TRANSFORMER THERMAL MODEL OF THE DISK COILS WITH NON DIRECTED OIL FLOW

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ABSTRACT

A power transformer is a static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at same frequency for the purpose of transmitting electrical power. The temperature of disk coil has a close relation with the transformer age. In oil immersed transformers, oil guides are applied generally to enhance the cooling effects for disc windings. In some cases disk windings without oil guides are used. Non directed oil flow of a disk transformer in this model is non-guided by the oil flow natural circulation (thermally driven). The model is focus to investigate the temperature rise in the oil-filled transformer windings. An iterative solution is required to solve the equation to find the oil velocities, change in the oil temperature rise after each disk coil that passing through it, and disk temperature. The concept in all disks coil is the same because no block washer for each group (pass) to control of the oil flow as directed oil flow. Pressure decrease with increase the total number of coil disk or high of coil is effecting the frication and gravitation acceleration. As a disk temperature is very sensitive to the changes of the variables, so designing a suitable parameter for a single power transformer is very important. Matlab software that a good way to solve the iterate equations and modeling disk transformer where the result is nearly accurate.

Keywords: disk transformer, thermal model, oil temperature rise, oil velocity, pressure, iterative solution

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LIST OF ABBREVIATIONS

IEC	-	International Electrotechnical Commission
IEEE	-	Institude of Electrical and Electronic Engineer

CHAPTER 1

INTRODUCTION

1.1 Overview

Power transformers represent the largest portion of capital investment in transmission and distribution substations. In addition, power transformer outages have a considerable economic impact on the operation of an electrical network since the power transformers are one of the most expensive components in an electricity system [1].

In fact most of power transformers use paper and oil as the main from of insulation. There are- three possible mechanisms that contribute to the insulation degradation are hydrolysis, oxidation and pyrolysis .The agents responsible for the respective mechanisms are water, oxygen and heat temperature indeed the temperature has been considered as the main parameter affecting the loss-of- life of insulation. Hence, the heat produced (internal temperature) in the transformers as a result of loading and the effect of ambient temperature is the important factor that affecting the life other transformer [2].

The temperature affects the insulations. The structure of insulating materials using in transformer, mainly those based cellulose, is subject to aging. Aging modifies the original electrical, mechanical and chemical properties of the insulating paper used. From laboratory experiments on insulating materials, it has found that determinable dangerous temperature limit can be found for the material used in. There is an exponential relation between temperature, duration of thermal effect and the extent of aging of insulating material.

The thermal stress reduces the mechanical and dielectric performance of the insulation. The experiments, which were carried out by Montsinger indicate that when the transformer temperature has the values between90-110 C^{o}, 8 C^{o} increments on these values results in halving the life of the insulation. Therefore, the temperature limits permitted in the active parts, influence the on structional design, size, cost, load carrying capacity and operating conditions of the transformers have already been precisely defined. The thermal design of transformer windings has relied on determining temperature distribution. After applying further simplified assumptions, it is possible to determine the axial temperature distribution of the windings as well as the radial temperature distribution within each individual coil [3, 4].There are two types of winding and ducts arrangement in power transformer; disk type winding and layer type winding. The case considered is a disc type of winding which is cooled sometimes by directed oil flow and sometimes by non-directed oil flow. The basic design of a single phase of a transformer is shown in Fig 1.1 it consists of an iron core around which is wound a low-voltage and a high-voltage winding.

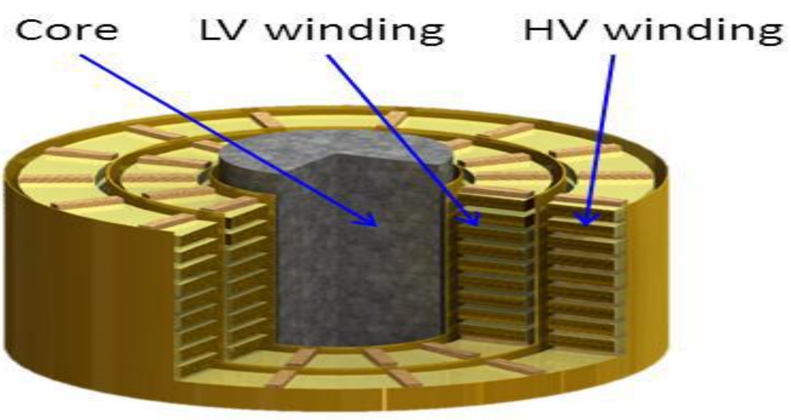

Fig 1.1 schematic diagram of windings for single phase of a transformer

The mathematical model described in this section applies to either of these windings. The winding consists of an insulated conductor which is wound spirally into disks. Each disk is separated from its neighbours so that there are gaps, referred to as ducts, between the adjacent conductor disks through which cooling oil can flow, Fig. 1.2

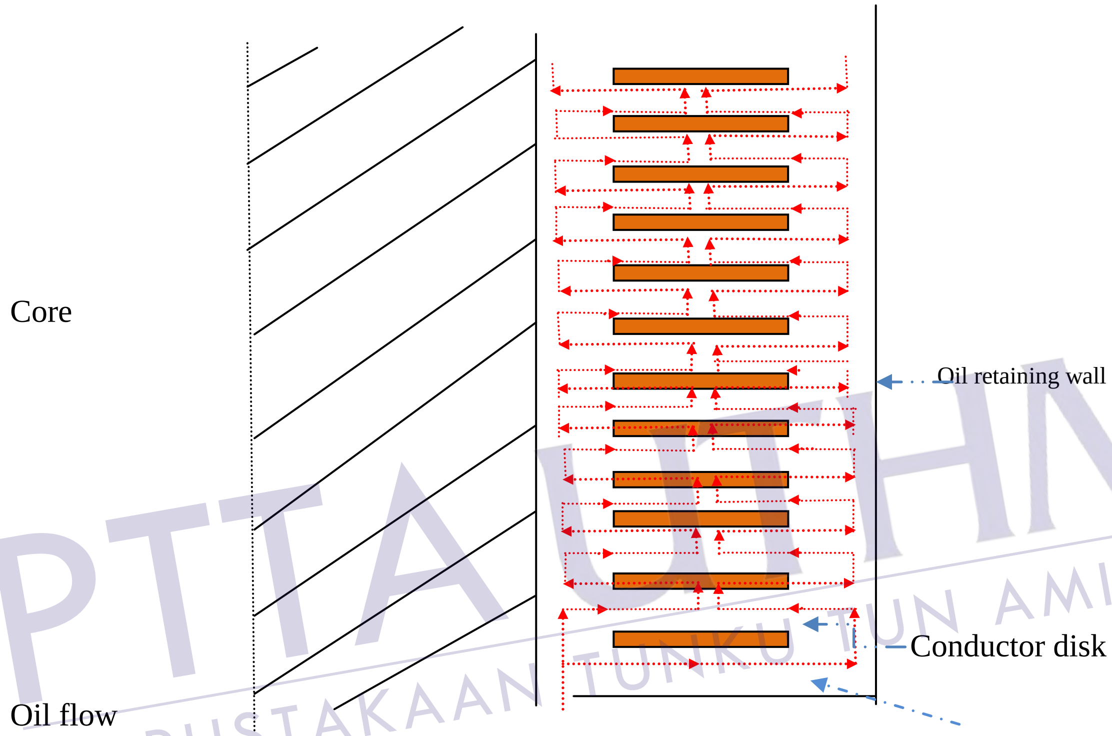

Fig 1.2 Disk coil with non-directed oil flow

Oil is passing into the bottom of the transformer. From there it flows into the regions occupied by the windings and then the design is such that is should flow up the windings in the manner shown in Fig 2. The winding is made up of many similar disk (depended on high of coil) in series until reaching the top of the winding the oil passes into a header and then onto the coolers [5].

1.2 Problem Statement

The no load losses and the load loss consist of $\mathbf{I^2R}$,all these losses cause heating in the corresponding parts of transformer and this heat must be taken away to avoid high temperature which will cause deterioration of insulation.

In liquid-immersed power transformers, the temperature of the winding is very important in order to longer the term-of life of the transformer. Knowing the temperature distribution especially hot spot temperature at each point of transformer is very importance [6, 7, 8, 9, 10] in order to make it operate safety for a long period. The winding made of copper can hold their mechanical strength up to several hundred degrees Celsius without deterioration and the transformer oil dose not significantly degrade blow 140 C ^{o}, however this is not case for the paper insulation. The paper insulation deterioration rapidly if its temperature is more than 90 C^{o} [11].

Most of the transformers that are using mineral oil as transformer insulating oil. The insulating oil temperature depends on the winding temperature and is usually used to indicate the operating conditions of the transformer [9]. The increase in temperature will influence the insulating material and may cause aging. Depends to the insulating material type, the transformer has a maximum limit of temperature rise [12].

There are some types of transformer numerical protection relay made to protection functions and to calculate losses of the transformer life due to high temperature generated inside the transformer and also to predicted oil temperature due to the load.In this project, software is used to predict the heat distribution in liquid-immersed transformers. There are various ways that can be used in modeling power transformer but some of them are complicated, so by choosing programming in Matlab life becomes easier.

1.3 Project Objective

The main objectives of this research are listed as follows:

(i) To investigate the temperature distributions and oil velocity inside coil of the power transformer.

(ii) To model and develop a program using MATLAB, that can modulate the suitable parameter that not exceeds maximum temperature rise in disk coil transformer.

(iii) Test the program by using different value in the parameter such as the hydraulic diameter and total losses.

1.4 Scope of the Research

There are some limitations in this project to be considered:

(i) Oil flow not guided through the disk coil and just determined for coil disk shape power transformer.

(ii) The model consider vertical and horizontal cooling duct (2D).

(iii) Using matlab simulation to solve the equations to find unknown parameters.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

A power transformer is the electrical device which is used to change the voltage of AC in power transmission system. The first transformer in the world was invented in 1840s. Modern large and medium power transformers consist of oil tank with oil filling in it, the cooling equipment on the tank wall and the active part inside the tank. As the key part of a transformer, the active part consists of 2 main components: the set of coils or windings (at least comprising a low voltage, high voltage and a regulating winding) and the iron core, as Figure 2.1 shows. For a step-up transformer, the primary coil is low voltage (LV) input and the secondary coil is high voltage (LV) output. The situation is opposite for a step-down transformer. The iron core is the part inducing the varying magnitude flux. Nowadays, transformers play key roles in long distance high-voltage power transmission.

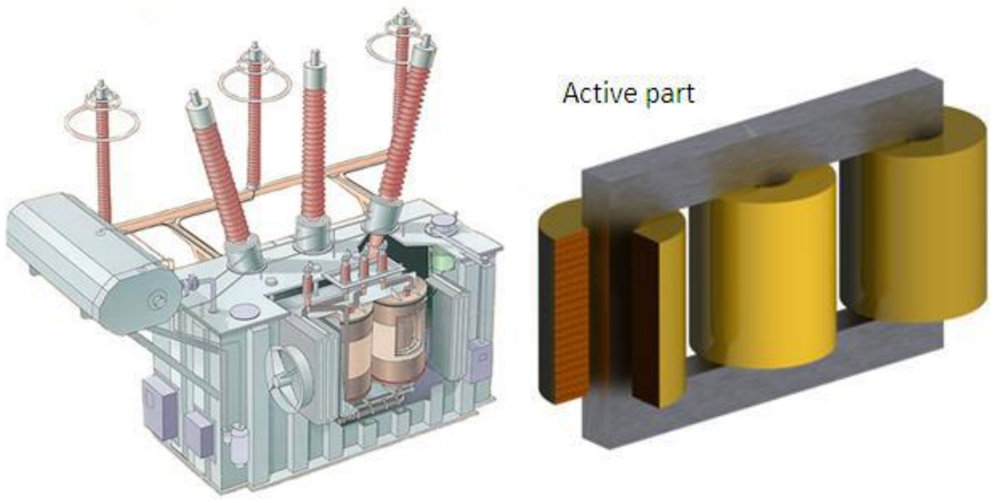

Figure 2.1 Structures of disc winding transformer

The term power transformers used to refer to those transformers used between the generator and the distribution circuits and these are usually rated at 500 kVA and above. Power systems typically consist of a large number of generation locations, distribution points, and interconnections within the system or with nearby systems, such as a neighboring utility. The complexity of the system leads to a variety of transmission and distribution voltages. Power transformers must be used at each of these points where there is a transition between voltage levels.

Power transformers are selected based on the application, with the emphasis toward custom design being more apparent the larger the unit. Power transformers are available for step-up operation, primarily used at the generator and referred to as generator step-up (GSU) transformers, and for step-down operation, mainly used to feed distribution circuits. Power transformers are available as single-phase or three-phase apparatus. The construction of a transformer depends upon the application. Transformers intended for indoor use are primarily of the dry type but can also be liquid immersed. For outdoor use, transformers are usually liquid immersed.

The normal life expectancy of a power transformer is generally assumed to be about 30 years of service when operated within its rating. However, under certain conditions, it may be overloaded and operated beyond its rating, with moderately predictable “loss of life.” Situations that might involve operation beyond rating include emergency rerouting of load or through-faults prior to clearing of the fault condition. Power transformers have been loosely grouped into three market segments based on size ranges [10, 13, 14].

These three segments are:

1. Small power transformers: 500 to 7500 kVA
2. Medium power transformers: 7500 to 100 MVA
3. Large power transformers: 100 MVA and above.

2.2 Review of previous experience

Robert M. Del Vecchio and Pierre Feghali (1999) have modeled a thermal model of a disk coil with directed oil flow. In this model each path segment, oil velocities and temperature rises are computed. The oil Flow is assumed to be thermally driven. The model includes temperature dependent oil viscosity, resistivity, oil density, and temperature and velocity dependent heat transfer and friction coefficients a computer code based on the analysis The code calculates temperatures of the coil disks and of the oil in all the ducts as well as duct oil velocities[15].

GüvenKömürgöz İbrahim ÖzkolNurdanGüzelbeyoğlu (2001) in this study the temperature distribution in the disk coil of transformer winding, there are series of numerical experiments are conducted so as to develop a new thermal model for oil immersed transformer windings. A line of eight-disc-coil has been modeled as a series of heat producing sources in a vertical channel. The heat transfer equations for the model in hand were solved by a semi numerical-analytical method to obtain temperature distribution. Also, the results obtained are verified by ANSYS packet program [4].

Zoran R. Radakovic and Marko S. Sorgic (2010) they have introduced basics of detailed thermal hydraulic model for thermal design of oil power transformers .The paper presents the method for the calculation of temperatures inside oil power transformers, and the transformer in more detail starting from the construction of a transformer, physical parameters of applied materials, temperature of the outer cooling medium, and distribution of power losses, and the calculation temperature distribution of the winding, in each conductor of the oil, temperature in each cooling channel and in each characteristic point, and in the core, on the surfaces and the hottest spots[16].

Even though most of the analysis of thermal performance of transformer disc windings are based on oil guided disc windings, the methods and experience for conducting such studies of disc windings can also be gained and digested for non-oil guided cases. The detail calculation is important in order to reduce used material such as copper, iron and oil.

Table 2.1 list the summary of technology development that done by other researcher.

Author	Findings						
	Oil Velocity	Pressure	Flow Rate	Temperature			
				Disk	Oil	Path	Nodal
A.J. Oliver [5]	√	√		√	√		
A.Weinlader [17]	√	√	√	√	√	√	
E.P. Childs [18]		√		√			
F. Torriano [8]			√	√	√		
Del Vecchio[12]	√	√		√	√	√	√
J.Zhang [19]		√		√			√
J.Zhang [20]			√	√		√	√
L. W. Pierce [21]				√	√	√	

2.3 Energy losses

As one kind of electrical components, an ideal transformer has no energy losses. However, in reality, a transformer cannot reach a 100% efficient. The main losses come from the winding resistance thermal loss, the eddy current loss and the hysteresis loss [27] .

Windings consist of helix wires made of copper or other conductors. Even though the resistance is low, the current through the wire can still cause resistive heat. Especially under a condition with high frequencies and high temperature in a transformer, the resistance will be increased. Eddy currents are circulating through the core and windings and the coupling effects of the frequency and material thickness could also lead to resistive heat loss. The hysteresis loss is mainly happening in the core which is a coupling effect from frequency and material properties [16]. Besides, there still some other reasons contributing to the energy loss, such as mechanical loss, stray loss, magnetostriction loss, generally during transformer operation losses are generated and these losses can be categorized into no load losses and load losses as shown in Figure 2.2.

However, the transformer life is limited by the age of insulation materials inside the transformer, such as insulation paper wrapping around the windings. The insulation materials, such as cellulose, will be destroyed if the transformer keeps working in the environment with high temperature. It is said from experience that when the hotspot temperature is in the range 80-140, the transformer life will be halved for every 6 degree increase [24]. Thus, measures must be taken to avoid high temperature inside the transformer by removing the heat generated in the core and windings effectively. As described above, according to the size and capacity of the transformer, different methods are applied to achieve the cooling targets.

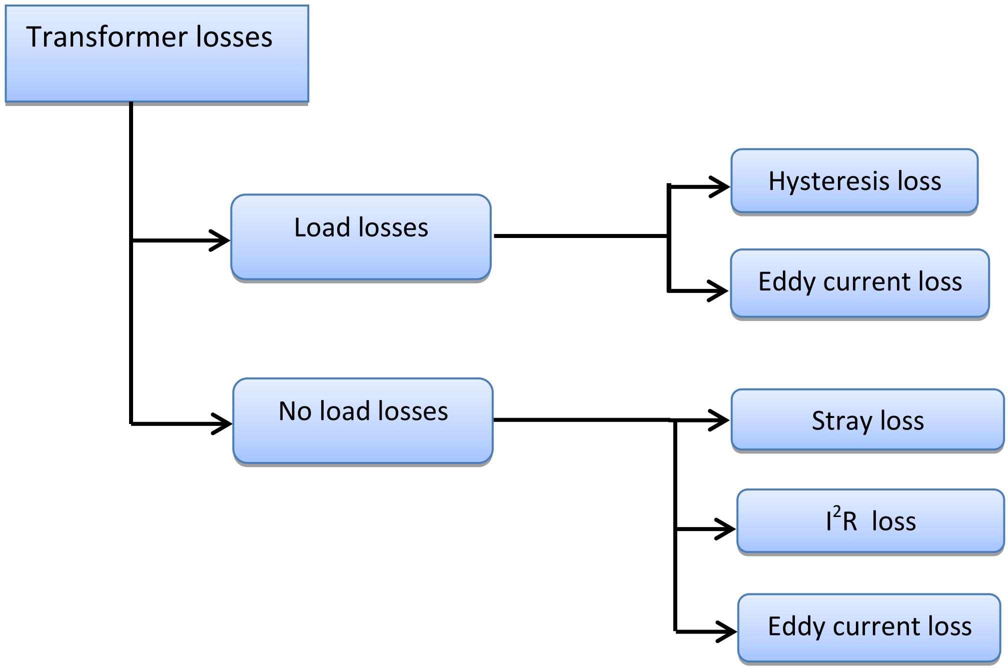

Figure 2.2: Transformer Losses

2.4 Transformer Thermal Diagram

A basic thermal model for power transformers is given in Figure 2.3, where it is assumed that the change in the oil temperature inside and along the winding is linearly increasing from bottom to top. The increase in the winding temperature from bottom top is linear with a constant temperature difference (g). At the winding top the hot spot temperature is higher than the average temperature (g) rise of the winding. The difference in the temperature between the hot spot and the oil at the top of the winding is defined as (H.g), where H is a hot spot factor. It may be varied from, depending on short circuit impedance, winding design and transformer size [25].

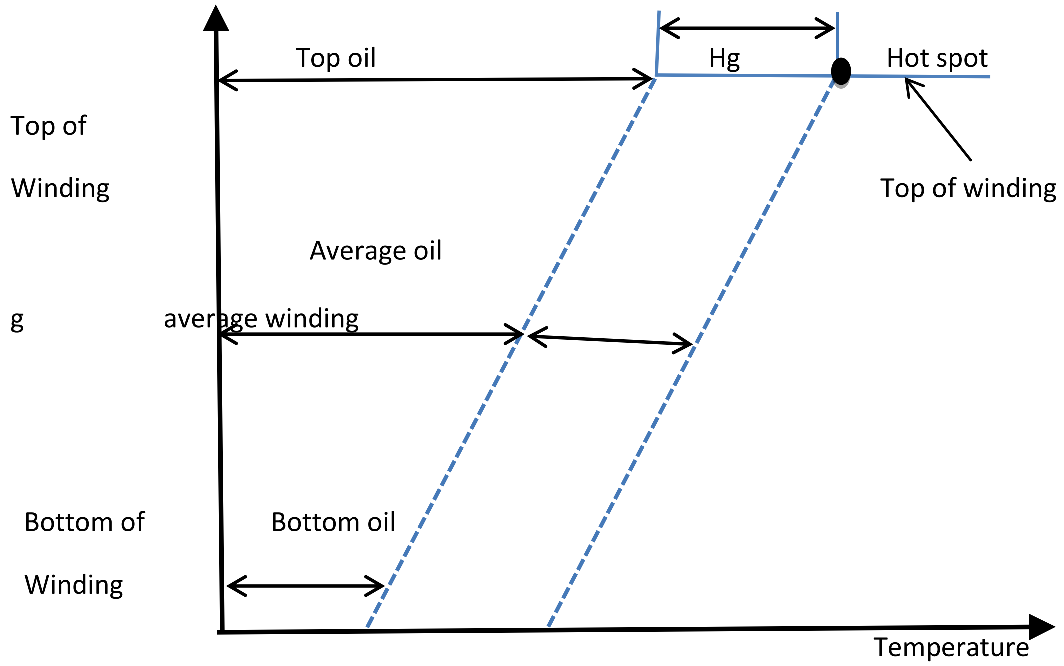

Figure 2.3: Transformer Thermal Diagram

2.5 liquid – filled transformer

There are two types of transformers used for power or distribution applications; liquid-immersed and dry-type transformers. They are differentiated by the type of fluid used to cool and to provide dielectric insulation. As their name implies, a liquid-immersed transformer uses oil where a dry type unit uses the surrounding air as its cooling and insulating medium.

Historically, industrial facilities have utilized liquid-immersed transformers for medium voltage systems. In more recent times, transformers with less flammable, environmentally friendly, biodegradable liquids have also been installed. Liquid immersed transformers are a well proven, reliable, long service life technology for onshore and offshore facilities.

A Comparison of Liquid-Filled and Dry Type Transformer Technologies written by Tommy Nunn [12] of IEEE-IAS Cement Industry Committee evaluated the comparison both types of the transformers. He stated that both type have pro and cont in terms of loads, environment, purchase cost, safety, availability to operate, materials and manufacturing process. In recent years, transformers technologies have improved especially in less flammable and environmentally friendly fluids in liquid-filled transformers. In dry type transformer, vacuum technology has been introduced to improve the insulation system, core material and computer design programs.

Another research has been done by Jeffery Wimmer, M. R. Tanner, Tommy Nunn and Joel Kern on the specification Installation and operational impact of both types in a marine environment [26] . They found that fiber glass winding will have maximum operating size through 25000kVA and also application of vacuum technologies increased the reliability on tap changing reduced the maintenance. Table 2.1 list some advantage and disadvantage of liquid-immersed transformers.

Table 2.2: Liquid-filled transformer

Advantage	Disadvantage
Transformer oil is combustible	Needs oil regular checking filtration and replacement of oil
Smaller size	Costly and need high recurring expense
Lower cost	Produce a little bit of danger
Greater overload capability	Located away from the main building

2.6Oil guided and non-oil guided disc windings

Oil guided and non-oil guided windings are proposed in disc windings transformers. In the active part, as shown in Figure 2.1, between winding and core, LV windings and HV windings, and windings and outer casing, there are insulation board layers. Then, a closed space can be formed for each layer of windings. Figure 2.5 shows the 2D cross sectional area of one layer of disc windings. As Figure 2.3 (a) shows, the guides are set in vertical ducts every 6 discs are oil guides. The purpose of setting oil guides is to improve the natural convection capability of the oil flow by avoiding the stagnation of the oil inside ducts. Cold oil come in the windings from the bottom and the go through the vertical and horizontal ducts, the oil guides would change the oil flow direction and make the global oil distribution even.

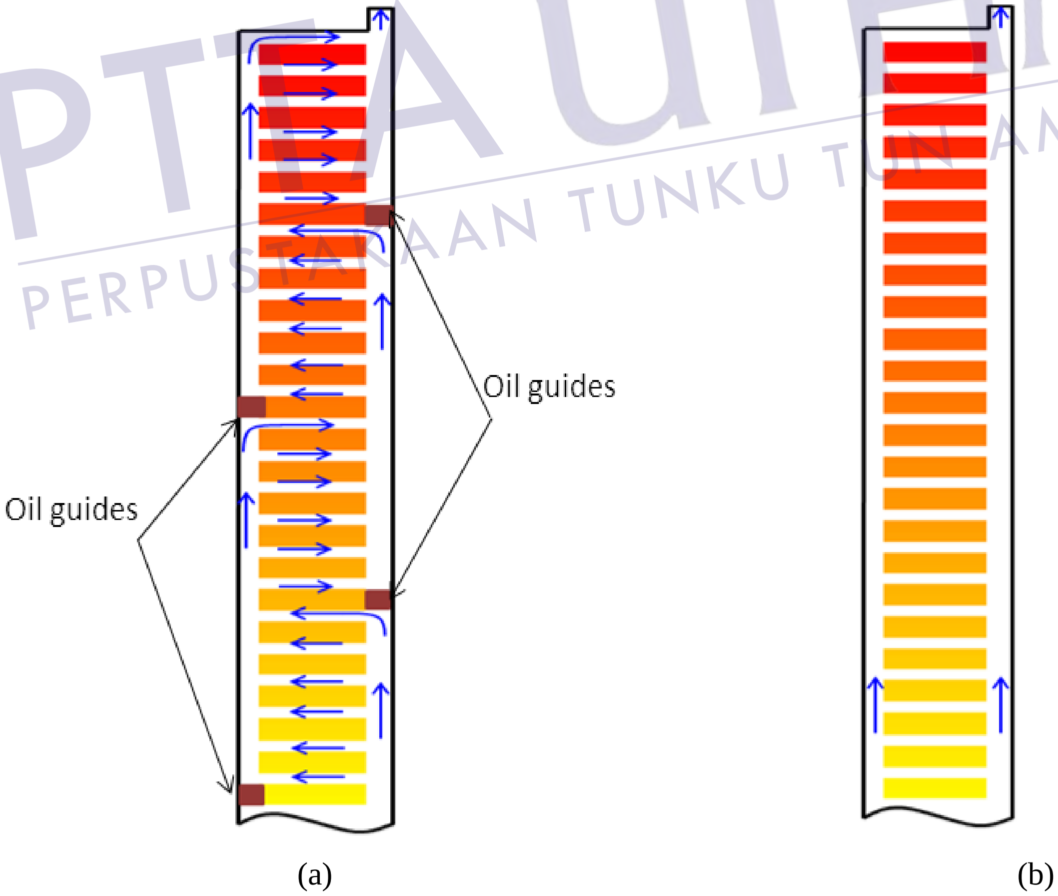

Figure 2.4 2D cross-sectional images of disc windings

In reality and the real manufacturing process, considering some situation with quite small windings radius as well as cost effective consideration, the non-guided disc windings may be applied. Figure 2.3 (b) shows the 2D cross-sectional image of non-oil guided winding. It can be seen that the construction of non-oil guide winding looks like a longer section of winding with oil guides. For non-oil guided model, due to its large scale in the vertical length, the oil flow distribution as well as the temperature distribution is expected to become complex [4, 5, 27].

2.7Transformer cooling system

The heat produced in a transformer must be dissipated to an external cooling medium in order to keep the temperature in a specified limit. If transformer insulation is experienced higher temperature than the allowed value for a long time, it will cause rapid degradation of insulation and hence severely affect the transformer life.

In oil immersed transformer, the heat is transferred from the active parts (core, winding and structural components) to the external cooling medium by the oil. The heat from the active parts is transferred by the process of oil circulation. The process of transferring heat from involves three different heat transfer mechanisms which are conduction, convection and radiation. The conduction process involves the heat transfer between the solid parts, whereas the convection process involves the heat transfer between a solid surface to a liquid or vice versa. The heat transfer by radiation is between solid or liquid to the surrounding ambient temperature.

The most important heat transfer mechanism in an oil immersed transformer is through the convection. The convection process occurs between transformer winding and oil. It is always neglected in thermal calculation because of low surface temperature and small area available on a transformer for radiation process to occur [28].

There are four common types of cooling arrangement have been used .

2.7.1 Natural Cooling of Oil and Air (ONAN)

The simple and most common cooling type used in the practice is ONAN. ONAN refers to Oil Natural Air Natural. The ONAN cooling is achieved when the oil flow through the transformer winding is driven by pressure difference between the tank oil and the cooler oil. This pressure difference is due to a temperature difference between the oil temperature in the tank and the oil temperature in the radiators. This natural circulation of oil sometimes has been referred as a “thermo siphon” effect. The ONAN design is shown in Figure 7 .and arrows in the figure show the oil flow direction in the transformer.

The oil velocity in this natural circulation is relatively slow throughout the transformer and radiators. For this reason, ONAN transformers have large temperature difference between top oil and the bottom oil. They also have relatively large temperature difference between the winding temperature and the oil temperature. This ONAN cooling mode is normally used for smaller rating transformer (distribution transformer)[28,22].

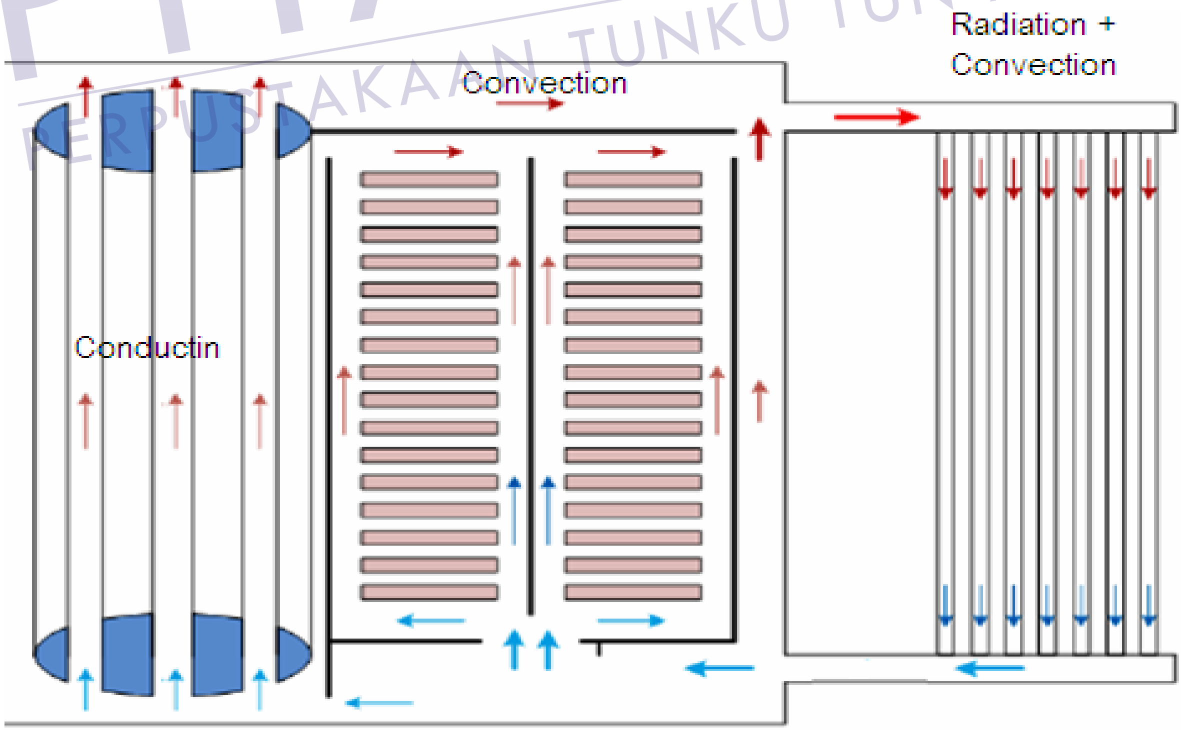

Figure 2.5 ONAN cooling diagram

2.7.2 Natural cooling of oil and force air (ONAF)

One way to increase the oil circulation rate is by improving the efficiency of the external heat dissipation. This can be done by using the fans to blow air onto the cooling surfaces of radiators. The forced air from the fans takes away the heat from the radiators (cooling) at a faster rate than natural air hence gives a better cooling rate. This leads to a lower average oil temperature (MO) hence increases the capability of the transformer to operate at a higher load. This type of cooling is termed as ONAF (Oil Natural and Air Forced) as shown in figure 8 . The introduction of the fans to the radiators improves the cooling characteristics of the radiators thereby reducing the number of radiators required to achieve the same amount of cooling. This also leads to smaller overall dimensions of the transformer/cooling design [28,22].

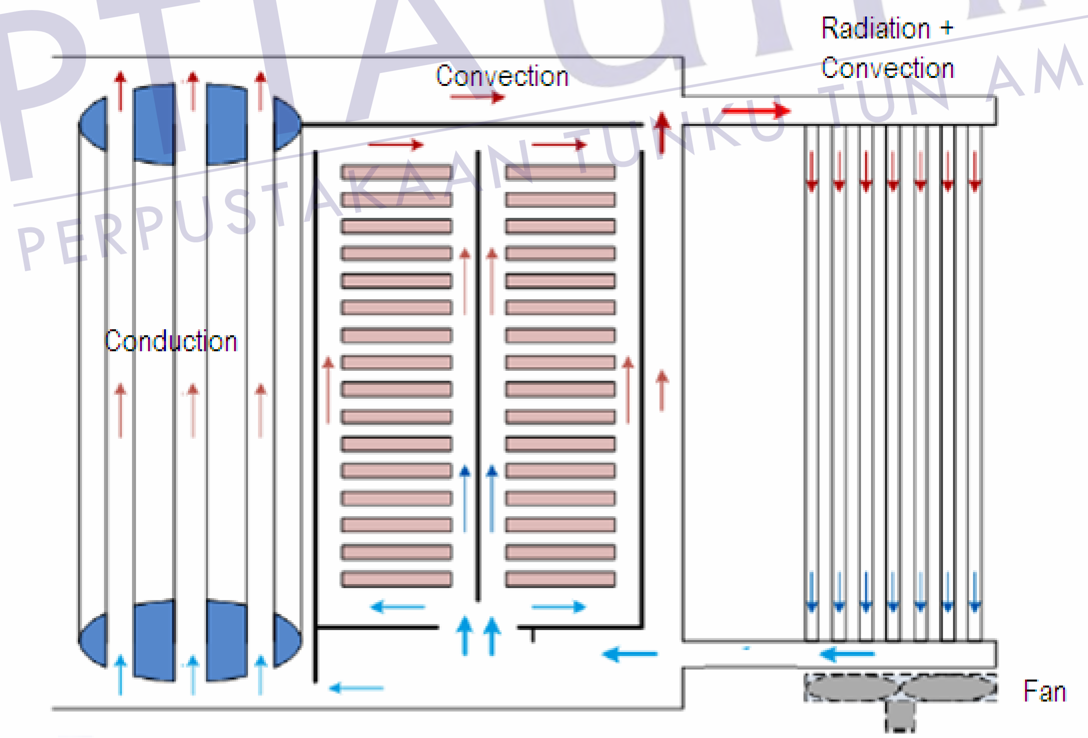

Figure 2.6ONAF cooling diagram

2.7.3 Force Cooling of Oil and Force Air (OFAF)

One way to improve the heat dissipation capability is to increase the value of mass flow rate; m and this can be done by using a pump to circulate the oil. Moreover to increase heat transfer rate, fans have to be always operating at the radiators. This improves the heat transfer to the radiators (cooling) and reduces considerably the temperature difference between the top and bottom of the radiators hence lower the oil temperature rise in the top parts of the transformer. This type of cooling is called OFAF (Oil Forced and Air Forced) as shown in Figure 9 [28,22] .

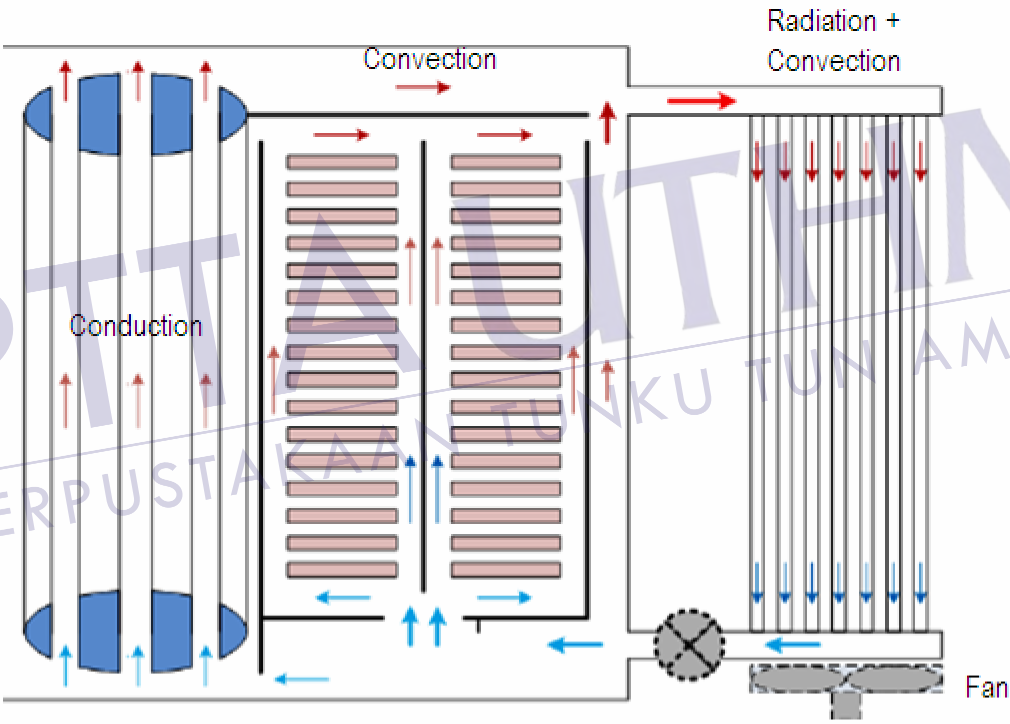

Figure 2.7 OFAF cooling diagram

2.7.4 Force and Directed Cooling of Oil and Force Air (ODAF)

As shown in Figure 2.9 a group of conductors surrounded by vertical and horizontal cooling ducts. The heat generated in each conductor must be transferred to the oil to keep the temperature within the limits. The heat flow in the horizontal direction from a central conductor is limited by the similar temperature conductors on either side of it. Therefore the heat can transferred via vertical directions.

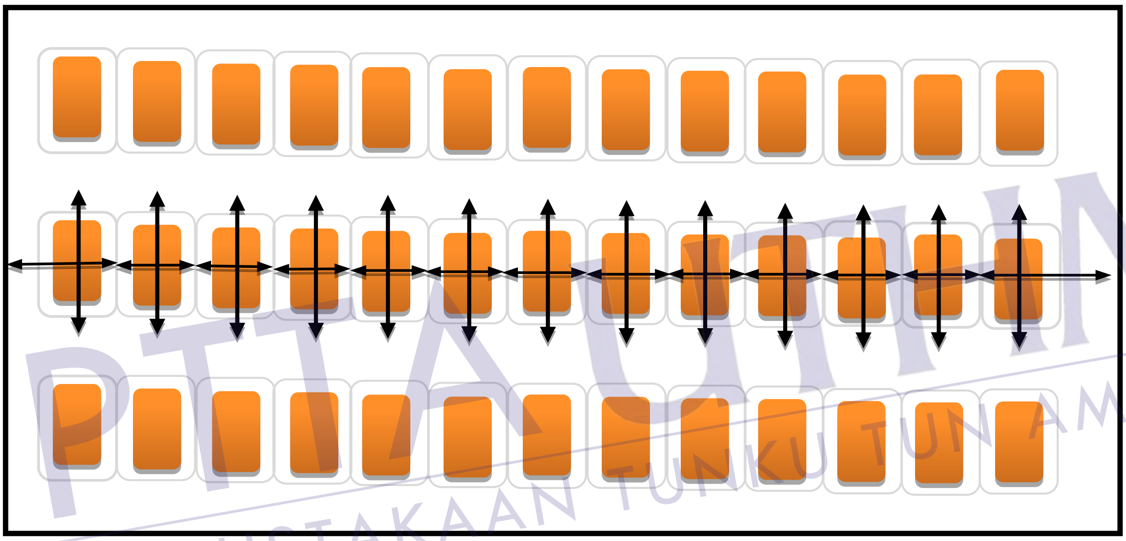

Figure 2.8 Cross section of a disc or helical winding showing heat flow paths

Naturally the oil tends to rise when it became hot. The vertical ducts provide a natural circulation path for this hot oil. This causes the oil flow through the horizontal ducts is much less than that in the vertical ducts and hence poor heat transfer between the conductors and the oil in the horizontal ducts. However the discs depend on the horizontal oil ducts for their cooling. This is the reason why directing the oil through the winding using block washer to occasionally block the vertical ducts is so important in achieving effective heat transfers from the conductors[28,22].

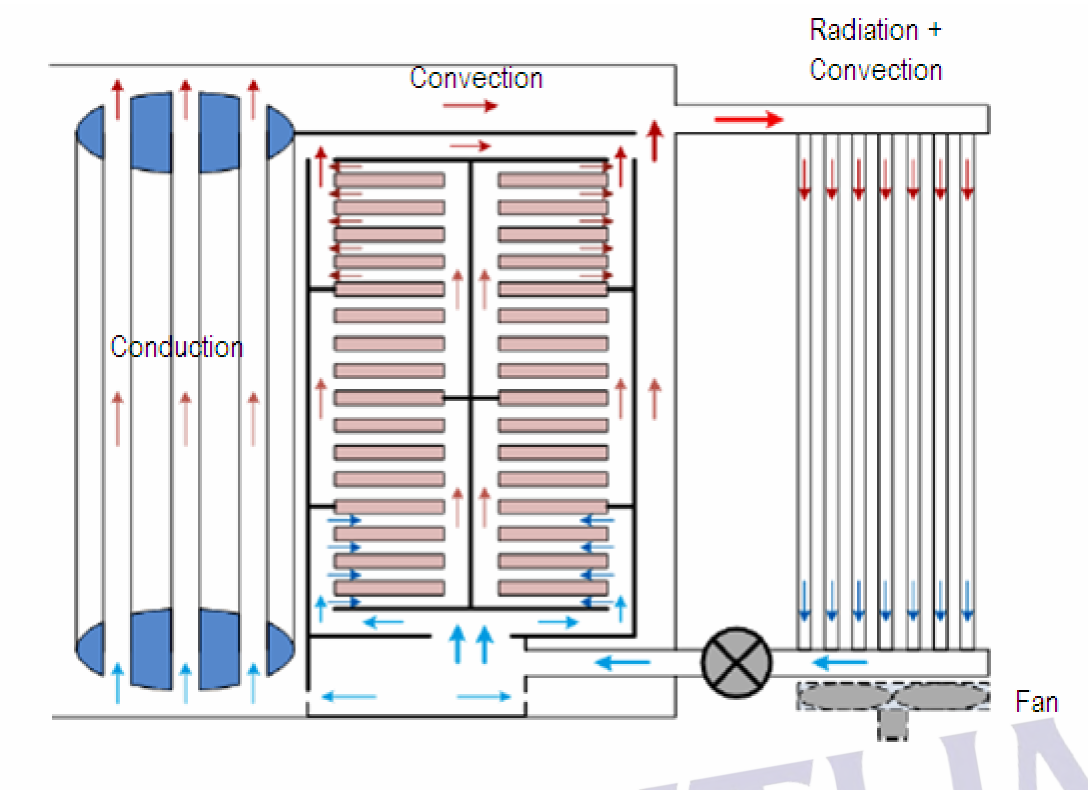

Figure 2.9 ODAF cooling diagram

2.8Circular core and coil winding

Circular core and coil winding construction with layer windings can provide improvement forwinding cooling, but usually does not provide complete circulation of the oil to every conductorand every layer of the windings. The circulation of the oil through the windings into the tank and radiators is the process that removes the heat generated by the windings and allows it to be disbursed to the surrounding environment see fig 2.11.

Oil flows vertically up through the windings in the ducts between the core and LV coil, LV and HV coils, the radial cooling ducts in the HV and LV coils, and along the outer surface of the HV coil. There is also horizontal oil flow between the coil sections for helical and disc windings. This horizontal oil flow can be further directed by the use of oil flow washers that will guide the vertical oil flow horizontally back and forth through the windings.

As the heat is transferred from the windings to the oil, the density of the oil decreases and rises up through the windings continuing to collect even more heat until it finally reaches the top of the windings. The oil over the top of the windings migrates to the tank and radiator surfaces where it cools off and becomes denser and is circulated back to the bottom of the tank and windings where the process repeats. Circular disc and helical winding design provides maximum contact of the winding conductors with the circulating oil [23].

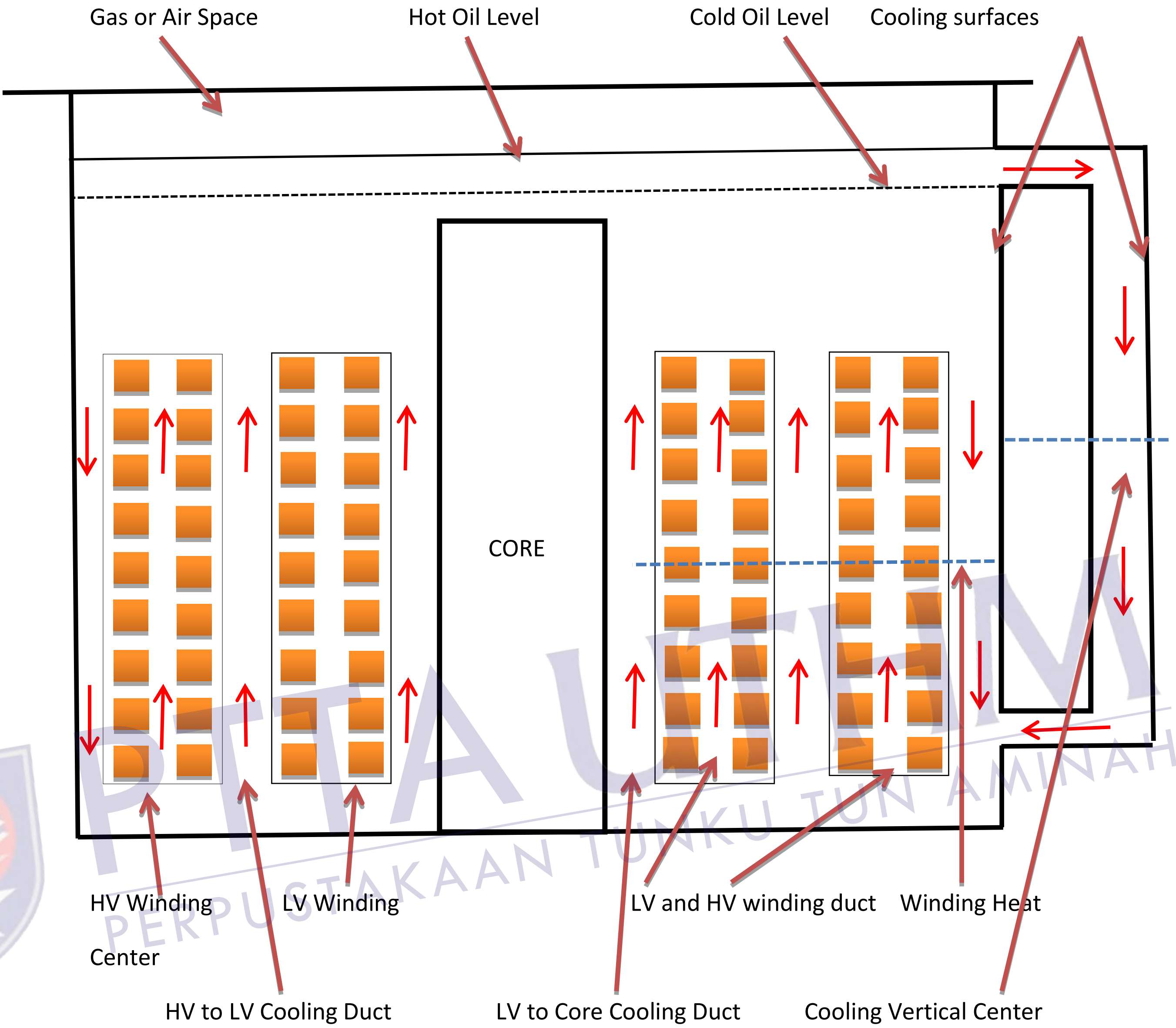

Fig 2.10 arrows represent the typical flow patterns of oil circulation in the winding and tank

2.8 Programming in MATLAB

Matrix Laboratory or known as MATLAB is a high level-programming language and it provides interactive environment with hundreds of built-in functions which is very suitable for technical computation, graphics and animation [30].

A product of the math works, matlab started life as a program designed to perform matrix mathematics, but over the years it has grown into a flexible computing system capable of solving essentially any technical problem. Matlab can manipulate and invert large matrices and can be used in many numerical applications. Matlab's capabilities can be extended with addition called simulink, a program which is normally used in the analysis and synthesis of modern systems simulink, now incorporated into matlab, can also be used to analyze and design of power systems. During last four decade's simulation of power systems have gained more importance.

The features of the MATLAB toolboxes used in the analysis of power systems are, facilitating future revision and expansion of software. This is very important for researches that are interesting in developing and testing new for various power system applications. It provides an avenue to easily prepare input data files in commonly accepted formats for networks that are created and the results produced by one application can be easily used either fully or partially by any other application supported by the package [27]

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