Test and Fault Analysis for High Power High Frequency HV Transformer

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Abstract: In order to analyze the causes for a high power high frequency HV transformer faults, a test platform is established; no-load test and wave recording are conducted for a faulty transformer and a faultless transformer. Features of test waveforms are summarized via current waveform comparison method. Based on the structure of power transformer, an equivalent circuit of the transformer considering stray parameters is put forward and a simplified circuit is come up with. The test result shows that it is distribution capacitance rather than air gap abnormity that causes high no-load current. Through the comparison of current waveforms, we can draw a conclusion that the fault is caused by the insulation breakdown of high voltage line package (layers or turns), which accords with the results through observation after the dismantlement of power transformer.

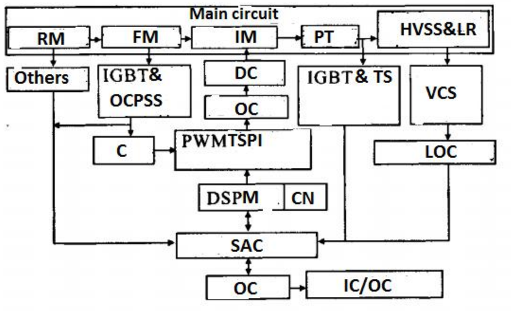
Key words: high power, high frequency, insulation, power transformer, test, fault analysis

Introduction

There have been a large amount of research achievements and practical methods with regard to fault diagnosis of power frequency transformer. As the high power HV DC power source is widely used, research on the protection and fault diagnosis of high power HV high frequency transformer needs to be further advanced. The effect of stray parameters complicates its equivalent circuit and generates many new problems (such as several resonant points). Hence, some methods of diagnosing the faults of common power transformer are not suitable for high frequency HV transformer, and even lead to incorrect conclusions. In this paper, no-load test and wave recording are conducted for a faulty transformer and a faultless transformer. The analysis results are much similar to the results through observation after the dismantlement of power transformer.

1. Test Platform

The test platform is composed of main circuit and control system, which is shown in Fig.1. The TMS320F2812 digital control chip is the core of control system.



RM: rectification module; FM: filter module; IM: inverter module; PT: power transformer; HVSS & LR: HV silicone stack & limit resistance; IGBT & OCPSS: IGBT and over-current protection signal sample; DC: drive circuit; OC: optoelectronic isolator; IGBT & TS: IGBT and temperature sample of transformer; VCS: voltage and current sample of output terminal; C: comparator; PWM TSPI: PWM trigger signal protection interlock; LOC: linear optoelectronic isolator; DSPM: DSP main-board; CN; communication; SAC: signal adjust circuit; IC/OC: Inlet circuit/Outlet circuit.

IGBT. D_1, C_1, D_5 and R_3 are snubber circuit of switch component represented by T_1. The snubber circuit of T_3 - T_4 is shown in Fig.2.

2. Faults

2.1 Test requirements

Voltage of three-phase input line: 100V

Trigger signal frequency: 18kHz

Duty cycle: 0.3557

Square wave inverter: T_1 &T_4 at the same phase; T_2 & T_3 at the same phase; the difference between two groups is 180°

Impulse width of all signals is the same.

The no-load of HV output terminal is only connected with resistance voltage divider.

Parameters of faulty transformer are as follows:

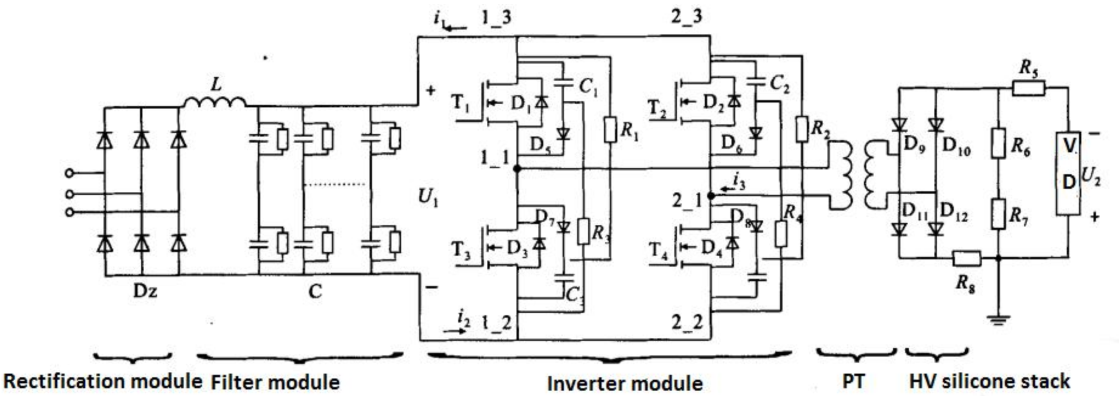


Fig.2 Main circuit diagram

The main circuit is shown in Fig.2. From left to right: rectification module - filter module LC - inverter module - power transformer - HV silicone stack - limit resistance R_5 -voltage sample resistance R_6 and R_7 - voltage sample resistance R_8 - voltage divider. T_1-T_4

Input voltage: 510V

Turn ratio of primary side to secondary side: 7/780

Output power: 60kW

Working frequency: 20kHz

2.2 Test results

The voltage of output terminal is between 20.63 and 21.99kV while input current of transformer is about 70A. Besides, snubber resistance of switch component is very hot and the radiator is slightly hot. Acquired fault waveforms are in the following: ① u_{T4} -- trigger signal waveform of switch component T_4; ② u_{12} -- input voltage waveform of primary side; ③ i_3 -- input current waveform of primary side. All faulty waveforms are shown in Fig.3.

The above waveforms are recorded into excel format through TDS3012 oscilloscope. Then waveforms are restored via MATLAB.

2.3 Result analysis

The formula of no-load voltage after rectification:

$$U_{out} = \frac{\sqrt{2}U_{in}n_1}{n_2} \quad (1)$$

Where:

U_{in}: line voltage of three-phase input voltage

U_{out}: HV rectification output voltage

n_1: number of primary windings

n_2: number of secondary windings

When the three-phase input line voltage is 100V, U_{out} should be 15.758kV. However, output terminal voltage measured by voltage divider is 20.63-21.99kV. Some conclusions are made based on Fig.3:

1) The voltage ratio of DC output terminal is relatively high;

2) No-load input current of power transformer is high;

3) Current waveform phase is more than 90°than voltage;

4) The current waveform severely distorts and has abnormal peaks;

5) Average output power for one cycle of filter module is about zero.

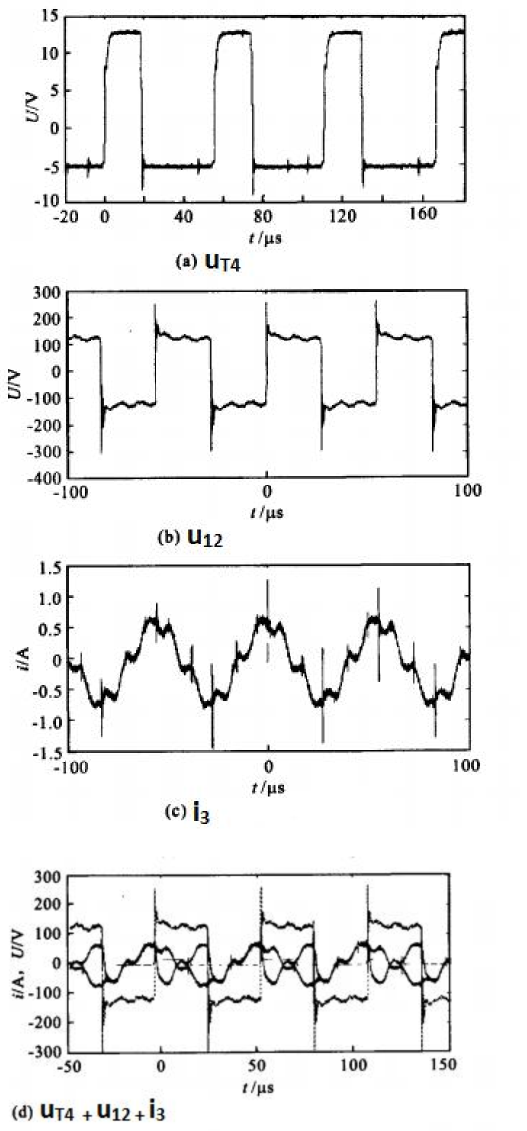


Fig.3 Waveforms of fault recording

3. Fault Analysis

3.1 Structure and equivalent circuit of power transformer

The structure of power transformer is

shown in Fig.4. Details of insulation materials are as follows: the framework adopts epoxy board while polyester film for inter-layer insulation and inter-turn insulation; the insulation board is thick. The magnetic core is made of 8 U-shaped magnetic cores in parallel. The whole transformer core is immersed in the transformer oil.

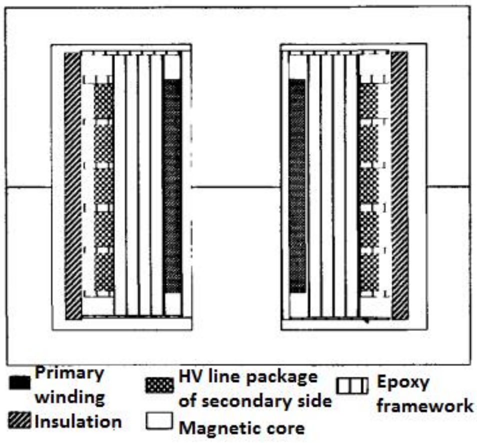


Fig.4 Structure of transformer insulation

The equivalent circuit of power transformer is shown in Fig.5. R_1: resistance of primary winding; C_1: distribution capacitance; L_{1s}: leakage inductance. $R'_{2\ 1}$: the resistance of first HV line package of secondary winding; $C'_{2\text{-}1}$: distribution capacitance of secondary winding; $L'_{2s\text{-}1}$: leakage inductance of secondary winding. $C_{12\text{-}1}$: the capacitance between first HV line package of primary winding and that of secondary winding. L_m: exciting inductance; R_c: the resistance representing the magnetic core loss.

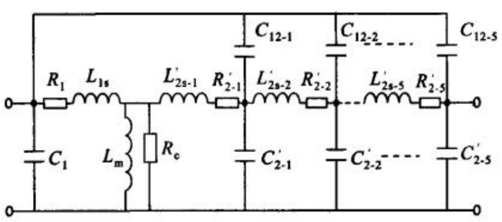


Fig.5 Equivalent circuit of transformer

Based on features of step-up transformer insulation structure, the equivalent circuit can be simplified: ① the capacitance between primary and secondary windings is combined with secondary circuit ; ② the HV line packages of secondary side is regarded as one line package; ③ leakage inductance of primary and secondary side are combined.

The simplified circuit of power transformer is shown in Fig.6. In the Figure.6, L_s - equivalent leakage inductance of primary and secondary side; R'_2 - equivalent resistance of secondary side. C'_2 - distribution capacitance between primary side and secondary side, distribution capacitance of secondary side windings and total equivalent capacitance. C' - output equivalent capacitance. R' - reverse resistance of HV rectification arm and voltage divider resistance.

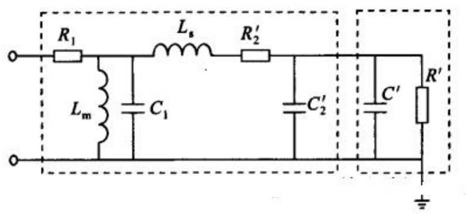


Fig.6 Simplified working circuit

3.2 Fault analysis

There may be two causes of the faults: ① The air gap becomes larger during the hoisting process of power transformer; ② the influence of winding insulation breakdown and distributive capacitance.

3.2.1 Analysis of air gap

For the formula of air gap length, see below:

$$l_\delta \approx \frac{2\pi f n_1^2 \mu_0 A_\delta I_1}{\sqrt{2} U_{in}} \qquad (2)$$

Where:

l_δ: length of air gap

A_δ: section area of magnetic core (41.6cm^2)

u_0: air permeability

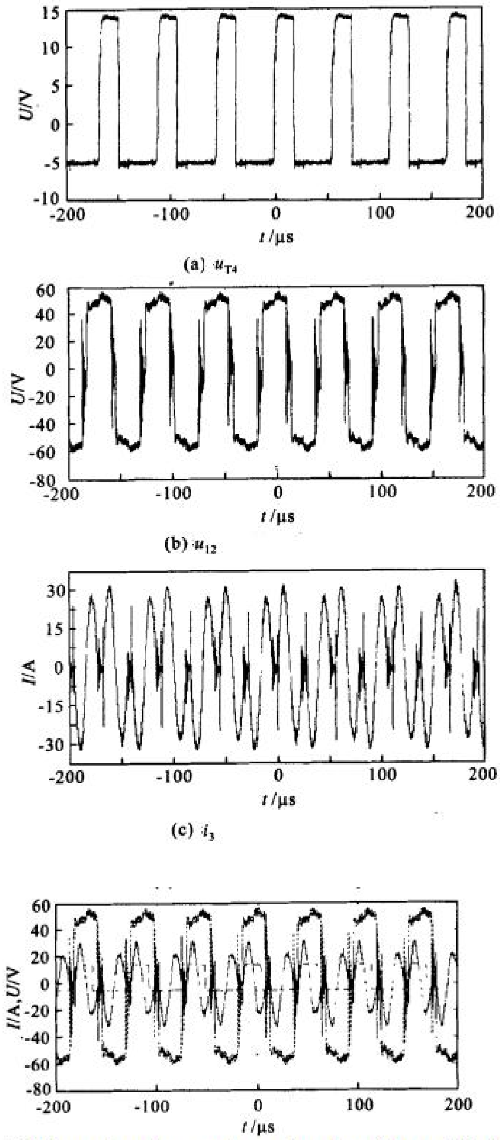
I_1: effective value of primary current

f: exciting power supply frequency

According to the formula (2), the length of air gap is 14.34mm. Based on the structure of power transformer, the hoist is less likely to produce 14mm air gap; in addition, the current waveform distorts and abnormal peaks arise. Therefore, it is not air gap that causes the no-load input current to become higher.

3.2.2 Influence of winding insulation breakdown and distribution capacitance

In order to facilitate the comparable analysis, we conduct no-load test and record the waveform for faultless transformer with same specification under the same condition. ① u_{T4} -- trigger signal waveform of switch component T_4; ② u_{12} -- voltage waveform of primary input; ③ i_3 -- current waveform of primary input. Details of waveforms are shown in Fig.7.



(d)Trigger signal u_{T4} voltage signal u_{12} (dotted-line) current signal i_3 (real line)

Fig.7 Waveforms of faultless transformer

Comparison of Fig.3 (c) and Fig.7 (c) indicates that the current waveform of faulty transformer distorts seriously and abnormal current peaks arise. Hence, the short circuit occurs owing to insulation breakdown for the transformer winding. There is no possibility that interturns of primary winding short-circuit or primary and secondary winding breakdown and short-circuit. It is believed that high voltage line packages breakdown, resulting in short circuit of some interturns or layers of secondary winding. Part of abnormal current peaks are caused by the surface discharge. That are the causes for the faults.

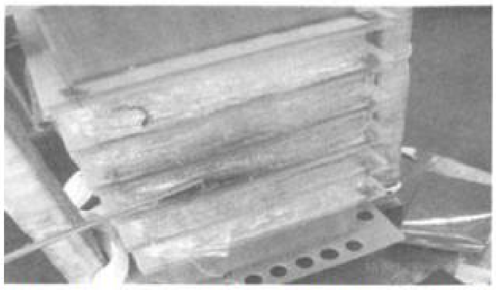
As shown in the Fig.7 (c), the no-load input current of faultless transformer is still high, which is caused by distribution capacitance of transformer winding. As for power transformers with same structure and distribution capacitance, the capacitive reactance reduces according to frequency rate, leading to prominent problems such as high no-load current and heating inverter no-load. However, in terms of faulty transformer, the effect of short circuit causes no-load current to be higher, which is shown in Fig.3 (c). Many measures can be taken to eliminate the negative effect of distribution capacitance on the system. Generally speaking, they can be grouped into three categories: ① make use of distribution capacitance; ② make a supplement to distribution capacitance; ③ upgrade the structure of power transformer ro reduce the distribution capacitance.

Moreover, there seems a contradiction between short circuit of high voltage line package and great numerical value of output voltage ratio. In fact, on the one hand, power transformer carries a large amount of distribution parameters, which tend to produce the resonance; on the other hand, the equivalent capacitive load of output terminal leads to capacitive rise effect. Hence, the voltage of DC output terminal is still higher than theoretical value when interturn short circuit arises at the secondary side.

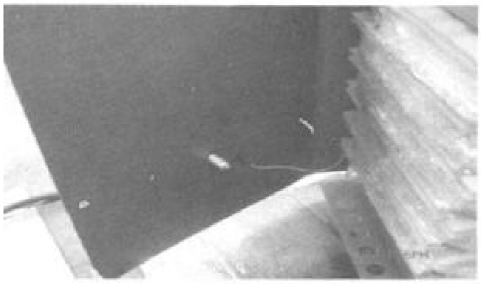
4. Dismantle the Transformer to Verify the Results

It is found that there indeed exists a phenomenon of insulation breakdown for secondary HV line package. For further details, see Fig.8. There are three faults in total.

(a) Insulation breakdown of HV line package-1



(b) Insulation breakdown of HV line package-2



(c) Fault point of HV output terminal (Black)

Fig.8 Fault images

The cause is that there are small air bubbles between polyester films of breakdown points. Air bubbles lead to partial discharge, thus resulting in insulation breakdown. The high-class vacuum oil process is recommended for polyester films or cable paper insulation for common vacuum oil process. In addition, the strength of HV output terminal should be paid more attention to.

5. Conclusions

The no-load test and wave recording are conducted for a faulty transformer and a faultless transformer. Test results are analyzed to figure out the causes. Based on the structure of power transformer, the equivalent circuit of transformer is simplified. According to the structure of power transformer and comparison of current waveforms of two transformers, we can draw a conclusion that the fault is caused by the insulation breakdown of high voltage line package (layers or turns), which accords with the results.