Review of Cooling Methods for Oil-Immersed Transformers

Xinyue Gao [1, *], Shunyu Wang [1], Huaixuan Gao [2]

[1] College of Electronic Information and Automation, Tianjin University of Science and Technology, Tianjin, China, 300457

[2] Intelligent Manufacturing College, Tianjin Sino-German University of Applied Sciences, Tianjin, China, 300350

* Corresponding Author Email: 18098588096@163.com

Abstract. With the growing demands for electricity, the safe and stable operation of transformers are crucial. Oil-immersed transformers are widely used in power systems due to their excellent heat dissipation and insulation properties. However, the traditional oil-immersed transformer cooling methods are difficult to meet the needs of modern power systems, therefore, new cooling methods need to be developed. The existing oil-immersed transformer cooling methods are varied, including oil natural air natural (ONAN), oil-natural air-forced (ONAF), oil-forced water-forced (OFWF), oil-forced air-forced (OFAF), oil-direct air-forced (ODAF), oil-direct water-forced (ODWF) and natural oil circulation cooling method with directed structure, each of which has its own advantages and disadvantages and is applicable to different scopes. In addition, the choice of cooling medium also has an important impact on the cooling effect of the transformer, mineral oil, natural esters, synthetic esters and other different medium have different properties. This review introduces the medium, principles and practical application of oil-immersed transformer cooling methods, aiming to help power system engineers and technicians have an in-depth understanding of the oil-immersed transformer cooling methods and provide references for them to select suitable cooling methods and optimize transformer cooling systems. Moreover, this review also provides certain theoretical basis and ideas for the research and development of transformer cooling methods, promotes the progress of transformer cooling methods and provides more reliable guarantee for the safe and stable operation of the power system.

Keywords: Oil-Immersed Transformers, Cooling Medium, Cooling Methods.

1. Introduction

Power system is an indispensable infrastructure of modern society, its stable operation is directly related to the development of national economy and the well-being of people's lives. Transformer is the core equipment in the power system and its safe and stable operation is crucial. Transformer will generate a large amount of heat in the process of operation, if the heat cannot be effectively emitted, it will lead to high operation temperature, affecting its insulation property, and even cause fire and other safety accidents. Therefore, the transformer cooling method has been an important direction of power system research.

The oil-immersed transformer is the most widely used type of transformer, and its cooling method mainly relies on insulating oil as the cooling medium. Insulating oil has good insulation properties and high heat exchange efficiency, can transfer the heat inside the transformer to the external environment effectively, ensuring the safe and stable operation of the transformer. With the continuous expansion of the scale of the power system and the continuous increase of the voltage level, the transformer cooling requirements are also higher and higher. Traditional oil-immersed transformer cooling methods have been difficult to meet the needs of modern power systems, therefore, the research and development of new transformer cooling methods are particularly important. In recent years, oil-immersed transformer cooling methods have made great progress, emerging a variety of new cooling methods, such as oil-direct cooling method and natural oil circulation cooling method with directed structure. However, there is no systematic review to summarize and analyze these new cooling methods. This review will fill this gap and provide a comprehensive and in-depth discussion on the development of cooling methods for oil-immersed transformers.

This paper will start from the following two aspects: (1) Introduce oil-immersed transformer cooling medium, including mineral oil, natural esters and synthetic esters, etc. and analyze their advantages and disadvantages [1-6]. (2) Introduce the principles and practical applications of various cooling methods in detail [7-32].

2. Oil-Immersed Transformer Cooling Medium

Mineral oil is the oil initially used in transformers, which is mainly extracted from petroleum and consists of a variety of hydrocarbons. Mineral oil, which is less expensive to produce, has good insulating property and can effectively prevent transformer leakage and short circuits, so it is widely used in the power industry. In the early stages of development, mineral oil was mainly based on paraffin oil, due to the high pour point of paraffin oil, it was gradually replaced by naphthenic oil [1]. Mineral oil has safety risks, such as its low flash point, which makes it easy to be ignited and cause fire. Furthermore, mineral oil may leak during use, leading to environmental pollution. Since mineral oil is difficult to be degraded naturally, once it enters the soil and water, it will have a long-term impact on the ecosystem. Although mineral oil is still widely used in the power industry, new insulating oil such as the nanofluid, palm oil, natural esters, synthetic esters and methyl esters are being researched as alternatives to mineral oil.

In 2020, Cristian Olmo et al. investigated the cooling and insulating properties of the TiO_2 vegetal-based dielectric nanofluid and compared them with previously studied effects of the ferrofluid. It was found that the TiO_2 vegetal-based dielectric nanofluid significantly enhanced the breakdown voltage of vegetable oil insulating oil, however, in terms of cooling properties, it was slightly less effective compared to the base fluid. However, the ferrofluid can improve transformer cooling effects and lower its temperature [2]. In the same year, Noor Khairin Mohd et al. found that palm oil and its products have great potential to serve as coolants in oil-immersed transformers, and the use of palm oil may be safer compared to the conventional mineral oil [3]. In 2021, Suhaib Ahmad Khan et al. tested the insulating ability of synthetic ester-based oil and natural rapeseed oil, showing that these oils have the potential to be viable alternatives to conventional transformer oil in high voltage equipment [4]. In 2022, Yilong Li et al. evaluated the heat transfer performance of FR3 natural ester insulating oil compared to traditional mineral oil in large oil-immersed transformers, finding that FR3 has superior heat transfer properties in certain conditions, particularly near the guide plate, but this advantage may diminish with higher inlet temperature or flow rates [5]. In 2023, Samson Okikiola Oparanti et al. found that methyl esters derived from non-edible vegetable oil have higher dielectric property compared to mineral oil and are considered to be a promising alternative to oil-immersed transformer insulating oil [6].

3. Cooling Methods of Oil-immersed Transformer

3.1. Oil-Natural Air-Natural (ONAN) Cooling Method

Oil-natural air-natural (ONAN) transformers are designed without an oil pump. The buoyancy force generated by the gravity and density difference of the transformer oil drives the oil circulation to realize the cooling process of the transformer. As shown in Figure 1, the heat generated by the core and windings inside the transformer during operation is absorbed by the transformer oil, resulting in an increase in oil temperature. Due to the difference in density between the hot oil and coold oil, heated oil rises to the top of the tank due to the lower density and then flow into of the oil collector ducts of the panel type radiators for heat exchange, cooled oil flows through the radiator of the various fins back to the bottom of the tank due to the increased density. In this process, convection heat transfer realized in the transformer oil and the inner wall of the radiators, the heat transfer to the surface of the radiators. Due to the large number of radiators and compact spacing, most of the heat needs to be taken away from the bottom of the radiators through the air. The heat on the outer surface of the radiators is dissipated to the environment through natural convection with the surrounding air and radiation heat transfer near the outer radiators. Eventually, the cooled oil flows back to the transformer tank through the lower oil collector ducts, completing the whole heat dissipation cycle and realizing the cooling of the transformer.

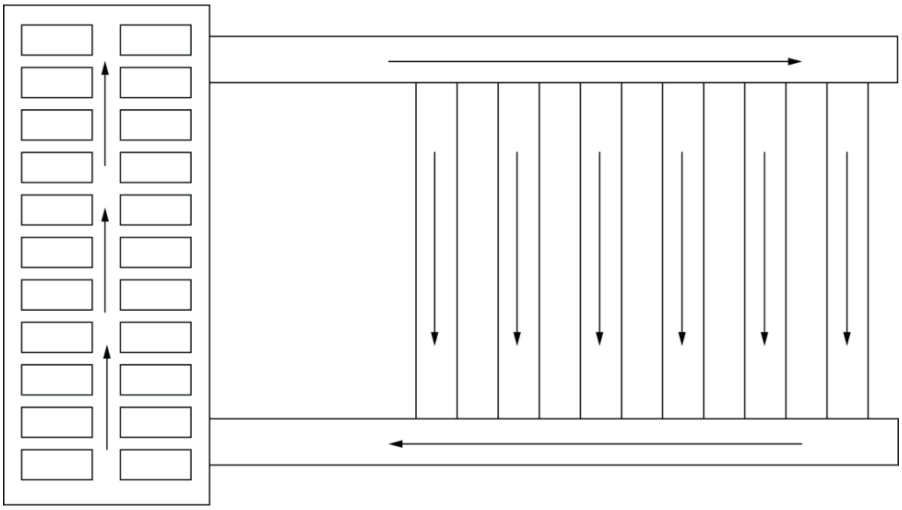

Figure 1. Cooling principle of the ONAN transformer [7]

In 2020, Liu Changfu et al. developed a portable external cooling device, which was experimentally verified to significantly reduce the temperature and thus effectively improve the operating condition of the transformer [8]. In 2021, Deng Bin studied the heat transfer characteristics of oil-immersed self-cooling transformers using three-dimensional (3-D) finned tube heat sinks, and confirmed through experimental and numerical simulation methods that the 3-D finned tube radiator is superior to the traditional plate radiator in terms of heat exchange efficiency, thus providing a theoretical basis for the use of this type of radiator in industrial applications [9]. In 2022, Sicheng Zhao et al. presented a simplified computational fluid dynamics (CFD) model for transformer radiators in ONAN cooling method by replacing airflow simulation with an optimized air heat transfer coefficient equation, validated against a full radiator CFD model and demonstrated its accuracy across various conditions for improving radiator design and transformer CFD modeling [10]. In the same year, Luo Huadong investigated the use of interrupted offset fins to enhance the heat dissipation efficiency of radiator for ONAN transformer, and confirmed the effectiveness of this radiator design through experimental and numerical simulation methods [11]. In 2024, Aliihsan Koca et al. used artificial neural networks to predict the cooling capacity of power transformer radiators in ONAN cooling method by adjusting radiator design parameters with computational fluid dynamics simulations aligning closely with experimental data, the model's property is validated using Bayesian regularization with high accuracy [12].

3.2. Oil-Natural Air-Forced (ONAF) Cooling Method

For transformers with the capacity of 8000 to 40000kVA, the heat dissipation method commonly used at present is oil-natural air-forced (ONAF) cooling method. This method utilizes oil as the cooling medium and brings the heat inside the transformer to the surface through the flow of oil, then accelerates the cooling of the oil by using the airflow generated by the fan, so as to achieve excellent heat dissipation effect. Due to the large capacity of these transformers, the heat generated is also relatively large, and increasing the area of the oil tank in contact with the air alone is unable to meet the heat dissipation requirements. Therefore, the fan's auxiliary heat dissipation becomes a necessary means. The fan can force the air flow, improve the cooling efficiency, ensure that the temperature of the transformer remains within safe limits during operation. ONAF transformers have the advantage of automatically switching the cooling method according to load changes. The internal temperature rise and heat dissipation properties of the transformer are mainly affected by its structure. The core components of the transformer include the windings, core, transformer oil, tank wall, etc. The heat transfer efficiency between them determines the heat dissipation property of the transformer. The windings and core will generate heat in the process of energization, and the heat is transferred to the tank wall through the transformer oil, then emitted to the external environment through the auxiliary heat dissipation of the fan. Therefore, optimizing the structural design of the transformer and improving the heat transfer efficiency is the key to improving the cooling properties of ONAF transformers. The cooling principle of ONAF transformer is shown in Figure 2.

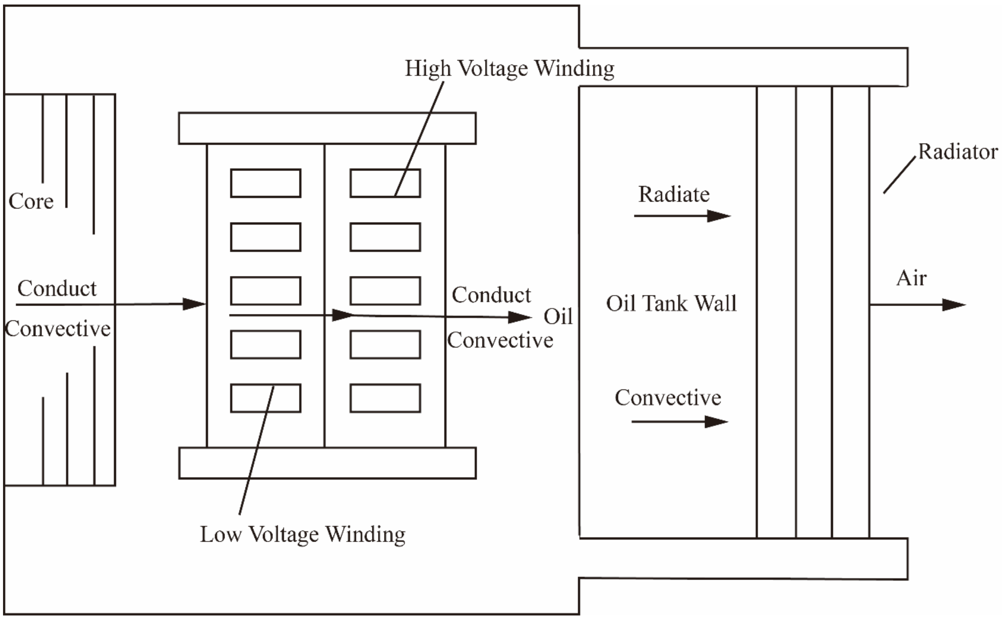

Figure 2. Cooling principle of the ONAF transformer [13]

In 2021, Lujia Wang et al. developed a technique for identifying potential fan failures in ONAF transformers using top-oil temperature monitoring, which was achieved by analyzing the available data of the oil temperature at the top of the transformer to detect fan abnormalities [14]. In 2023, Liu Ye et al. presented a three-dimensional transient simulation model of oil-immersed air-cooled transformers, studying temperature distribution and hotspot drift under various operating conditions, verified through experimental tests. [15]. In the same year,Yuan Li et al. developed a closed-loop model for a 110-kV transformer with ONAF cooling method to predict the hot-spot temperature (HST), validated experimentally with temperature-rise tests and investigated winding and radiator arrangements to improve oil circulation and reduce temperatures, suggesting the addition of washers and optimal radiator elevation [16]. In the same year, Li Shuangcheng significantly enhanced the effectiveness of the radiator by applying and improving the water -cooled spray technology of the transformer, ensuring that the transformer can be maintained in the appropriate temperature range for the specific operating environment [17]. In the same year, Wang Lujia et al. constructed a fast iterative optimization analytical model for radiators in ONAF transformers, verified the effects of fan diameter on cooling efficiency and air loss through experiment and simulation and proposed the optimal cooling conditions [18].

3.3. Oil-Forced (OF) Cooling Method

In the absence of radiators and oil pipes, the transformer's insulating oil is cooled by ducts and oil pumps into an oil cooler, then returned to the transformer. Depending on the type of cooler used, transformers can be categorized as either oil-forced water-forced (OFWF) or oil-forced air-forced (OFAF) cooling method. These methods are usually used for large transformers above 63,000 kVA. Water-forced transformers are suitable for use in water-rich areas due to their more complex construction and higher water consumption, and their cooling efficiency is better than that of air--forced transformers.

3.3.1. Oil-Forced Water-Forced (OFWF) Cooling Method

The operating principle of the oil-forced water-forced (OFWF) transformer is to utilize an oil pump to pump the high-temperature oil from the top layer of the transformer to a water-cooled cooler, where the oil is cooled. Subsequently, the cooled oil is pumped back to the bottom of the transformer again and redistributed to the transformer's tank and windings through the oil inlet. Through this circulation, most of the heat generated by the transformer is effectively removed through the water-cooling system, while only a small amount of heat is emitted through the transformer tank into the space of the main transformer room because the temperature of the oil is higher than that of the surrounding air, thus realizing the overall heat dissipation effect. The cooling principle is shown in Figure 3.

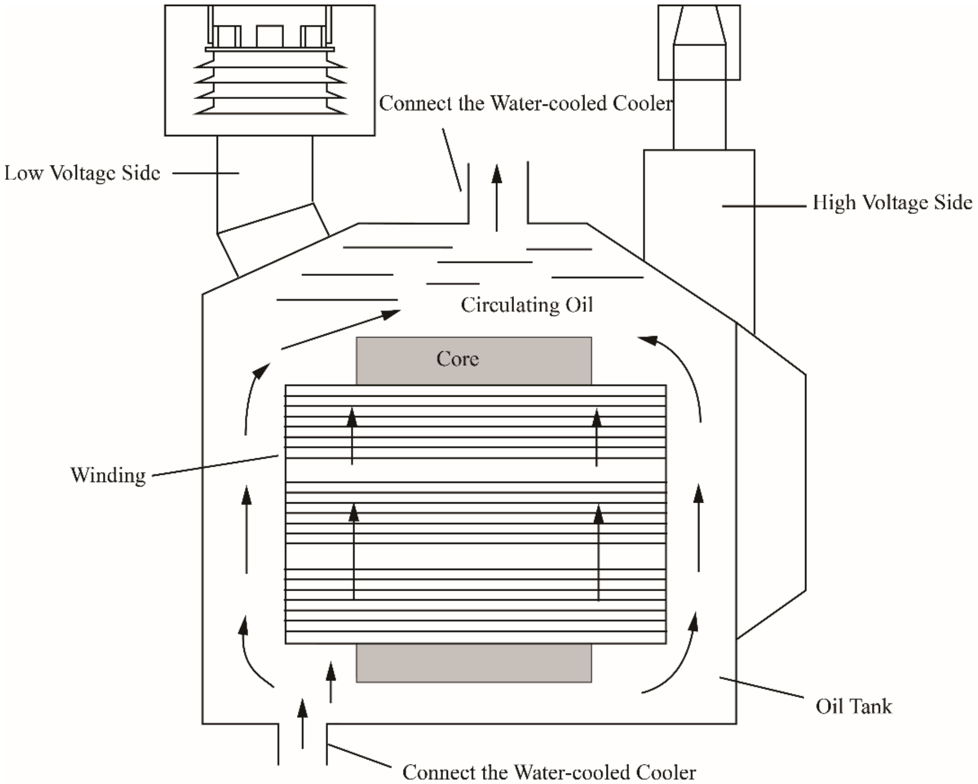

Figure 3. Cooling principle of the OFWF transformer [19]

In 2003, ZORAN RADAKOVIĆ and ANA POPOVIĆ developed a thermal model for calculating the top oil temperature of transformers with forced oil and water circulation, and applied the model to 2×190MVA/380MVA transformers in a hydroelectric power station in order to evaluate the load potential of the transformer and to provide a reference for maintenance or reconstruction planning [20]. In 2020, Fang Guowei et al. used CFD techniques to simulate the oil flow distribution system of the OFWF transformer, which can maximize the heat dissipation properties of the transformer while ensuring that the oil flow does not carry any electric charge [21].

3.3.2. Oil-Forced Air-Forced (OFAF) Cooling Method

Oil-forced air-forced (OFAF) cooling method, where an oil pump connects the oil in the cooler to the transformer's tank. In this method, the oil flow is divided into two parts, one part of the oil goes into the windings of the transformer and another part of the oil flows back to the cooler through the gap between the windings and the tank. The oil flow in the windings is a mixed convection where natural and forced convection coexist, but natural convection is dominant. The cooling principle of the OFAF transformer is shown in Figure 4.

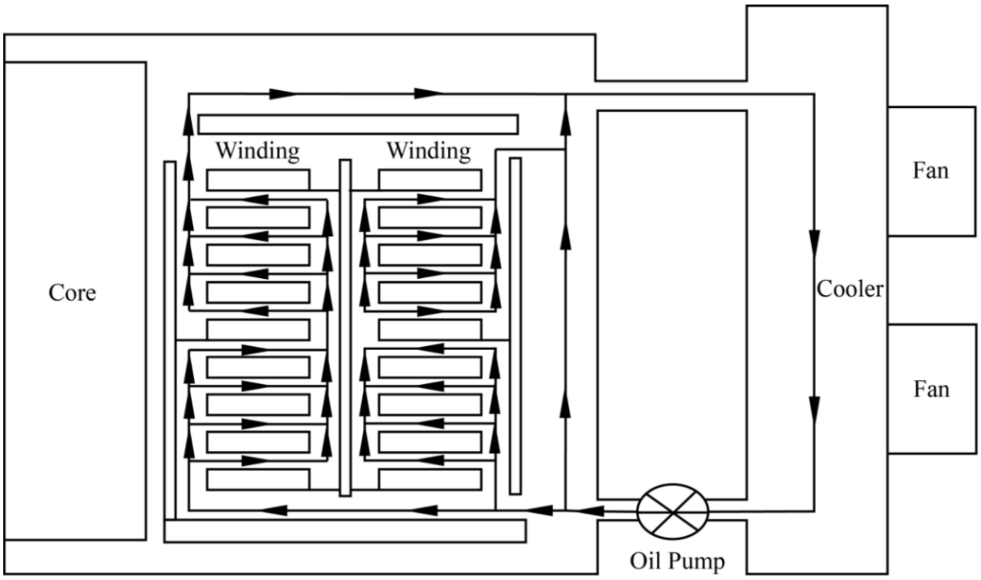

Figure 4. Cooling principle of the OFAF transformer [22]

In 2021, Fan Li et al. conducted a simulation and analysis of forced oil non-directed transformers using the fluid software to optimize the oil circuit design of the transformer, enhancing the thermal efficiency of the cooler, not only ensuring the safe use of the product, but also reducing production costs [22]. In 2022, Zhang Haoyang carried out research on the OFAF transformer, and used the numerical simulation method to analyze the temperature and flow field distribution inside the transformer winding. Aiming at the phenomenon of high temperature in the hot spot of the low-voltage winding, a design scheme to improve the structure is proposed, and it is confirmed that the scheme can effectively solve the problem. [23]. In 2024, Tu Menya et al. summarized a set of fuzzy control rules based on the study of the mechanism of the OFAF cooler to realize the closed-loop control of the transformer oil temperature, and compensated for the effect of transformer power fluctuation on the oil temperature through the feedforward control [24].

3.4. Oil-direct (OD) Cooling Method

The main principle of the oil-direct cooling method is that the oil is fed by the oil pump into the oil circuit inside the transformer tank after passing through the cooler, thus achieving the purpose of cooling. In this process, the amount of oil distribution is determined according to the loss ratio of the windings and the core, and this design can make the cooling effect more effective. The oil-direct air-forced (ODAF) and oil-direct water-forced (ODWF) are two commonly used oil-direct cooling methods, and they are mainly applicable to large transformers with complex insulation structures and large winding sizes. However, it should be noted that the rapid flow of transformer oil in the guiding device may generate static electricity, and the accumulation of static electricity may cause the partial electric field of the windings to be elevated or distorted, increasing the risk of insulation partial discharge, thus affecting the reliability of the insulation. Especially for 500kV class UHV transformers, the phenomenon of charged oil flow is a particularly dangerous factor that needs to be noted and avoided.

In the ODAF cooling method, the oil in the cooler is pulled directly into the windings via an oil pump and the windings are sealed. Almost all of the oil flow in the cooler enters the winding, in which the heat dissipation of the oil is mainly realized by forced convection, as shown in Figure 5.

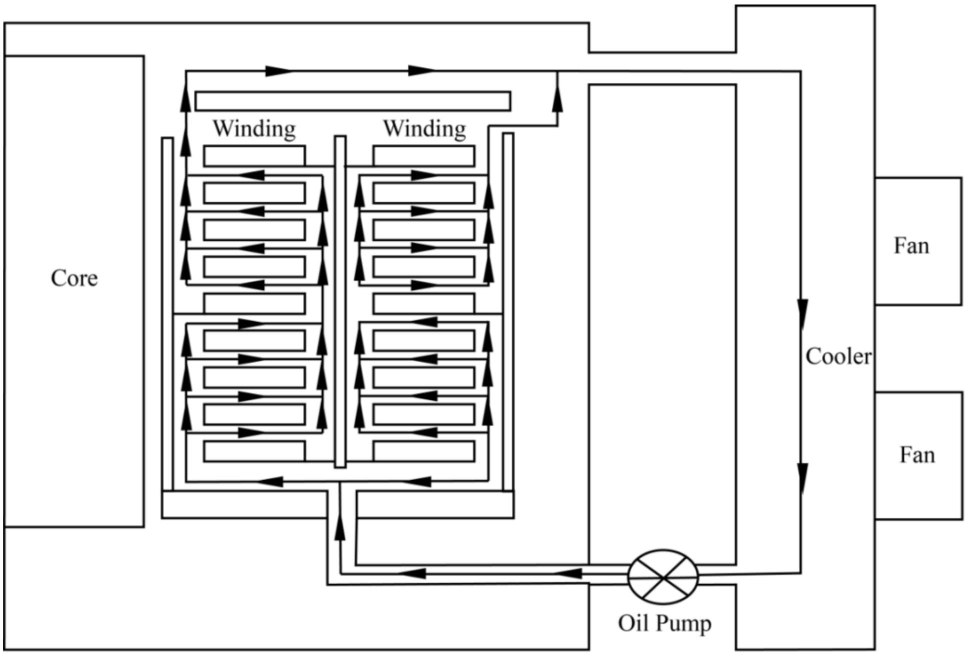

Figure 5. Cooling principle of the ODAF transformer [22]

In 2020, Peng Guangyong et al. discussed the calculation and analysis of temperature rise in transformers with ODAF cooling method, focusing on factors influencing winding temperature rise [25]. In 2020, Huo Feng et al. carried out the calculation related to the modification and the analysis of the principle of cooling efficiency through the field modification research and application of the ODAF cooling system of 500kV main transformer [26]. In 2024, Liu Gang et al. evaluated the load capacity of ODAF transformers by analyzing their temperature rise properties and developing a thermal model considering fan, oil pump, and oil viscosity effects [27].

3.5. Natural Oil Circulation Cooling Method with Directed Structure

Based on the principle of oil-forced method with directed structure, a new type of natural oil power transformer with directed structure cooling method was born. This method effectively prevents the phenomenon of charged oil flow and improves the safety and reliability of the transformer. The directed structure facilitates the flow of transformer oil so that the oil can be more evenly distributed throughout the transformer, thus reducing the temperature rise of the windings to the oil. To realize this directed structure, the windings are equipped with oil barriers to direct the oil flow along a specific path.

By installing oil barriers inside the winding, thermal buoyancy can be utilized to direct the flow of oil along a specific path through the winding. This method has the potential to eliminate areas of poor oil flow, enhance the cooling effect and reduce the temperature rise of the winding, and reduce its temperature rise. The practice of installing oil barriers inside the winding is an effective strategy used to improve the internal cooling property of the transformer, enhancing its capacity and load handling capability. The path of oil in directed structure is shown in Figure 6.

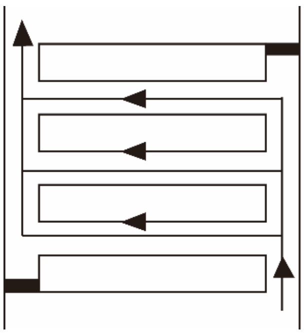

Figure 6. The path of oil in directed structure [28]

In 2005, Han Peng constructed the mathematic model of heat transfer and oil flow, and successfully calculated the oil flow distribution and temperature field of the large natural oil circulation power transformer with oriented cooling structure, which provided credible parameter support for the design and monitoring of the transformer and helped to further optimize the structural design of the transformer [29]. In 2003, Su Lina developed a calculation method for evaluating the temperature rise of average oil, top oi, coil of the large natural oil power transformer with directed circulation and analyzed the influence of the transformer's temperature rise on the average oil temperature rise. temperature rise and analyzed the main factors affecting the temperature rise of the transformer [28]. In the same year, Di Shuangkui studied the winding temperature rise of ONAN 110kV and 220kV transformers and significantly enhanced the heat dissipation property of the transformers by creating axial oil ducts inside the windings and installing oil barriers [30]. In 2007, Yang Bei developed a comprehensive software that calculates the temperature field of the large natural oil circulation power transformer with oriented cooling structure and predicts the transformer's life span and loading capacity [31]. In 2018, Niu Peng constructed mathematical model and physical model to calculate the unsteady temperature field of the large natural oil circulation transformer with directed structure under overload conditions, in order to facilitate remote monitoring of the transformer [32].

4. Conclusion

This paper summarizes the development of cooling methods for oil-immersed transformers, covering their cooling medium, basic principles, and cooling methods. Mineral oil is widely used because of its good insulating and heat transfer properties, but its flammability and environmental problems are increasingly prominent. New insulating oils such as the nanofluid, palm oil, natural esters, synthetic esters and methyl esters have attracted a great deal of attention because of their excellent environmentally friendly properties, despite the need for more in-depth research and optimization, they are seen as strong contenders for the next generation of transformer insulating oil materials. ONAN cooling method is suitable for small transformers, which has simple structure but lower heat dissipation efficiency. ONAF cooling method is suitable for medium-sized transformers, which has higher heat dissipation efficiency but additional configuration of the fan is required. forced oil circulation type is suitable for large transformers, which has the highest heat dissipation efficiency but the structure is complex and the cost is high. Oil-forced cooling method and natural oil circulation cooling method with directed structure are two new cooling methods, which can effectively prevent the phenomenon of charged oil flow and improve the safety and reliability of the transformer. One of the key marginal contributions of this review lies in its systematic categorization and critical assessment of various cooling methods. By meticulously examining the principles, practical applications and suitability of each method, this review offers valuable insights that can provide a valuable foundation for engineers and researchers seeking to improve the design and operation of oil-immersed transformers, offering a clear understanding of the trade-offs between cooling efficiency, safety, and environmental impacts.

References

[1] Ma Bingwei, Chen Xiaoguo, Zheng Yu, et al. Research progress and trends of eco-friendly insulating oil for power transformers [J]. Southern Power System Technology, 2024, 18 (05): 12 - 21+30.

[2] Olmo C, Mendez C, Ortiz F, et al. Titania nanofluids based on natural ester: Cooling and insulation properties assessment [J]. Nanomaterials, 2020, 10 (4): 603.

[3] Mohd N K, Wen-Huei L, Abu Hassan N A, et al. Potential application of palm oil products as electrical insulating medium in oil-immersed transformers [J]. Environmental Progress & Sustainable Energy, 2021, 40 (6): e13728.

[4] Khan S A, Tariq M, Khan A A, et al. Effect of iron/titania-based nanomaterials on the dielectric properties of mineral oil, natural and synthetic esters as transformers insulating fluid [J]. IEEE Access, 2021, 9: 168971 - 168980.

[5] Li Y, Shen W, A G, et al. Comparison of heat transfer characteristics between natural ester oil and mineral oil in large oil-immersed transformer[J]. Heat and Mass Transfer, 2023, 59 (4): 729 - 739.

[6] Oparanti S O, Salaudeen I K, Adekunle A A, et al. Physicochemical and Dielectric study on Nigerian Thevetia Peruviana as a potential green alternative fluid for transformer cooling/insulation [J]. Waste and Biomass Valorization, 2023, 14 (5): 1693 - 1703.

[7] Zhai Qian, Analysis and research on heat dissipation efficiency of large transformer plate radiator [D]. Shenyang University of Technology, 2019.

[8] Liu Changfu., Zhong Xian, Li Fuqin, et al. Air-cooling modification of oil-immersed self-cooling transformer radiator and analysis of its effects [J]. Shixenze Science and Technology, 2020, (05): 51 – 55.

[9] Deng Bin. Heat transfer characteristics of 3-D finned tube radiator for oil-immersed self-cooling transformer [D]. Chongqing University, 2021.

[10] Zhao S, Liu Q, Wilkinson M, et al. A reduced radiator model for simplification of ONAN transformer CFD simulation[J]. IEEE Transactions on Power Delivery, 2022, 37 (5): 4007 - 4018.

[11] Luo Huadong. Heat transfer characteristics of the radiator with interrupted offset fins for oil natural air natural power transformer [D]. Chongqing University, 2022.

[12] Koca A, Senturk O, Çolak A B, et al. Artificial neural network-based cooling capacity estimation of various radiator configurations for power transformers operated in ONAN mode [J]. Thermal Science and Engineering Progress, 2024, 50: 102515.

[13] Liang Feng, Yang Xin, Le Xiaowen, et al. Hot spot temperature prediction method for oil-natural air-forced transformers based on ACO-SVM model [J]. Transformer, 2023, 60 (06): 6 – 12.

[14] Wang L, Zuo W, Yang Z X, et al. A method for fans' potential malfunction detection of ONAF transformer using top-oil temperature monitoring [J]. IEEE Access, 2021, 9: 129881 - 129889.

[15] Ye L, Xin Y, Jia P. The temperature and drift law of hot spots of oil-immersed air-cooled power transformers[C]//Journal of Physics: Conference Series. IOP Publishing, 2023, 2530 (1): 012006.

[16] Li Y, Gao Y, Wang C, et al. Thermofluidic investigations of oil natural transformer: Closed-loop modelling and experimental validation[J]. High Voltage, 2024, 9 (1): 230 - 240.

[17] Li Shuangcheng. Exploration and application of heat dissipation efficiency and water-cooling spray cooling methods of oil-immersed air-cooled transformer in Chengzigou Hydropower Station [J]. Science, Technology Innovation and Application, 2023, 13 (23): 176 - 180.

[18] Wang Lujia, Cai Zhenlu, Qiu Yabo, et al. Heat dissipation efficiency optimization method for onaf external cooling system taking into account airflow losses [J]. Journal of Electrotechnology, 2023, 38 (17): 4767 - 4778.

[19] Liu Xichen. Formation mechanism of hot and humid environment in underground power stations and energy-saving regulation strategies [D]. Chongqing University, 2024.

[20] RADAKOVIĆ Z, POPOVIĆ A N A. Variation of steady-state thermal characteristics of transformers with OFWF cooling in service [J]. Electric Power Components and Systems, 2003, 31 (8): 817 - 829.

[21] Fang Guowei, Pang Bo, Zhu Zhiyong, et al. Study on oil flow distribution system of OFWF transformer [J]. Transformer, 2020, 57 (04): 47 - 50+53.

[22] Fan Li, Li Huachun, Du Yun, et al. Thermal characteristic analysis and optimization design of transformer with forced oil non-directed cooling system [J]. Transformer, 2021, 58 (04): 10 – 13.

[23] Zhang Haoyang. Numerical research on temperature rise and structural improvement of ofaf transformer windings [D]. Dalian University of Technology, 2022.

[24] Tu Mengya, Li Chunli, Hou Suning, et al. Research on feedforward fuzzy control of transformer coolers in large scale gas-fired power plants [J]. Industrial Control Computers, 2024, 37 (04): 35 - 37.

[25] Peng Guangyong, Liu Dongsheng, Liuliqiang. Calculation and analysis of temperature rise of transformer with odaf cooling mode [J]. transformer, 2020, 57 (04): 1 - 5.

[26] Feng H, Jianling W, Shangbin L, et al. Field Modification and Application of ODAF Cooling System for 500kV Transformer [C]. Journal of Physics: Conference Series. IOP Publishing, 2020, 1550 (4): 042024.

[27] Liiu Gang, Lan Hetong, Jiang Xiongwei, et al. Load capacity evaluation of forced guided oil circulation air-cooled transformer based on temperature rise characteristics [J]. High voltage technology, 2024, 50 (01): 232 - 241.

[28] Han Peng. The calculation research of temperature field of large natural oil circulation power transformer with oriented cooling structure [D]. Hebei University of Technology, 2005.

[29] Su Lina. The calculation Research of temperature rise of large natural oil circulation power transformer with directed structure with the means of natural air cooling and forced air cooling [D]. Hebei University of Technology, 2006.

[30] Di Shuangkui. Research on the calculation method of temperature rise of natural oil circulation power transformer [D]. Shandong University, 2006.

[31] Yang Bei. The caleulation research of unsteady state temperature field and age of natural oil circulation large power transformer with oriented structure [D]. Hebei University of Technology, 2007.

[32] Niu Peng. Study of the unsteady temperature response forlarge natural oil transformer with directed structure on overload [D]. Hebei University of Technology, 2016.