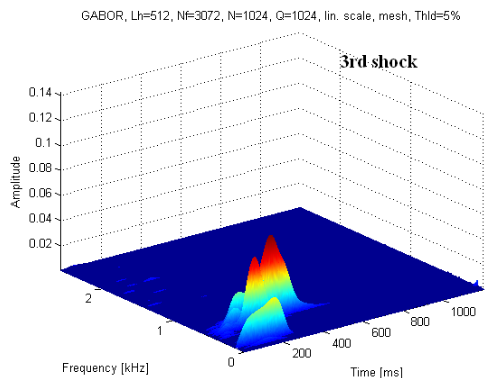
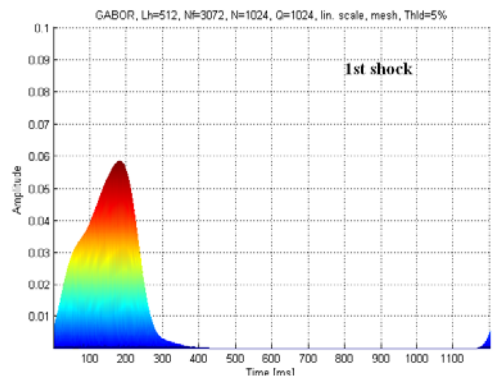


Fig 8 The time-frequency diagrams of Measuring point ac3 of phase C for the short-circuit shocks

From the above diagrams, it can be seen that the time-frequency diagrams of phase C have the most differences, and the next is those of phase A, and the least is those of phase B. There're nearly no change in the amplitude of all the frequencies, except for 500-Hz hamonic compnent. This means that the winding of phase B is normal after the short circuit shock, which is the same conclusion with short-circuit reactance method and vibration intensity method. The vibration magnitude of phase A maily changes in the frequency of 100 Hz, where the component increases obviously with every shock (as shown in Fig. 9). However, there's nearly no change for phase C in terms of the components of 50Hz and 100 Hz. The difference exists maily in the scope of 450Hz～600Hz, especially in the frequency of 500Hz. With every shock, the component of 500Hz not only changes obviously, but its peak shift obviously (as shown in Fig.10). For example, the maximal response peak of the third shock appears in the 0.05s after the short-circuited current, which is different with the normal state after the shock and means there's some fault in the winding of phase C. And the reactance method also detects this problem.



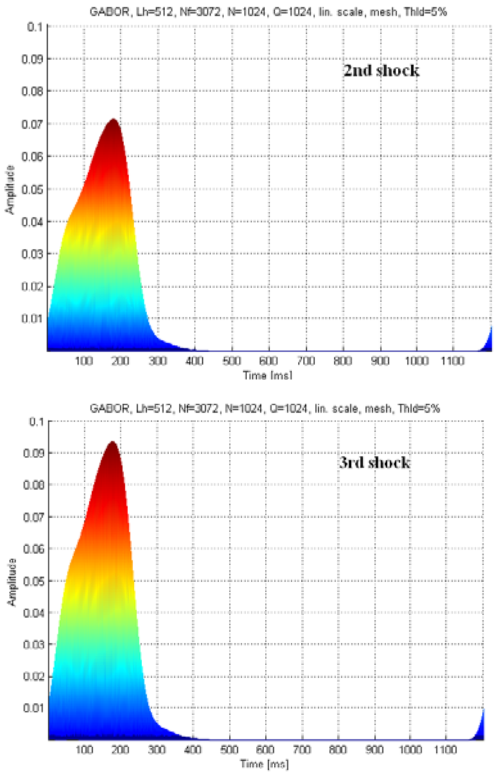
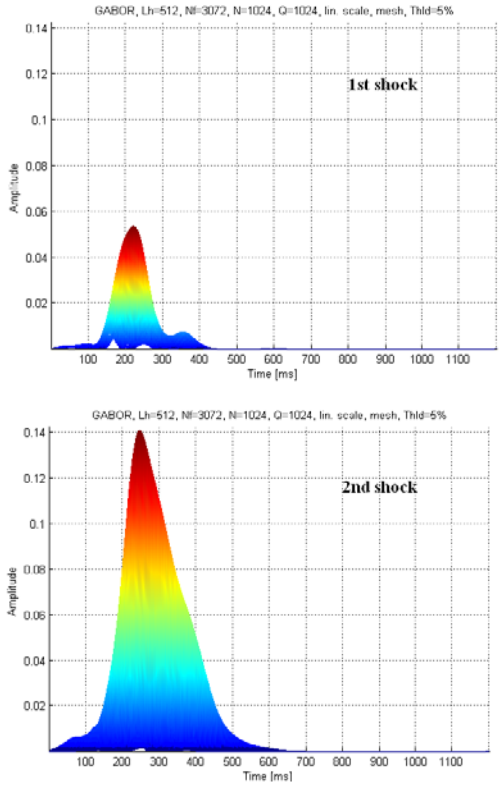


Fig 9 The time-frequency diagrams of Measuring point ac1 of phase A for the short-circuit shocks (100Hz)



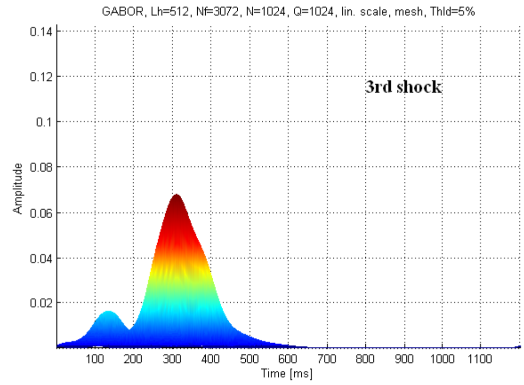


Fig 10 The time-frequency diagrams of Measuring point ac3 of phase C for the short-circuit shocks (500Hz)

In addition, from the above figures it can be seen that the fault characteristics of phase A and C are not the same. 100 Hz is the exciting frequency of electromagnetic force. When the short-circuit current keeps constant, the response amplitude of 100Hz keeps no change for the normal windings. However, the response amplitude of 100Hz for phase A increases gradually, which means that the winding of phase A goes wrong[43]. The fault may be because of the looseness of the clamping pressure, which causes the shift of the natural frequency, finally resulting in the change of response amplitude of 100Hz.

Therefore, these experiments tell that the online vibration intensity method can show the change of winding's states, more precisely than the reactance method. Meanwhile, based on this initial judgment, the time-frequency analysis can further precisely show the fault characteristics.

5 Conclusion

From the study of the short-circuit shock test for this large power transformer of 50000KVA, we can get the following conclusions:

1. The measuring points should be located in the bottom and the side of the transformer body.
2. Vibration intensity can be used to on-line monitor the winding's states. Compared with the off-line short-circuit reactance method, this method is more effective and timely to show the change of the windings' states.
3. Based on the judgment of vibration intensity, time-frequency analysis can be used to more precisely show the fault characteristics and the reasons of winding's states change by analyzing the vibration signals.

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