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Study Committee A2
PS2 Outside of the Mineral Oil Immersion Transformer and the Reactor

A New Solution of Higher Energy-Efficient Dry-Type Transformers with Silicon Rubber Casting Technology

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SUMMARY

The loss and reliability of dry-type transformers are of great concern. At present, the mainstream technology of dry-type transformers adopts epoxy resin as the primary insulation material. The epoxy resin produces volatile toxic gas in the manufacturing process and seriously affects workers' health. It cannot meet the operational requirements of dry-type transformers with an insulation grade higher than H due to the inherent low glass transition temperature of the material. There is also a risk of explosion due to a sudden increase in winding temperature caused by a short-circuit current. Another insulation technology is called an open ventilated distribution transformer. It mainly relies on air to insulate between windings. The environment dramatically affects air insulation, especially in a humid, dusty, or lower atmosphere pressure workspace, which can cause specific safety hazards.

Currently, a new type of primary insulation with silicone rubber material in a dry-type transformer is safer than epoxy resin. The insulation system consists of two layers of solid dielectrics and air. This fault-tolerant structure effectively improves the insulation reliability of the dry-type transformer and reduces the unnecessary air distances between windings, and then significantly reduces the no-load loss of the transformer. Tests and practical applications have proved its safety, reliability, and energy efficiency.

This paper provides a new design concept, technology development and roadmap for dry-type transformers, which is fully in line with the strategic goal of "achieving carbon peak by 2030 and carbon neutrality by 2060" issued by the Chinese government.

KEYWORDS

Silicone rubber cast dry-type transformer; fault-tolerant primary insulation; safety and reliability; higher energy efficiency and environmental friendship; carbon peak; carbon-neutrality

0 Preface

Dry-type transformers are key electrical equipment in power distribution networks and electric power generation. Its safety, reliability, and energy consumption level are becomingincreasingly important. It is estimated that by 2055, the electrification rate of China's whole society will exceed 60%, and the carbon emissions of energy consumption will drop from 5 billion tons in 2028 to 640 million tons [1], and electricity will achieve nearly zero emissions. The implementation of the new energy efficiency standards issued in 2021 and the proposed national dual carbon strategic goal will promote the full application of safe, efficient and energy-saving transformers.

1. Main issues of traditional dry-type transformers

Traditional dry-type transformers [2] include two main insulation types: epoxy resin cast dry-type transformer and open ventilated dry-type transformers with insulated paper-covered conductors.

The primary insulation of the cast resin dry-type transformer windings is composed of epoxy resin and the external air gap. Under the combined action of the vast electromotive force caused by the short-circuit current and the local high temperature in winding, it is easy to cause the primary insulation failure.

The glass transition temperature of epoxy resin is too low to meet the operational requirements of dry-type transformer with insulation grade higher than H insulation levels [18]. When an internal fault occurs in the transformer and the winding temperature rises too fast, the cast resin will crack or even explode [16,17]. It will endanger the personal safety of on-site staff and the safety of electric equipment operating around them.

Insulating partitions are usually added in the air gap between the high and low voltage windings. However, the insulation strength of the open structure partition depends not only on the insulation performance of the partition body but also on the creeping distance of its surface and the degree of contamination. Surface contamination will reduce the partition's insulation strength [3], so there are risks in the insulation with this partition structure. Figure 1 is a photo of the insulation breakdown of the partition between the high and low voltage windings of a 35kV cast resin dry-type transformer.

Fig. 1 Insulation broke down between the high and low-voltage winding with a partition in a 35kV cast resin dry-type transformer.

Epoxy resin materials in the mixing, curing and mold cleaning process requires to the use of a large number of organic solvents, including strong carcinogenic materials such as epichlorohydrin, phthalic anhydride and tetrachloroaniline, which will seriously affect the health of production personnel and cause serious pollution when discharged. When the transformer is decommissioned, the cured cast resin will take about 3000 years to decompose naturally. At present, It can only be landfilled or used for roadbed treatment by mixing with asphalt but it will still contaminate groundwater and soil. In addition, the firm adhesion of epoxy resin makes the recycling of metallic conductor materials very difficult. Therefore, the cast resin dry-type transformer is not eco-friendly throughout its life cycle.

The high-voltage windings of open-ventilated dry-type transformers usually use high-performance insulating paper to wrap the wires first, and then coat or impregnate the insulating varnish and then dry. The primary insulation between the windings or layers is air. But the air pressure, humidity, and dust pollution will affect the insulation performance of the air gap. During the long-term operation of the transformer, dust and various impurities are embedded in the gaps and layers of the windings and are difficult to remove. If the transformer is operated in a damp environment for a long time, breakdown accidents may occur between the layers and phases of the transformer. Although solid insulating partitions can also be installed in the interphase air passages of open ventilated dry-type transformers, insulation degradation will occur when the partitions are contaminated. The insulation performance of dry-type open ventilated transformers depends entirely on the used insulating paper, coated or impregnated insulating varnish, which is more limited by the operating environment [4]. Figure 2 shows a phase partition plate broken down in a 10kV open ventilated dry-type distribution transformer.

Fig. 2 Photo of partition plate broken down in a 10kV open ventilated dry-type distribution transformer (from the internet)

2. A new technology to solve the above problems

In the past 30 years, the technological innovation of dry-type transformers has mainly focused on the steel core material and its manufacturing process [5]. It is highly expected to develop new insulating materials and new-type insulating structure to improve the safety, reliability, energy conservation, and environmental protection level of dry-type transformers. Silicone rubber for electrical engineering is a green high-performance insulating material [6], with a stiffness of 55-70, a dielectric strength of about 20kV/mm, a dielectric constant of 3-3.5, and it can withstand high temperatures above 220 ℃ and resistance below -50 ℃. It has significant advantages, including high elasticity, high mechanical strength, high insulation strength, non-flammability, strong hydrophobicity [7], no pollution, and recyclability. It has been widely used in power systems [8-9] and is very suitable as the main insulation material of dry-type transformers.

By using these advantages of high-performance electrical silicon rubber [10], a new dry-type transformer is developed, a new fault-tolerant primary insulation structure with triple-redundant insulation based on two layers of solid dielectrics and air is designed, and a new casting and curing process is developed. The transformer has the characteristics of strong short-circuit resistance, high overload capacity, high climate adaptability, and low no-load loss. It can be used in extreme cold, high altitude, high salt spray, high humidity and heat, environmental protection and other harsh environments. The shortage of cast resin dry-type transformers and open ventilated dry-type transformers is well overcome.

3. Analysis of performance, cost, and environmental protection of silicone rubber dry-type transformer with a triple-redundant main insulation structure

3.1 Safety analysis of triple redundant insulation structure

Combined insulation [11-13] can be considered as the most basic dual-redundant insulation method. However, if defects in solid dielectrics are invloved, a multiple redundant insulation structure should be chosen, such as the triple redundancy insulation structure shown in Figure 3.

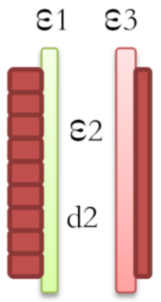


Fig. 3 Schematic diagram of the triple-redundant structure of primary transformer insulation

In Figure 3, the high-voltage winding insulating cylinder ε1, air ε2, and the low-voltage winding insulating wrapping ε3 constitute a solid-gas-solid three-fold redundant insulation structure, in which air also serves as the primary airway for heat dissipation. The dielectric strength of air is designed to withstand the applied withstand voltage test voltage under standard conditions. The two solid insulating layers are designed to have a much higher dielectric strength than air. If air insulation is unstable, the two layers of solid dielectrics insulation strength will protect the conductors' insulation against breakdown. In tha case that a layer of solid dielectric is defective for some reason, the primary insulation still has the characteristics of fault tolerance with one layer of air and one layer of solid dielectric as primary insulation and backup insulation. Such insulation defect fault-tolerant structure significantly reduces the failure rate of the primary insulation of dry-type transformers and dramatically improves the reliability of the dry-type transformers.

3.2 Description on advantages of triple redundant insulation fault-tolerant structure of silicone rubber dry-type transformer

3.2.1 Overall structure design of silicone rubber transformer

The high voltage winding of the silicone rubber cast dry-type transformer adopts a multi-cake structure with an insulating inner cylinder and flange. The voltage between the cakes is actively reduced to eliminate partial discharge, and it is filled and encapsulated by elastic silicon rubber. The partial discharge amount is no more than 5pC. The low-voltage winding is co-wound with copper foil and self-adhesive insulating filmand has an outer envelope with high insulation strength. The product photo is shown in Figure 4.

Fig. 4 Silicone rubber dry-type transformer

The high-voltage primary insulation of silicone rubber dry-type transformer is composed of insulation between the high and low-voltage windings, the high voltage winding phase to phase insulation, and insulation of the high voltage windings to the ground (iron core and clamps). The structure is shown in Figure 5.

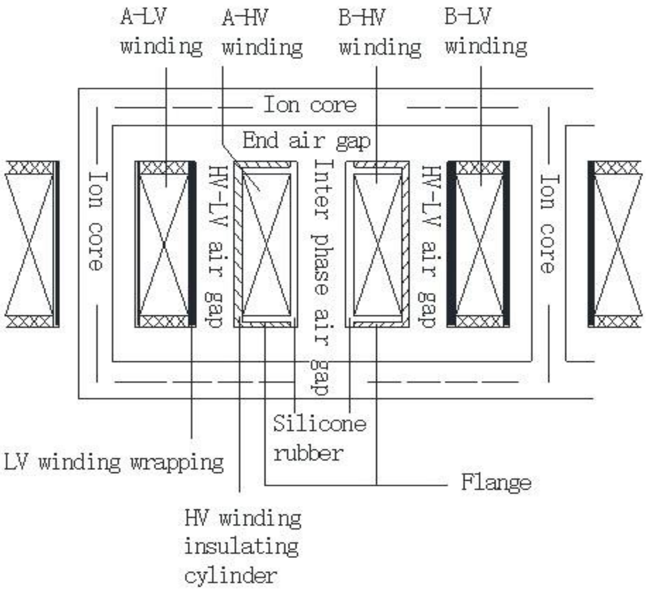


Fig. 5 Schematic diagram of transformer high-voltage main insulation structure

3.2.2 Design of triple redundant insulation structure between high and low voltage windings of silicone rubber dry-type transformer

In Figure 5, a triple-redundant insulation structure between the high and low voltage windings is composed of the high voltage winding inner insulating cylinder, the high and low voltage air passages, and the low voltage winding outer envelope. Among them, the high-voltage winding inner insulating cylinder is prefabricated with high-strength insulating materials. On the one hand, it needs to meet the structural stability requirements of the high-voltage winding, especially to withstand the mechanical stresses caused by sudden short circuits. On the other hand, it also serves as the dielectric between the high- and low-voltage windings. Its design insulation strength U_h is:

$$U_h = K_{bh} U_b \qquad \ldots\ldots \ (1)$$

In formula 1, U_b is the power frequency withstand voltage, K_{bh} is the safety factor, and K_{bh}=1.5-2.

There is an air duct between the high and low voltage windings, and the design insulation strength Ug should meet the following standard by atmospheric conditions:

$$U_g = U_b \qquad \ldots\ldots \ (2)$$

Considering the process error, the design margin should be appropriately increased.

The external insulation of the low-voltage winding is wrapped by high-strength composite insulating film winding or encapsulated by silicone rubber, and its design insulation strength U_l is:

$$U_l = K_{bl} U_b \qquad \ldots\ldots \ (3)$$

In formula 3, K_{bl} is the safety factor, K_{bl}=1.5-3. Higher K_{bl} is selected to improve lightning protection.

3.2.3 Design of triple-redundant insulation structure between phases of high-voltage windings of silicone rubber dry-type transformers

In Figure 5, the silicone rubber outsourcing sealing layer of one-phase high-voltage winding, the interphase air gap, and the silicone rubber outsourcing sealing layer of the other-phase constitute a triple-redundant insulation structure between the high-voltage windings. The design insulation strength U_{hp} of the silicone rubber outer sealing layer is:

$$U_{hp} = K_i U_i \qquad \ldots\ldots \ (4)$$

In formula 4, U_i is the induced overvoltage withstand test voltage, K_i is the safety factor, and K_i=1.5-2.

The design insulation strength U_{gp} of the interphase air gap ~~way~~ should meet the following requirements under standard atmospheric conditions:

$$U_{gp} = U_i \quad \text{…... (5)}$$

Considering the process error, the design margin should be appropriately increased.

3.2.4 High-voltage winding end-to-earth triple-redundant insulation structure design

In Figure 5, the flange of the insulating inner cylinder and the silicone rubber end filling layer form a composite solid insulation, which forms a triple-redundant insulation structure at the end of the high-voltage winding with the end air gap. The silicone rubber in the solid composite insulation is an elastic solid. Therefore, there is no tremendous internal stress between it and the rigid inner cylinder flange, so the solid composite insulation is safe and reliable. However, because of extreme electric field distortion between the end of the high-voltage winding and the ground (iron core and clamp) and the low-voltage lead wire, and more consideration should be given to lightning protection. Therefore, the design insulation strength of each layer of solid dielectric is:

$$\mathrm{U}_{\mathrm{ht}} = K_t U_t \quad \text{…... (6)}$$

In formula 6, Ut is the lightning impulse withstand voltage; Kt is the safety factor, Kt=1.5-2;

The design insulation strength Ugt of the air gap at the upper and lower ends should meet the following requirements under standard atmospheric conditions:

$$U_{gt} = U_{\mathrm{t}} \quad \text{…... (7)}$$

Considering the process error and the extreme distortion of the end electric field, it is advisable to significantly increase the design margin.

3.3 Economic advantage analysis of triple redundant insulation structure silicone rubber dry-type transformer

The silicone rubber dry-type transformer designed with this structure has an excellent performance of dielectric fault tolerance to eliminate the primary insulation broken down against high voltage and lightning during operation, and to appropriately reduce the insulation design margins of air gap between high and low-voltage windings and between phases to minimize the core yoke length and the diameter of the high-voltage winding, and then to reduce the amount of core and wire of the dry-type transformer. Due to the shortened magnetic circuit and the reducedwire length, both no-load loss and load loss of the transformer are reduced, saving energy.

This triple-redundant main insulation structure makes full use of the insulation materials necessary for the winding construction itself, and the cost increase is minimal. Moreover, after the transformer is decommissioned, the total material recovery rate will reach 98% and above. As a result, the life cycle cost will be more than 10% lower than cast resin dry-type transformer. On the premise of significantly improving the reliability of the transformer, the real maintenance-free during the life span can reduce the user’s operating cost, and the overall economy is outstanding.

3.4 Analysis of environmental protection advantages of silicone rubber dry-type transformers with a triple-redundant insulation structure

A unique casting and curing process is used to produce the windings of the dry-type transformer with this insulation structure. The high-performance silicone rubber is a dual-component high-viscosity liquid. Before pouring, it does not require any solvents and only relies on catalysts. Curing at a high temperature above 120 ℃, the whole production process does not produce any toxic and harmful substances. Pouring is performed in a mold in a vacuum box at room temperature. Deaeration and pouring are completed at the same time under 100Pa air pressure. It takes 0.5-1 hour, according to the size of the winding. After pouring is completed, atmospheric pressure is used to pressurize, and only the vacuum pump consumes electricity in the process; the curing process is carried out in a convection oven. The temperature is set at 125℃, and the curing time is selected according to the mold size. The heat is entirely conducted into the winding through the mold and maintained for about 30 minutes to complete curing. The total time is less than 2 hours. Thus, the energy consumption of the production process is significantly reduced than that of cast resin casting process.

Silicone rubber is not sticky to most materials, so it is easily separated from winding conductors and insulating parts. It is also easily cut and broken by manpower, and is very convenient for the recovery of metal materials such as windings, silicon steel, and clamps. Silicone rubber can be used as rubber filler after being crushed. After cracking by chemical method, it can be used as silicone rubber raw material.Therefore, the triple-redundant insulation structure silicone rubber cast dry-type transformer is very environmentally friendly.

4. Simulation analysis, test verification, and application

4.1 Digital simulation analysis

In order to thoroughly verify the feasibility of the technical scheme of the triple-redundant insulation structure, we selecte a 10kV/630kVA dry-type transformer designed with this structure for simulation analysis. The simulation results are shown in Figures 6 and 7.

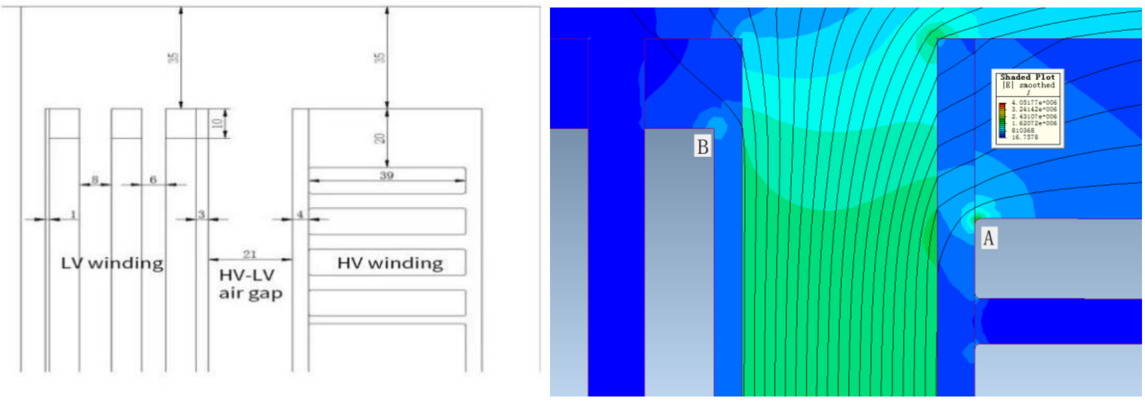


Fig. 6 Power frequency electric field distribution diagram at the upper end between the high-voltage coil and the low-voltage coil

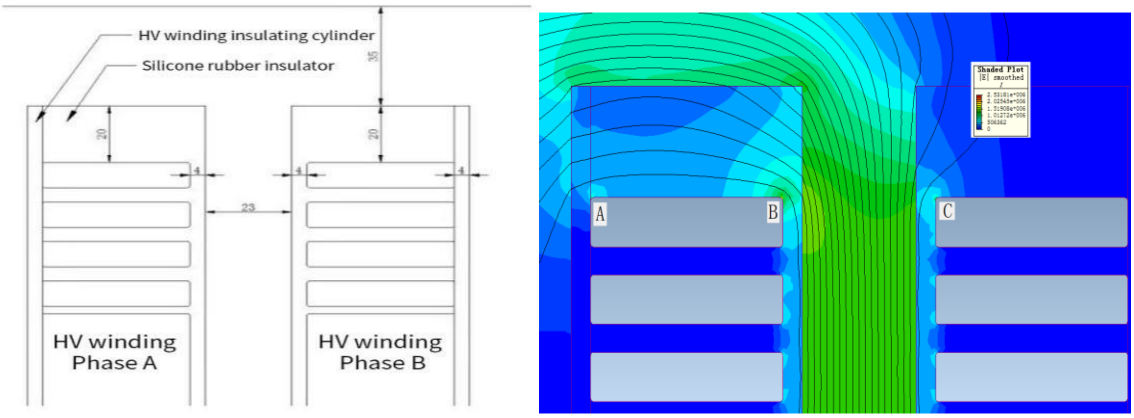


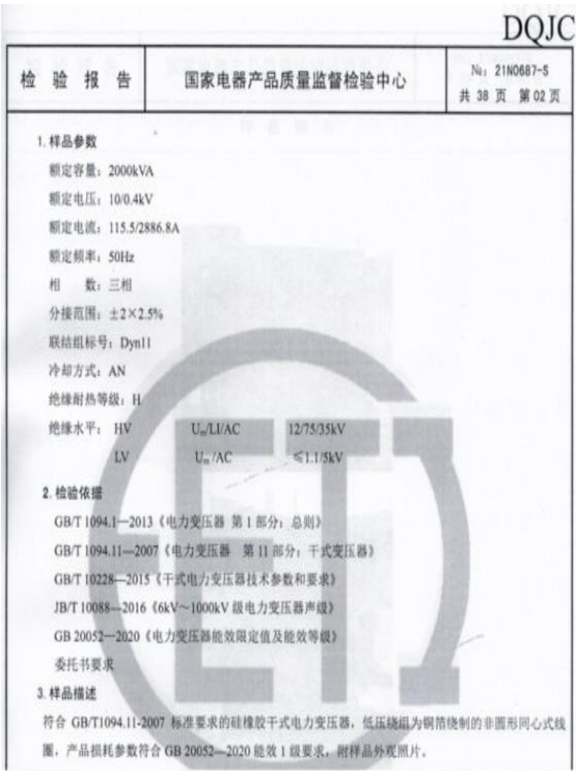
Fig. 7 Power frequency electric field distribution diagram at the upper end of the high voltage coil phase

It can be seen from the simulation results that the main insulation electric field distribution of this structure is very reasonable, which can meet the transformer operation requirements, and there is still a certain insulation margin.

4.2 Type test verification

Figure 8 is the type test report of the H-class 10kV/2000kVA triple-redundant insulation structure silicone rubber dry-type transformer. All technical indicators fully meet the requirements of the "*GB/T*

1094.11 Power Transformer Dry-type Transformer" [14] standard, and the product has passed successfully. In the type test conducted by the National Electrical Product Quality Supervision and Inspection Center, all test items witch include the sudden short circuit are qualified, the noise is only 46dB, and the no-load loss and load loss are better than the limited value of class I energy efficiency in the "*GB20052-2020 Power Transformer Minimum Energy Efficiency Performance sStandard*" [15]. The energy-saving effect is pronounced.



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检 验 报 告	国家电器产品质量监督检验中心	№：21N0687-S 共 38 页 第 02 页

1. 样品参数

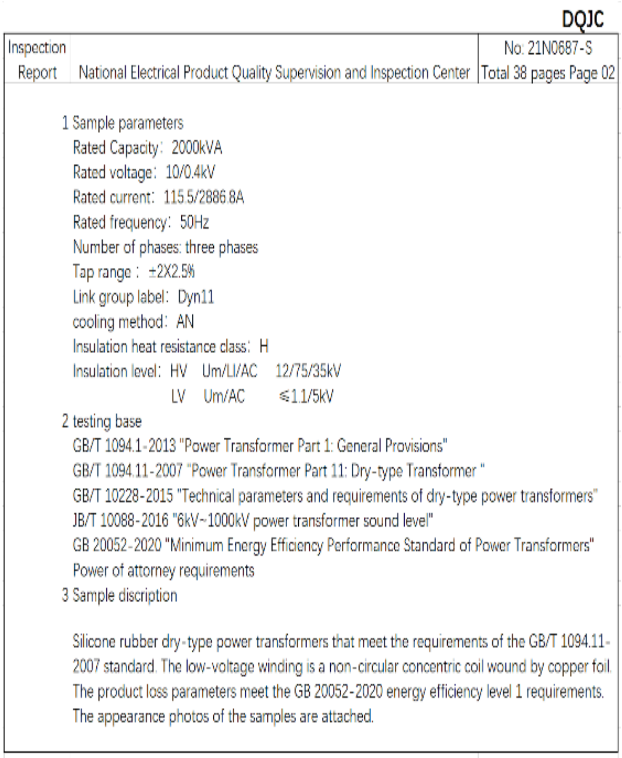
额定容量：2000kVA
额定电压：10/0.4kV
额定电流：115.5/2886.8A
额定频率：50Hz
相 数：三相
分接范围：±2×2.5%
联结组标号：Dyn11
冷却方式：AN
绝缘耐热等级：H
绝缘水平： HV U_m/LI/AC 12/75/35kV
LV U_m/AC ≤1.1/5kV

2. 检验依据

GB/T 1094.1—2013《电力变压器 第1部分：总则》
GB/T 1094.11—2007《电力变压器 第11部分：干式变压器》
GB/T 10228—2015《干式电力变压器技术参数和要求》
JB/T 10088—2016《6kV～1000kV 级电力变压器声级》
GB 20052—2020《电力变压器能效限定值及能效等级》
委托书要求

3. 样品描述

符合 GB/T1094.11-2007 标准要求的硅橡胶干式电力变压器，低压绕组为铜箔绕制的非圆形同心式线圈，产品损耗参数符合 GB 20052—2020 能效 1 级要求，附样品外观照片。



DQJC

Inspection Report	National Electrical Product Quality Supervision and Inspection Center	No: 21N0687-S Total 38 pages Page 02

1 Sample parameters

Rated Capacity: 2000kVA
Rated voltage: 10/0.4kV
Rated current: 115.5/2886.8A
Rated frequency: 50Hz
Number of phases: three phases
Tap range: ±2X2.5%
Link group label: Dyn11
cooling method: AN
Insulation heat resistance class: H
Insulation level: HV Um/LI/AC 12/75/35kV
LV Um/AC ≤1.1/5kV

2 testing base

GB/T 1094.1-2013 "Power Transformer Part 1: General Provisions"
GB/T 1094.11-2007 "Power Transformer Part 11: Dry-type Transformer "
GB/T 10228-2015 "Technical parameters and requirements of dry-type power transformers"
JB/T 10088-2016 "6kV~1000kV power transformer sound level"
GB 20052-2020 "Minimum Energy Efficiency Performance Standard of Power Transformers"
Power of attorney requirements

3 Sample discription

Silicone rubber dry-type power transformers that meet the requirements of the GB/T 1094.11-2007 standard. The low-voltage winding is a non-circular concentric coil wound by copper foil. The product loss parameters meet the GB 20052-2020 energy efficiency level 1 requirements. The appearance photos of the samples are attached.

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检 验 报 告	国家电器产品质量监督检验中心				№：21N0687-S 共 38 页 第 04 页
试验结果汇总					
序号	试验项目	规定值 标准（委托要求）	测量值 短路前	测量值 短路后	项目结论
1	绕组对地及绕组间直流绝缘电阻测量（例行）	提供绝缘电阻值（GΩ）	H-L.E：179 L-H.E：128 H.L-E：101 铁心-地：3.79	H-L.E：204 L-H.E：149 H.L-E：123 铁心-地：4.05	/
2	电压比测量和联结组标号检定（例行）	主分接电压比偏差：规定电压比的±0.5%和实际阻抗百分数的±1/10 两者间取低值 联结组标号：Dyn11	0.04%～0.06% Dyn11	0.03%～0.07% Dyn11	合格
3	绕组电阻测量（例行）	最大电阻不平衡率 线电阻： ≤2%	高压(线)：0.31% 低压(线)：1.42%	高压(线)：0.18% 低压(线)：1.56%	合格
4	外施耐压试验（例行）	高压：35 kV 60s 低压：5 kV 60s	35.0kV 60s 5.0kV 60s	35.0kV 60s 5.0kV 60s	合格
5	感应耐压试验（例行）	施加电压（kV）：2Ur 感应电压（kV）：20 持续时间（s）：120(f_n/f) 频率（Hz）：>50	0.800 20.0 30 200	0.800 20.0 30 200	合格
6	空载损耗和空载电流测量（例行）	I_0（%）：0.70 +30% P_0（kW）：1.760 +0%	0.13 1.722	0.13 1.724	合格
7	短路阻抗和负载损耗测量（例行）	t：145℃ Z（%）：6.0 ±10% P_k（kW）：14.005 +0% P（kW）：15.765 +0%	6.05 13.672 15.394	6.07 13.667 15.391	合格
8	局部放电测量（例行）	三相测量 施加电压（kV）：1.3Ur 持续时间（min）：3 放电量（pC）：≤5	0.520 3 A：<4、B：<4、C：<3	0.520 3 A：<3、B：<4、C：<3	合格
9	温升试验（型式）	绕组温升限值（K）：125	高压绕组温升：113.6 低压绕组温升：113.5		合格
10	声级测定（特殊）	声压级 $\overline{L_{PA}}$ dB(A)：≤53 声功率级 L_{WA} dB(A)：≤62	46 60		合格
11	短路承受能力试验（特殊）	每相试验次数：3 次 持续时间（s）：0.5±10% 试验波形无异常 试验前后测量相电抗差≤7.5% 实体检查无明显变化 短路后复试例行试验合格	3 次 0.500～0.506 无异常 最大相电抗差 1.41% 无明显变化 复试例行试验合格		合格
12	雷电冲击试验（型式）	全波（kV）：75 ±3%	74.31～76.71		合格
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SJJJ-GB004 5

DQJC

Inspection Report	National Electrical Product Quality Supervision and Inspection Center				No: 21N0687-S Total 38, Page 04
Summary of test results					
Serial number	Test content	Specified value Standard (required by commission)	test value Before short circuit	test value After short circuit	test results
1	Winding to ground and DC insulation resistance measurement between windings (routine)	Provide insulation resistance value (GΩ)	H-L.E: 179 L-H.E: 128 H.L-E: 101 Core-ground: 3.79	H-L.E: 204 L-H.E: 149 H.L-E: 123 Core-ground: 4.05	/
2	Voltage ratio measurement and connection group label verification (routine)	Main tap voltage ratio deviation: the lower value between ±0.5% of the specified voltage ratio and ±1/10 of the actual impedance percentage. Connection group label: Dyn11	0.04%~0.06% Dyn11	0.03%~0.07% Dyn11	qualified
3	Winding resistance measurement (routine)	Maximum resistance unbalance rate Wire resistance： ≤2%	High voltage (line): 0.31% Low voltage (line): 1.42%	High voltage (line): 0.18% Low voltage (line): 1.56%	qualified
4	External pressure test (routine)	High-Voltage：35kV 60s Low-Voltage：5kV 60s	35.0kV 60s 5.0kV 60s	35.0kV 60s 5.0kV 60s	qualified
5	Induction withstand voltage test (routine)	Applied voltage (kV): 2Ur Induced voltage (kV): 20 Duration (s): 120（fn/f） Frequency (Hz): >50	0.800 20.0 30 200	0.800 20.0 30 200	qualified
6	No-load loss and no-load current measurement (routine)	Io（%）：0.70 +30% Po（kW）：1.760 +0%	0.13 1.722	0.13 1.724	qualified
7	Short-circuit impedance and load loss measurement (routine)	t：145℃ Z（%）：6.0 ±10% Pk（kW）：14.005 +0% Po（kW）：15.765 +0%	6.05 13.672 15.394	6.07 13.667 15.391	qualified
8	Partial discharge measurement (routine)	Three-phase measurement Applied voltage (kV): 1.3Ur Duration (min): 3 Discharge capacity (pC): ≤5	0.520 3 A:<4、B:<4、C:<3	0.520 3 A:<3、B:<4、C:<3	qualified
9	Temperature rise test (type)	Winding temperature rise limit (K): 125	Temperature rise of high voltage winding:113.6 Temperature rise of low voltage winding: 113.5		qualified
10	Sound level measurement (special)	Sound pressure level L_{PA} dB(A)：≤53 Sound power levelL_{WA} dB(A)：≤62	46 60		qualified
11	Short circuit withstand capability test (special)	Number of tests per phase: 3 times Duration (s): 0.5±10% No abnormal test waveform Measure the phase reactance difference before and after the test ≤7.5% No obvious changes in physical inspection Pass the routine test after the short circuit retest	3 times 0.500~0.506 No abnormality Maximum phase reactance difference 1.41% No significant changes Retest routine test qualified		qualified
12	Lightning impact test (type)	全波（kV）：75 ±3%	74.31~76.71		qualified
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Fig. 8 Test report of H-class 10kV/2000kVA triple-redundant insulation structure silicone rubber dry-type transformer

Figure 9 shows the comparison photos before and after the environmental combustion performance test (particular test) of the H-class 500kVA triple-redundant insulation structure silicone rubber dry-type transformer. It can be clearly seen from the photos that the silicone rubber of the winding and the insulating materials enclosed inside is not ignited or broken. In addition, the measured mass loss of the winding after burning is less than 1.5%, and it has excellent anti-combustion and explosion-proof performance.

Fig. 9 Comparison of before and after combustion

4.3 Practical application effect

Practice is the sole criterion for testing truth. Since the first triple-redundant insulation structure silicone rubber dry-type transformer was put into operation in January 2017 to the end of 2020, more than 50 transformers have been in serve across the country and exposed to various harsh environments, including high temperatures, severe pollution, and long-term humidity, and other extreme conditions. Operational transformers' rating voltage are from 6 to 35kV, and their capacities are from 30 to 2500kVA. The end-users include the State Grid of China, China Southern Power Grid, and other users. However, there has never been any failure in the past four years of operation, which completely solved various problems existing in traditional dry-type transformers.

In January 2020, Shenzhen Longgang Power Supply Bureau replaced and implemented a 10kV/1000kVA triple-redundant insulation structure silicone rubber dry-type transformer. As a result, compared with the traditional design, the no-load loss is reduced by 40%, the load loss is reduced by 10%, and the loss index is excellent. Furthermore, silicone rubber dry-type transformer loss is lower than the Grade 1 of "GB20052-2020" [15]. The noise of silicone rubber dry-type transformer is also reduced from 72dB to 43dB, which completely solves transformer noise disturbing the people's lives and plays an essential role in eliminating urban public transformers' noise and promoting the realization of China's dual carbon goal.

5 Conclusion

This paper proposes a new type of silicone rubber dry-type transformer based on silicone rubber insulation material. Its primary insulation has a triple-redundant fault-tolerant structure and its design method, which not only effectively solves many problems in traditional dry-type transformer, such as environmental pollution, poor weather resistance and difficult recycling of winding materials, but also greatly improves the insulation reliability and environmental protection performance of dry-type transformer, and the no-load loss and load loss of transformers are greatly reduced. Various verification and testing, including mathematical simulation, type test, particular test, and actual operation shows that the dry-type transformer with this innovative technology has the advantages of safety, reliability, fire safety, and explosion prevention, high efficiency, and energy saving, and environmental protection. Therefore, this technology will contribute to the development of a green and reliable power industry as a better choice in the future, and provide a new technical direction for the development and application of dry-type transformer technology. It has also contributed to China's strategic goals of carbon peaking and carbon neutrality.

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