**REPUBLIC OF TURKEY**

**ADANA ALPARSLAN TÜRKEŞ SCIENCE AND TECHNOLOGY UNIVERSITY**

**GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES**

**DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING**

# THERMAL ANALYSIS of DRY TYPE TRANSFORMER at the HOTTEST POINT in DIFFERENT LOAD CONDITIONS

**ALİ CAN ÖZDOĞAN**

**MASTER OF SCIENCE**

**ADANA 2020**

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**ADANA 2020**

I hereby declare that all information in this thesis has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all information that is not original to this work.

[Signature]

Ali Can ÖZDOĞAN

# ABSTRACT

**THERMAL ANALYSIS of DRY TYPE TRANSFORMER at the HOTTEST POINT in DIFFERENT LOAD CONDITIONS**

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Department of Electrical and Electronic Engineering
Supervisor: Asst. Prof. Dr. Tuğçe DEMİRDELEN
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The fireproof property of dry-type transformers makes them the most suitable transformers in residential and hospital use. And thanks to this feature, dry-type transformers have become more reliable than oil-filled transformers. In addition, these transformers are lighter than oil-filled types.

In recent years, with the development of high-temperature papers, it has become possible to decrease the amount of the core and conductive material with an increment of the working temperature of the windings. However, the losses in the winding and the core of the transformers cause an increase in the temperature of the transformer with the transformer structure design. This increase in temperature can affect the insulation material used in windings, which have a major impact on the service life of the transformer. The temperature rise and temperature distribution of the windings can be monitored by computer technology and the transformer can be safely overloaded and the production cost can be minimized. In addition, if winding temperature and hot spot temperature can be determined, the aging of the transformers is further minimized. By using ANSYS/Maxwell program transformer manufacturers will be able to control the hottest points and temperature increases in windings on the transformer model before production. The optimum transformer model which is obtained by Harmony Search Algorithm will be formed according to the electrical and mechanical design of the transformer and manufacturers will take the necessary precaution to ensure that this design works with the most reliable state of the transformer

**Keywords:** Dry-type transformer, ANSYS/Maxwell, winding temperature, hottest point.

# ÖZET


**FARKLI YÜK KOŞULLARINDA EN SICAK NOKTADA KURU TİP TRANSFORMATÖRLERİN TERMAL ANALİZİ**

Ali Can ÖZDOĞAN

Elektrik Elektronik Mühendisliği Anabilim Dalı

Danışman: Dr. Öğr. Üyesi Tuğçe DEMİRDELEN

Ocak 2020, 43 sayfa

Kuru tip transformatörlerin yanmaz özelliği, konut ve hastane kullanımında onları en uygun transformatörler haline getirmektedir. Ve bu özellik sayesinde kuru tip transformatörler yağ dolu transformatörlerden daha güvenilir hale gelmiştir. Ayrıca bu transformatörler yağ dolu tiplere göre daha hafiftir.

Son yıllarda, yüksek sıcaklıklı kağıtların geliştirilmesi ile, sargıların çalışma sıcaklığı artırılarak çekirdek ve iletken malzemeyi azaltmak mümkün hale gelmiştir. Bununla birlikte, bu kayıplarda ve maliyette bir artışa neden olmuştur. Ancak transformatörlerin sargısında ve çekirdeğinde meydana gelen kayıplar transformatör yapı tasarımının nedeni ile transformatörün sıcaklığında da artışa neden olmaktadır. Bu sıcaklık artışı, transformatörün çalışma ömrü üzerinde büyük etkisi olan sargılarda kullanılan yalıtım malzemesini etkileyebilir. Sargıların sıcaklık artışı ve sıcaklık dağılımı bilgisayar teknolojisi ile takip edilebilir ve transformatör güvenli bir şekilde aşırı yüklenebilir ve üretim maliyeti en aza indirilebilir. Ek olarak, sarım sıcaklığı ve en sıcak nokta sıcaklığı belirlenebilirse, transformatörlerin yaşlanmasını daha da en aza indirir. Transformatör üreticileri, ANSYS / Maxwell program kullanılarak, üretim öncesi transformatör modelindeki sargılardaki en sıcak noktaları ve sıcaklık artışlarını kontrol edebileceklerdir. Harmoni arama algoritması ile oluşturulan optimum transformatör modeli, transformatörün elektrik ve mekanik tasarımına göre oluşturulacak ve üreticiler, bu tasarımın transformatörün en güvenilir durumu ile çalışmasını sağlamak için gerekli önlemleri alacaktır.



**Anahtar Kelimeler:** Kuru tip trafo, ANSYS/Maxwell, sargı sıcaklığı, en sıcak nokta.

*Dedication*

*I would like to dedicate my thesis to my family*

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# NOMENCLATURE

| | |
|---|---|
| N | : Nitrogen |
| C2F6 | : Hexafluoroethan |
| SF6 | : Sulfur hexafluoride |
| PCB | : Polychlorinated Biphenyl |
| CRGO | : Cold Rolled Grain Oriented |
| CTC | : Continuously Transposed Cable |
| LV | : Low Voltage |
| AN | : Air Natural |
| Hz | : Frequency |
| $\Phi_m$ | : Magnetic Flux |
| e1 | : Induced Voltage |
| N | : Number of Turns |
| V1 | : Voltage Source |
| ω | : Angular Velocity |
| $\Phi_{mp}$ | : Magnetic Flux Peak Value |
| I | : Current |
| n | : Turn Ratio |
| rms | : Root Mean Square |
| S | : Apparent Power |
| C | : Transformer Core Section Acceptability |
| D | : Diameter of a Leg of the Transformer Core |
| $q_{fej}$ | : Yoke cross-section of the core leg |
| $q_{fe}$ | : Cross-Section of the Core Leg |
| $B_j$ | : Yoke Induction of the Core Leg |
| $q_1$ | : HV Windings Cross-Section of the Transformer |
| $q_2$ | :LV Windings Cross-Section of the Transformer |
| s | : Current Density of the Windings |
| $L_s$ | : Window Height of the Core |
| $A_s$ | : Specific Ampere Winding |

| | |
|---|---|
| $w_1$ | : Primary Windings Number of Turn of the Transformer |
| $w_2$ | : Secondary Windings Number of Turn of the Transformer |
| k | : Window Filling Factor |
| $l_{m1}$ | : Average lengths of HV windings |
| $l_{m2}$ | : Average lengths of LV windings |
| $G_1$ | : Weight of The HV Windings |
| $G_2$ | : Weight of The LV Windings |
| ⍰$_{CU}$ | : Copper-Specific Weights |
| r | : winding resistance |
| $P_{CU}$ | : Copper Losses |
| k | : Resistance Increase Factor |
| $P_{feb}$ | : Iron Loss for Each of the Three Legs |
| $P_{fej}$ | : Iron Loss for The Yoke |
| $G_{feb}$ | : Weight of 3 Legs of the Transformer Core |
| ⍰$_{fe}$ | : Iron Specific Weight Constantxvii |
| $G_{fej}$ | : Weight of the Transformer Yoke |
| $p_{fej}$ | : Specific yoke iron loss in the transformer core |
| $p_{fe}$ | : Leg Iron Loss in the Transformer Core |
| $\xi_2$ | : Loss Factor |
| $p_{10}$ | : Additional Loss Factor of the Core |
| $G_{total}$ | : Total Weight of the Transformer |
| η | : Efficiency |
| HMCR | : Harmony Memory Consideration Rate |
| PAR | : Pitch Adjustment Rate |

# 1. INTRODUCTION

## 1.1. Types of transformers

Transformers' purpose of usage is the transference of electrical energy with the electromagnetic field. Thanks to transformers, some components of the power grid become operable at optimal voltages.

In some parts of a power system, transformers play an important role in connecting a system with higher transmission voltages to a system of different voltage levels. Transformers are vitally important for the production stations and the points of use in the system. (Kulkarni and Khaparde, 2017).

In the last years, the transformer diversity available has increased appreciably. some types of transformers are below:

- Oil-Filled Transformers
- Gas-Filled Transformers
- Dry Type Transformers

Each of the above categories has a different production process. Because of the complexity of the options, it is extremely difficult to choose the best transformer type for a given application.

### 1.1.1 Oil-filled transformers

This type of transformer is the primary option that can be used in the small to medium power range. In general, in transformer design, the materials chosen for the insulation system affect each other considering their properties such as dielectric, thermal and cost. When one of these features improves, the performance of the other feature decreases. Oil and cellulose paper form the insulation system of oil-filled transformers. The oil-filled transformer is shown in Figure 1.1. This combination exhibited thermal and dielectric properties at an inexpensive cost.

In the absence of environmental concern, fire, leakage, and maintenance, it is more advantageous to use than other transformer options.

Before selecting each category, it should be known that each of these types has associated advantages and disadvantages. Historically, oil-filled transformers were the first choice; but because of known problems, others had developed.


**Figure 1.1** Oil filled transformer.

### 1.1.2 Gas-filled transformers

Gas-filled transformers have been produced that can be applied to any environment to provide the beneficial properties of the dry type. They are also these are dry-type transformers which is hermetically sealed. The gases recently used in these transformer designs are N2, C2F6 and SF6. The task of these gases is to provide the dielectric environment outside the windings. The gases act as a thermal field to transport heat between windings and tank walls.

### 1.1.3 Dry-type transformers

The dry type transformer has in fact existed before the oil-immersed transformers. The dry-type transformers are shown in Figure 1.2. In the early years, they were used in a small transformer class at low voltage levels and used the same materiels as oil-immersed transformers. Thanks to the creation of many advanced materials, the dry-type transformer has developed considerably over the years.

With the development of high-temperature papers, it has become possible to decrease the amount of the core and conductive material with an increment of the working temperature of the windings. But this causes an increment at losses and the cost was almost the same as the cost of oil-immersed transformers. Furthermore, many of the materiels used in these types have proved to be really inflammable. So, it was offered at a competitive price with a transformer that would leave behind the main problems, flammability and leakage of oil-filled transformers. (Nunn, 2000).

**Figure 1.2** Dry-type transformer.

## 1.2 Advantages of dry type transformer

Transformers have recently become an important component of the transmission and distribution system of electrical energy. Since dry-type transformers are protected against fire and explosion, experts and designers tend to turn to non-flammable transformers such as dry-type.

Dry-type transformers are seen as the most suitable transformers because they are more reliable than oil type transformers as well as the highly reliable distribution of electricity. Dry-type transformers are lighter and fireproof compared to oiled type. The lightweight and fireproof feature makes it suitable for residential and hospital use.

Dry-type transformers have many advantages.

These advantages;

- By using a dry-type transformer, we significantly reduce the risk of fire.
- Some liquid immersed transformers are filled with commercially and industry-avoided flammable oils.
- Environmentally dry-type transformers are more attractive. Liquid immersed transformers, especially PCB-filled transformers, threaten the environment due to possible leakage. Cleaning costs can be high if hazardous chemical spills are contaminated with drinking water and soil.
- Although the windings of dry-type transformers are larger than those of liquid immersed transformers, the total size is smaller since they do not require cooling radiators.
- Dry-type transformers have lower installation costs. In some cases, liquid immersed transformers may require additional assemblies, resulting in higher total installation costs. For example, liquid immersed transformers require a collection pit to prevent leakage.
- Dry-type transformers are easier to maintain and have lower operating costs. For liquid-cooled transformers, cores and coils must be removed from the tank when the repair is needed. This increases complexity and cost. (Aşkın, 2011)

## 1.3 The purpose of the thesis

Because of transformers' structure design, the losses occur in the winding and the core of high-efficiency transformers cause an increase in the temperature of the transformer. This temperature increase can affect the insulation material used in the windings, which have a major impact on the operating life of the transformer. The maximum temperature that each insulation material can withstand is limited. The maximum temperature increase limit varies according to the type of insulation material. In order to determine the maximum permissible temperature approximately, experimental data can be obtained by applying direct current pulses to the windings at the nominal power level. The points above the average temperature in the windings are called hot spots. The insulation material in the windings where these hot spots are located rapidly ages. Thus, short circuits occur between the windings. It is difficult to determine the temperature range and hot spots in the windings only by experiment. The thermal elements used to determine these disrupt the winding structure and therefore cause the thermal properties of the winding to change. Not enough research has been done on this important issue. Moreover, the standards are not clear enough.

The location of these hot spots, by the computer technology the temperature level and the temperature distribution of the windings can be found and the transformer can be safely overloaded and the production cost can be minimized. In addition, if the winding temperature and the hot spot temperature can be determined by controlling the overload, further minimizing the aging of the transformers. (Kömürgöz et al., 2003).

In this thesis, the idea is designing an optimum transformer by mathematical modeling and HS algorithm. With HS algorithm the parameters which are necessary to design an optimum transformer model are found. With those parameters, the optimum transformer model is designed. This transformer model's windings and core are analyzed with ANSYS/Maxwell software. According to the analyses, temperature distribution and temperature values are found. Then this optimum transformer is produced with parameters which are found by algorithms and mathematical model. After testing the transformer windings and core, the actual temperature rise test on the transformer and the temperature rise analysis to be performed through the ANSYS/Maxwell program on the 3D transformer design is verified. So the transformer model which is designed as an optimum transformer has produced successfully. In this way, transformer manufacturers will be able to control the transformer model which will be formed according to the electrical and mechanical design of the transformer and take the necessary measures to ensure that this design works with the most reliable and optimum state of the transformer before production.

# 2. LITERATURE REVIEW

The effect of air temperature in cooling ducts of a 2000 kVA dry-type transformer on foil-type winding temperatures of the transformer is examined in detail. The temperatures in the foil-type windings under different loads of 1500 kVA, 1750 kVA, and 2000 kVA were calculated and additionally, these temperatures were measured experimentally. Temperature distributions in foil type windings were calculated by applying constant and varying air temperatures inside vertical ducts. (Lee et al., (2011)

The safe operating limits and thermal response of a 10-kVA dry type transformer were determined and analyzed using Computational Fluid Dynamics Software (CFD) under different load conditions. The insulation aging of the dry-type transformer is examined comparatively under full load and overload conditions. Time the withstands overload condition of the transformer is calculated. In addition, the failure time under the overload condition is discussed. Safe working limits of a 10-kVA dry type transformer are presented With the information obtained from experimental and simulation results. (Alonso et al., 2017).

A CFD thermal model was created to investigate the cooling effect of a dry-type transformer unit with an external heat exchanger. The accuracy of the simulation results obtained from this model has been proved by experimental results. (Wu et al., 2016) The physical model of a dry-type transformer was created in SOLIDWORKS and transferred to COMSOL to perform temperature field analysis. The temperature data obtained from the transformer company and theoretical data were compared. As a result of all the studies, the hottest point of the dry type transformer was determined. In addition, extending the life of the transformer and about the economic benefits of the transformer production process are explained. (Ding and Ning 2012) Additional losses caused by harmonic currents and voltages in a three-phase 10kVA dry type transformer and the effect of heating resulting from these losses on transformer life are examined in detail. The error rates were determined by comparing the experimental results obtained by using the thermal camera and the temperature data obtained from the simulation results. (Silva et al., 2015).

The relationship between hot spot analysis of dry type transformer and loss of insulation life is discussed. In order to determine the hot spot temperature in the low voltage windings and high voltage windings of the transformer, a hot spot temperature calculation model was created. By calculating the aging ratio of transformer winding under the rated load, the loss of insulation life of the transformer was calculated. (Wang et al., 2015). The effect of under the load conditions and ambient temperature on transformer temperature was discussed by thermal modeling of a cast resin transformer. In this study, an online prognosis system that predicts the aging rate and lifetime of the transformer has been developed. (Bagheri et al., 2015) A fuzzy model of the transformer temperature control model has been developed to control the speed of the fan used in the cooling of transformers. In this model transformer temperature control model, the input parameters are load temperature, humidity, and pressure. Transformer life and safety have been increased by performing heating control of the transformer. (Kashyap et al., 2015) The thermal network model and the CFD model of a dry-type transformer were formed and compared by estimating the temperature rise data obtained from these models. (Wu et al., 2016)

In another study, a quasi-3D coupled-field method was presented to analyze the temperature rise of high voltage windings and low voltage windings in a dry-type transformer. The results obtained from this method were compared with the experimental data. (Liu et al., 2016). To determine the temperature rise of a 160 kVA dry type transformer, the finite element method was used under full load conditions. With this method, temperatures in primary and secondary windings were estimated with high accuracy. (Chitaliya et al., 2016). The thermal circuit model and the finite element model of a dry-type transformer were formed and the convective heat transfer coefficient of these models was calculated. In addition, the center of core low voltage windings and high voltage windings temperatures were obtained and compared for two methods. (Chen et al.,2019). Thermal analysis of a normal two-winding cast resin transformer with split windings was carried out and supported by experimental data. The transformer was modeled using a nite difference approach and the temperature data were obtained. (Azizian., 2016). A thermal model based on the finite element method was developed to analyze the heat transfer between ambient air and dry-type air-core smoothing reactors (DASR) Experimental results supported the accuracy of the proposed thermal model. (Wang et al., 2017).

Artificial Neural Network was used in modeling the effect of dry type transformer design parameters on internal temperature. Temperature test data obtained from 300 transformers were used in this method. The relationship between transformer design parameters and losses and winding temperatures have been shown to be modeled by ANN (Finocchio et al., 2017). A numerical approach has been proposed to determine the total harmonic distortion increase caused by linear and non-linear loads in a 5 kVA three-phase dry type transformer. In order to prove the accuracy of this numerical approach, experimental data were obtained. This developed method has helped to estimate transformer life. (Ebenezer et al., 2015). The temperature distribution in the core and windings of a 1.2 MVA single-phase Dry-type transformer was analyzed by simulating. Temperature increases in large power transformers are also high. In this case, thermal analysis has been done in detail since it directly affects the life of the transformer. (Nabhani et al., 2015). A thermal model based on the finite element technique was established to determine the relationship of the temperatures on the cast resin dry type transformer with various parameters. (Shaker., 2011) The winding temperatures of the dry type transformers with 3 different powers were obtained by using FLUENT software based on heat transfer theory. Measured and calculated temperature values were compared and error rates were calculated. (Li., 2012) The effect of dry-type cast-epoxy resin transformers on the operating temperature of the case is discussed in detail with simulation results. The temperature distribution of the Transformer without Case and with the case is presented by using electromagnetic analysis software. (Huo et al., 2012)

# 3. MATERIALS AND METHODS

## 3.1 Transformers

The transformer converts electrical energy from the primary winding to magnetic energy. Then the energy is converted back into electrical energy in secondary or tertiary windings.

That is, the primary and other windings are magnetically coupled. Depending on whether the primary is higher or lower than the secondary, the transformers may be step up or step down. Transformers are called high-voltage and low-voltage windings instead of primary and secondary windings, as they can be used for the gradual rise or drop voltage depending on need.

The transformers' internal structure is shown in Figure 3.1.

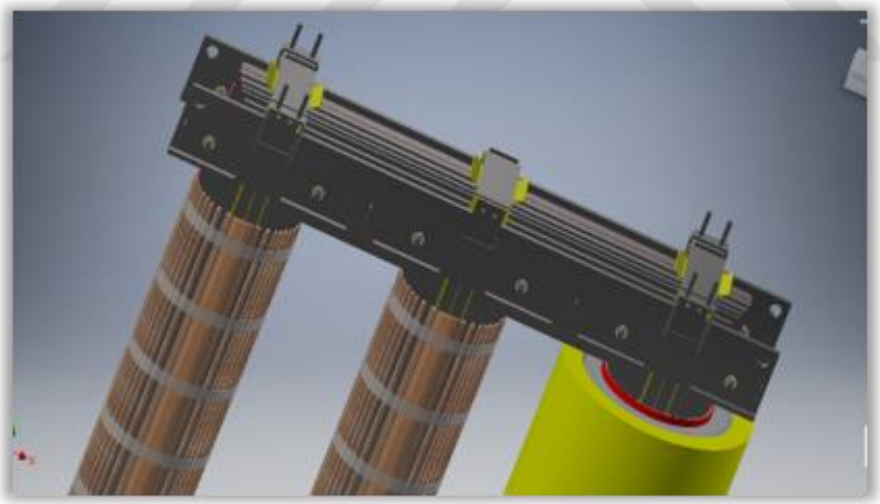

**Figure 3.1 Transformer internal sturcture**

### 3.1.1 Magnetic circuits

Since the transfer of electrical energy is carried out by means of a transformer without moving parts, the transformer operates at high efficiency and has lower maintenance costs than electrical machines. The materials used for the cores are improved. Varied model of silicon steels are below: non-oriented, hot rolled grain-oriented, cold rolled grain oriented (CRGO), Hi-B, mechanically drawn and laser-drawn. The last three models are more developed model within the CRGO material class. The saturation flow density for CRGO grades is around 2.0 Tesla, however, the technologies used to produce better quality materials have played an important role in the development of watts/kg and volt-amps/kg characteristics. Since the material quality option is limited, transformer designs are also limited. Using efficient design and manufacturing technology, the performance of the core can be improved and optimized.

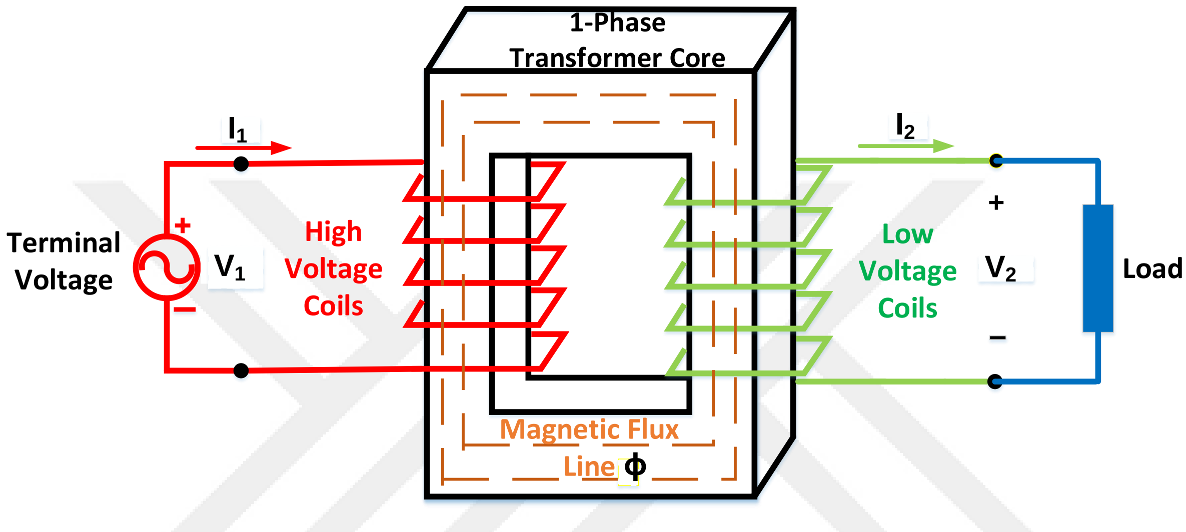


**Figure 3.2 1-Phase transformer core**

The transformers operate with electromagnetic induction of induced voltage by the flux in a coil. A single-phase transformer is being formed of two windings is wound on a magnetic core as in Figure 3.2 and connected by a mutual flux $\Phi_m$. The transformer is connected to the primary f Hz. the sinusoidal voltage source in the no loaded state. The primary winding adjusts the flux $\Phi_m$ in the core by drawing a small excitation current from the source. It is assumed that all flux occurs within the core. Winding 1 and winding 2 have N1 and N2 turns, respectively. The formula 1.1 gives the instantaneous value of the induced electromotive force in the winding due to the opposite flux.

$$e_1 = N1 \frac{d\Phi_m}{dt} \tag{1}$$

The induced voltage (counter electromotive force) is given in formula 1.2.

$$e_1 = -N1\frac{d\Phi_m}{dt} \quad (2)$$

If the resistance (with its leakage reactance already neglected) assumed to be zero;

$$v_1 = e_1 \quad (3)$$

The flux which is varying with frequency f is sinusoidal because $V_1$ (instantaneous voltage) is sinusoidal. Let

$$\Phi_m = \Phi_{mp} sin\omega t \quad (4)$$

We obtain equation 1.5 when substituting the value of mutual flux $\Phi_m$ in equation 1.1 according to $\Phi_{mp}$ is the peak value.

$$e_1 = N_1 \omega \Phi_{mp} cos\omega t \quad (5)$$

By dividing the peak value in equation 1.5 by $\sqrt{2}$, $E1_{(r.m.s)}$ of the induced voltage is obtained.

$$\omega = 2\pi f \quad (6)$$

$$E_1 = 4.44\Phi_{mp} f N_1 \quad (7)$$

Equation 1.7 shows the emf equation of the transformer. For the known number of turns and known frequency, the flux and flux density in the core can be determined by the applied voltage.

The induced voltage (counter electromotive force) is given in formula 1.8.

$$e_2 = N2\frac{d\Phi_m}{dt} \quad (8)$$

The equation 1.9 can be derived from Equations 1.1 and 1.8.

$$e_1/e_2 = N_1/N_2 = I_2/I_1 = n \quad (9)$$

The n is known as the ratio of transformation.

### 3.1.2 Windings

Paper-insulated conductors are generally used in medium power and large power transformers' windings. These types of conductors are separate strips, bundles or continuously transposed cables (CTCs). In distribution transformers when there is not much conversion for the low-voltage side of, copper or aluminum foils can be used. In order to increase the short-circuit withstand capacity, high-grade transformers are commonly used with work-hardened copper material. In transformers that draw high current on the low voltage (LV) side, CTC conductors are often used which provide a better field factor and a reduction of eddy loss in windings. The conductors used with the insulated upgraded material help to cope with thermal overload to temperatures of about 110 ° C. It offers a better life expectancy with its uses.

### 3.1.3 Insulation and cooling

Dry-type transformer insulation classes are F or C classes. Dry-type transformers are possible to use in indoor applications to minimize explosion with their reliable designs. Nomex paper insulation commonly used in dry-type transformers can withstand temperatures of 220 ° C. Although the initial cost of a dry-type transformer is 60 to 70% higher than the oil-cooled transformer, the total cost of the current energy ratios may be quite similar to that of the oil-cooled transformer.

### 3.1.4 Manufacturing

In production technology, the techniques used to reduce production time and improve product quality are listed below.

- Automation system for cutting step by step operations to provide dimensional accuracy in core lamination
- Cores' step-lap construction to provide lower core loss and noise level
- Production core construction without the yoke
- Setting automatic winding machines for distribution transformers

- Using for effective drying and fast-drying vapor phase drying
- Providing low-frequency heating for the drying process of distribution transformers
- Providing pressurized chambers to protect windings and to protect insulating parts from pollution and dirt
- For winding large-capacity transformer coils setting vertical machines
- Isostatic clamping for accurate sizing of windings
- High-frequency brazing for joints in the windings and connections. (Kulkarni and Khaparde, 2017).

### 3.2. Mathematical Modeling of a 3-Phase Dry-Type Transformer

For a transformer design, two important parameters which are cost and efficiency should be taken in to account. If these parameters which have the best condition can be assured, the optimum design of the transformer will be actualized. In this section, the mathematical model of 3 and 5 kVA 380/220 V Dyn11 connected 3-phase dry type transformer is given in detail.

$$\eta = \frac{S_2}{S_2 + P_{total\_loss}} \tag{10}$$

The efficiency of the transformer can be found in formula 10. For $\eta$ we need the value of output power and total loss of the transformer. Total loss can be found in formula 11.

$$P_{total\_loss} = P_{cu} + P_{fe} \tag{11}$$

$$P_{fe} = P_{feb} + P_{fej} \tag{12}$$

Total iron loss can be calculated by the sum of the yoke $P_{fej}$ and 3-leg iron loss $P_{feb}$.

$$G_{total} = G_1 + G_2 + G_{feb} + G_{fej} \tag{13}$$

The total weight of the transformer is equal to the total amount of HV and LV coils, the yoke weight and the 3-leg weight of the core.

$$P_{feb} = G_{feb} x p_{feb} \tag{14}$$

$$P_{fej} = G_{fej} x p_{fej} \tag{15}$$

$$p_{fej} = p_{10} x \xi_2 x {B_j}^2 \tag{16}$$

$$p_{feb} = p_{10} x \xi_2 x B^2 \tag{17}$$

$\xi_2$ denotes as the loss factor during the core process and $p_{10}$ express the additional loss factor of the core.

$$G_{feb} = 3x10^{-3} \gamma_{fe} q_{fe} L_s \tag{18}$$

$$G_{fej} = 310^{-3} \gamma_{fe} q_{fej} 2(0.8xM + 0.8xD) \tag{19}$$

$$M = 0.851\text{xD} + 0.1\text{x}L_s \tag{20}$$

One of the losses is copper losses which is part of total losses.

$$P_{cu} = P_{cu1} + P_{cu2} \tag{21}$$

$$P_{cu1} = 3{I_1}^2 r_1 \tag{22}$$

$$P_{cu2} = 3{I_2}^2 r_2 k \tag{23}$$

The resistance of HV and LV windings are $r_1$ and $r_2$;

$$r_1 = p_0 \frac{I_{m1} w_1}{q_1} \tag{24}$$

$$r_2 = p_0 \frac{I_{m2} w_2}{q_2} \tag{25}$$

$$G_1 = 3x10^{-5} \gamma_{al} w_1 q_1 I_{m1} \tag{26}$$

$$G_2 = 3x10^{-3}\gamma_{al}w_2 q_2 I_{m2} \tag{27}$$

The weights of the windings are going to be used for calculation of cost.

Calculating the $I_{m1}$ and $I_{m2}$ is used for help to calculate the weight of windings.

$$I_{m1} = \pi(D + 2x0.4 + 0.01x12.2 + 2x1.2) \tag{28}$$

$$I_{m2} = 0.1\pi(10xD + 8 + a_2) \tag{29}$$

$a_2$ express the radial height of the LV winding.

Width of the transformer (a) core can be obtained;

$$a = 4x\,\frac{w_1 x q_1}{100xkxL_s} \tag{30}$$

k represents the window filling factor.

$$L_s = 0.2x\,\frac{w_1 x I_1}{A_s} \tag{31}$$

Due to cross-section, winding turns and current density of the windings determine the window height of the core which is called $L_s$. And $A_s$ is called specific ampere winding. So we need to calculate the cross-section.

HV and LV winding cross-section of the transformer;

$$q_1 = \frac{I_1}{s} \tag{32}$$

$$q_2 = \frac{I_2}{s} \tag{33}$$

$$w_1 = \frac{U_1}{\sqrt{3}x4.44xfx\Phi} \tag{34}$$

$$w_2 = \frac{U_2}{\sqrt{3}x4.44xfx\Phi} \tag{35}$$

To find $w_1 and\ w_2$) we need to calculate the magnetic flux.

$$\Phi = Bxq_c \tag{36}$$

$$B_j = \sqrt{\frac{B}{1.2}} \tag{37}$$

$$D = \sqrt{\frac{4xq_c}{0.677x\pi}} \tag{38}$$

D is called the diameter of a leg of the transformer. Yoke cross-section $q_{cj} = q_c x1.2$ which is qfe is called cross-section. This case is inverse for the yoke induction of the core leg ($B_j$).

$$q_c = Cx\sqrt{S_2 x\frac{2}{3}} \tag{39}$$

C parameter is called as core section acceptability which is 0.7<C<1.5. If the value gets low it means the core has good quality.

The currents flowing in the windings can be obtained by Equation 40. The core section of the transformer $q_c$ can be obtained by;

$$S = \sqrt{3}xUxI \tag{40}$$

S is rated power, U is voltage, I is current which is flowing through the windings. (Çelebi, 2008).

These parameters are listed in order to calculate efficiency and cost.

As a result, for the optimization process of the transformer, by using the mathematical model of the transformer, the constraints, efficiency and cost functions of the transformer are obtained. Current density parameter (s) and the transformer core quality factor (C) are the constraints. These values have a significant role in transformer design and optimization. The cost, size and efficiency of the transformer are directly related to these constraints since they are the key parameters on the transformer losses, core and windings weights.

### 3.3. Harmony Search Algorithm

The HS algorithm is an optimization technique and developed by Geem et al.

The HS algorithm can be used to solve many problems in the engineering field. This method has many advantages. It does not require a special initial solution for decision variables. Since it continues the optimization process with more than one solution, searching for the general optimum solution in many ways, thus eliminating the local optimum solutions. Using both continuous and discrete variables in the optimization processes.

Although the HS algorithm has similarities with the genetic algorithm (GA) in terms of computational logic, the most significant difference between these two methods stems from the assumptions in the reproduction stage. While two individuals in the society are used to form a new decision variable with GA, the new individual created by the HS method can bear the characteristics of all individuals in society. In addition, it is faster to complete an iteration in HS than in GA.

The solution of an optimization problem with the HS algorithm is done in five steps (setting up the problem and determining the solution parameters, creating the harmonic memory, creating new harmonic, updating the harmonic memory, checking the stop condition).

**Step 1. Establishment of problem and determination of algorithm parameters:** In this step, the objective function (OF) of the optimization problem is defined as in equation 41.

$$OF = Minimum\ \{f(x)\}, x_i \epsilon X_i, \quad i = 1,2, \dots\dots N \tag{41}$$

In the equation, f (x) represents the objective function to be minimized, xi represents the solution space used for each decision variable, and N represents the total number of decision variables. Solution parameters of HS algorithm; harmonic memory capacity (HMS), harmonic memory consideration ratio (HMCR) and pitch adjustment ratio (PAR).

**Step 2. Harmonic memory generation:** In this step, the harmonic memory is filled with all randomly generated decision variables within the defined solution space. The objective function values corresponding to these solutions are found in equation 42.

$$\begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix} \Longmapsto \begin{bmatrix} f(x^1) \\ f(x^2) \\ \vdots \\ f(x^{HMS-1}) \\ f(x^{HMS}) \end{bmatrix} \quad (42)$$

**Step 3. Creating new harmony:** In this step, the new harmonic vector $x' = (x_1', x_2', x_3', \ldots \ldots x_N')$ is produced according to the tones in the harmonic memory and completely randomly selected tones. The first decision variable $(x_1')$ of the new harmonic vector in the harmonic memory is randomly selected from any value in the existing harmonic memory $(x_1', \ldots \ldots x_1^{HMS})$. The selection of other decision variables $(x_2', x_3', x_4', \ldots \ldots x_N')$ is done in a similar way. The determination of whether the variables are selected from the harmonic memory is made according to the HMCR value. Here, HMCR (ranging from 0 to 1) indicates the possibility of selecting the value of a decision variable from the current harmonic memory, while (1-HMCR) corresponds to the random selection of the new decision variable generated from within the existing solution space. The method of selection is shown in equation 43.

$$x_i' = \begin{cases} Possibility\ of\ HMCR & x' \in (x_i^1, x_i^2, x_i^3, \ldots \ldots x_i^{HMS}) \\ Possibility\ of\ 1 - HMCR & x' \in X_i \end{cases} \quad (43)$$

Each decision variable is then evaluated to determine whether tone adjustment is required. Pitch adjustment ratio (PAR) is made according to equation 44.

$$x_i' = \begin{cases} Possibility\ of\ PAR & x_i' \pm Rnd\{0,1\} xbw \\ Possibility\ of\ 1 - PAR & x_i' \end{cases} \quad (44)$$

In the equation, bw represents the randomly selected bandwidth and Rnd (0,1) represents the random number generated between 0 and 1. In the case of PAR, $x_1'$ the decision variable is changed and in the case of (1-PAR) nothing is done. HMCR and PAR parameters help the algorithm to find general and local optimum solutions, respectively.

**Step 4. Harmonic memory update:** In this step, a comparison between the newly created harmony a1, a2, a3, a4 .... aN and the worst harmony in memory is made in terms of the values of the objective functions. If the newly created harmonic vector yields better results than the worst harmonic vector, the worst harmonic vector is removed from memory and the new harmonic vector is assigned in its place.

**Step 5. Checking the stop condition:** It is checked whether the stop condition given in this step is met. If the condition is not fulfilled, the steps of reproduction, creating new harmonics, whether the variables are selected from the harmonic memory (HMCR), tone tuning (PAR) and updating the harmonic memory are repeated. When the stop condition is met, the search is ended with the best result. The flow diagram of the harmony search optimization algorithm showing these steps is given in Figure 3.3. (Özyön et al., 2011)

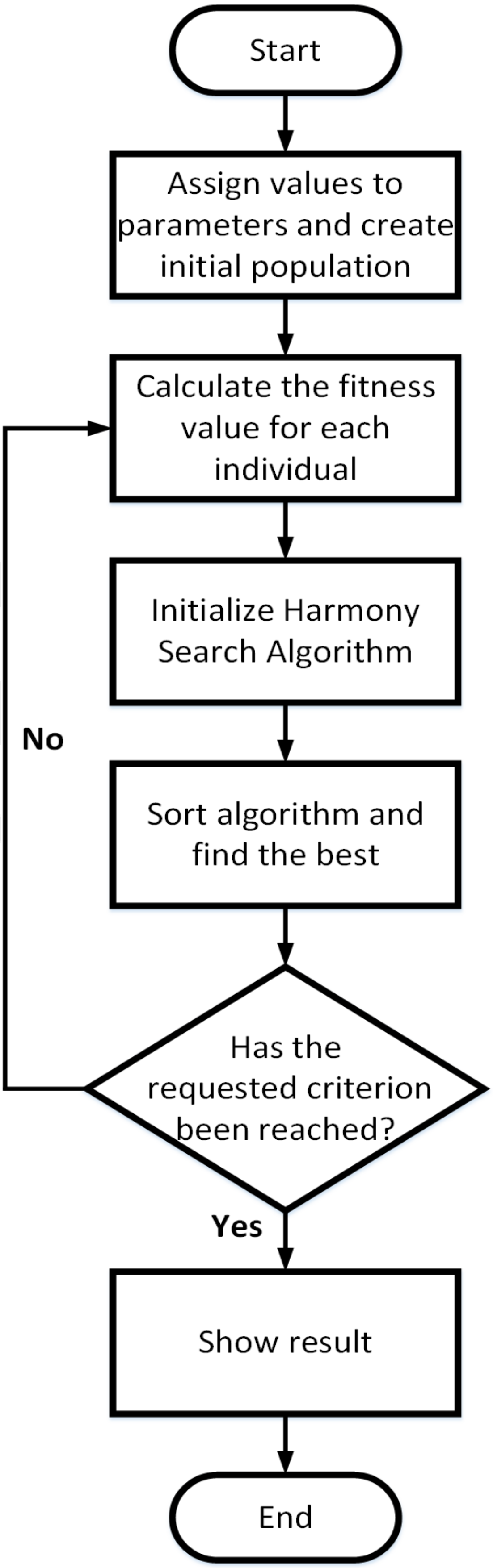


**Figure 3.3 Flowchart of the HS algorithm (Demirdelen., 2018)**

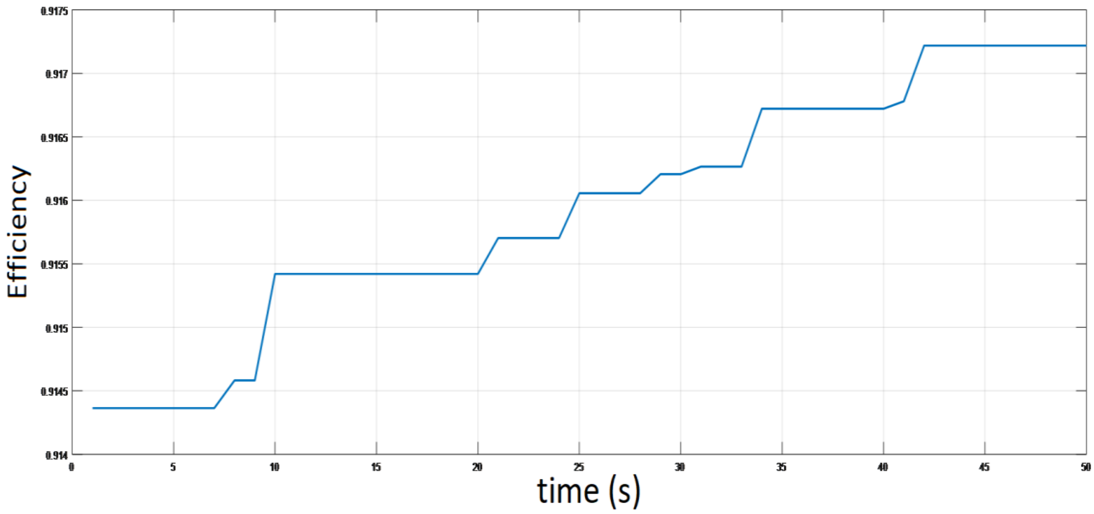


**Figure 3.4 Efficiency-Time Graph of 3 kVA**

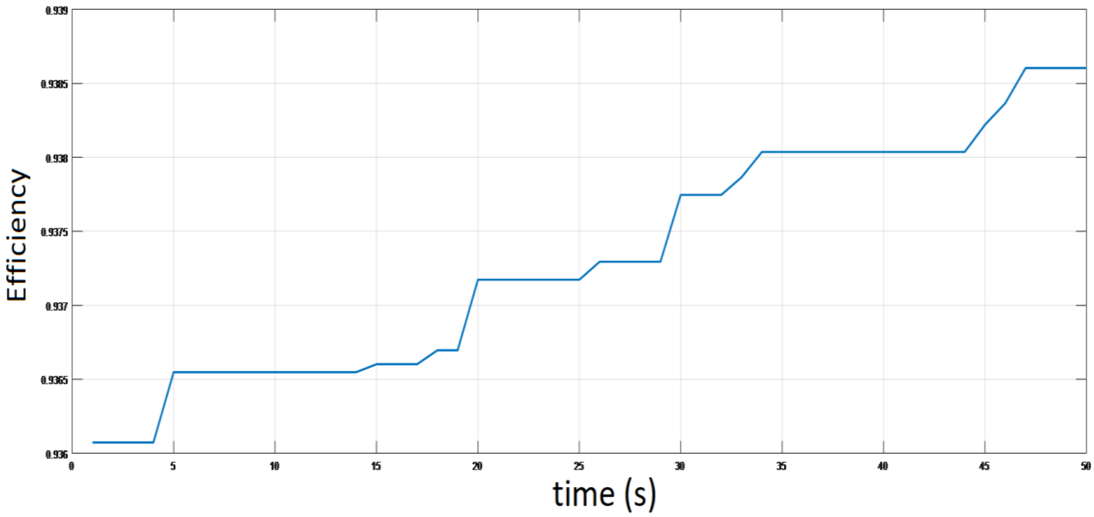


**Figure 3.5 Efficiency-Time Graph of 5 kVA**

The efficiency-time graphs are shown in Figure 3.4 and Figure 3.5. For 3 and 5 kVA the efficiency value, weight, cost, C value and s value are shown in Table 3.1 and Table 3.2.

As a result of 50 iterations, current density (s) and the transformer core quality factor (C) were found by the HS algorithm.

### 3.4. Technical specifications of transformers

**Table 3.1. Design parameters of 3 kVA 380/220 V 3-Phase dry type transformer**

| Characteristic | Unit | Values |
|---|---|---|
| **Product Name** | | 3 Ph. Dry-type transformer |
| **Rated Power** | S | 3000 VA |
| **Primary Voltage** | V1 | 380 V |
| **Secondary Voltage** | V2 | 127 V |
| **The core section of the transformer ($q_{fe}$)** | $q_{fe}$ | 35,51 $cm^2$ |
| **Current Density (s)** | s | 2.057 A/ $cm^2$ |
| **Transformer core section acceptability** | C | 7.2489 |
| **Primary windings** | $w_1$ | 395 turns |
| **Secondary windings** | $w_2$ | 132 turns |
| **Primary Current** | $I_1$ | 4.84 A |
| **Secondary Current** | $I_2$ | 7.93 A |
| **Primary Winding Cross Section** | $q_1$ | 2.2 $mm^2$ |
| **Secondary Winding Cross Section** | $q_2$ | 3.6 $mm^2$ |
| **Average lengths of HV winding** | $l_{m1}$ | 30.6 cm |
| **Average lengths of LV winding** | $l_{m2}$ | 36.25 cm |
| **Weight of the HV winding** | $G_{cu1}$ | 1.38 kg |
| **Weight of the LV winding** | $G_{cu2}$ | 2.1 kg |
| **Weight of 3 legs of the transformer core** | $G_{feb}$ | 11.1 kg |
| **Weight of the transformer yoke** | $G_{fej}$ | 11.94 kg |
| **Total weight of the transformer** | $G_{total}$ | 25 kg |
| **Efficency** | $\eta$ | 91,72 % |
| **Cost** | € | 146,5 € |

**Table 3.2. Design parameters of 5 kVA 380/220 V 3-Phase dry type transformer**

| Characteristic | Unit | Values |
|---|---|---|
| **Product Name** | | 3 Ph. Dry-type transformer |
| **Rated Power** | S | 5000 VA |
| **Primary Voltage** | V1 | 380 V |
| **Secondary Voltage** | V2 | 127 V |
| **The core section of the transformer ($q_{fe}$)** | $q_{fe}$ | 42 $cm^2$ |
| **Current Density (s)** | s | 2.0215 A/ $cm^2$ |
| **Transformer core section acceptability** | C | 7.2757 |
| **Primary windings** | $w_1$ | 395 turns |
| **Secondary windings** | $w_2$ | 132 turns |
| **Primary Current** | $I_1$ | 8.16 A |
| **Secondary Current** | $I_2$ | 13.12 A |
| **Primary Winding Cross Section** | $q_1$ | 4.0366 $mm^2$ |
| **Secondary Winding Cross Section** | $q_2$ | 6.4902 $mm^2$ |
| **Average lengths of HV winding** | $l_{m1}$ | 33.15 cm |
| **Average lengths of LV winding** | $l_{m2}$ | 38.80 cm |
| **Weight of the HV winding** | $G_{cu1}$ | 4.2 kg |
| **Weight of the LV winding** | $G_{cu2}$ | 2.6 kg |
| **Weight of 3 legs of the transformer core** | $G_{feb}$ | 11.2 kg |
| **Weight of the transformer yoke** | $G_{fej}$ | 12 kg |
| **Total weight of the transformer** | $G_{total}$ | 30 kg |
| **Efficiency** | $\eta$ | 93.86 % |
| **Cost** | € | 200 € |

The design parameters are optimized in the HS algorithm according to C and s values of the transformer. Therefore, efficiency and weight change of the transformer are performed depending on the core quality factor and the current density of the windings.

According to these parameters, the transformer 3D model is conducted as shown in figure 3.6.

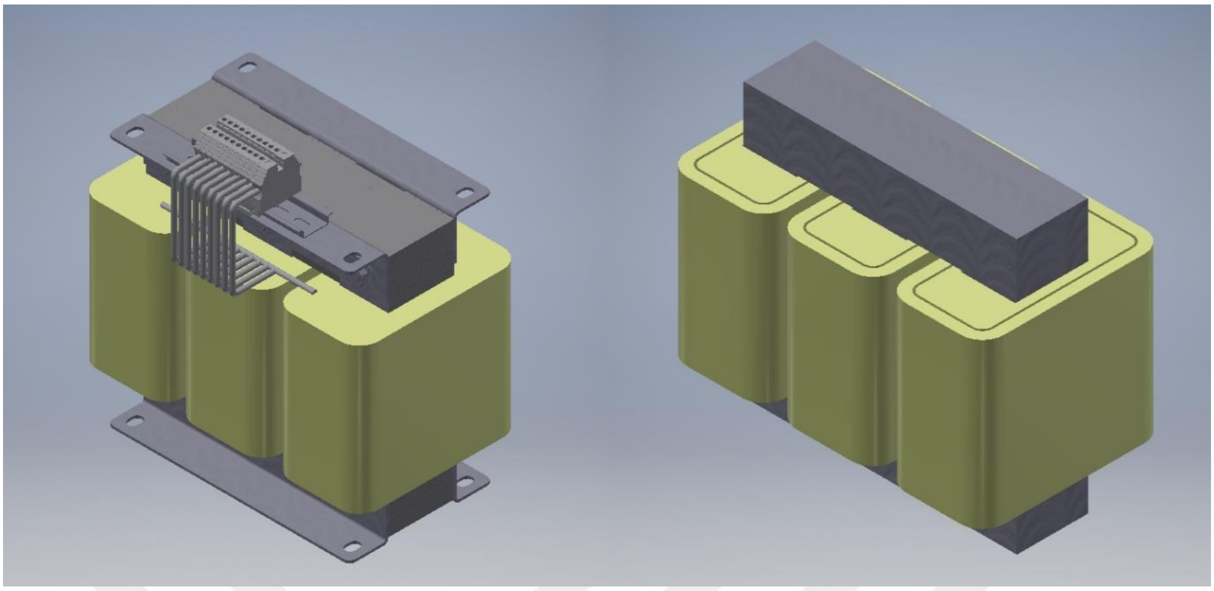

**Figure 3.6 Transformer 3D design**

Temperature distribution on 3 kVA dry type transformer core, the primary winding and the secondary winding are shown in Figure 3.7, Figure 3.8 and Figure 3.9.

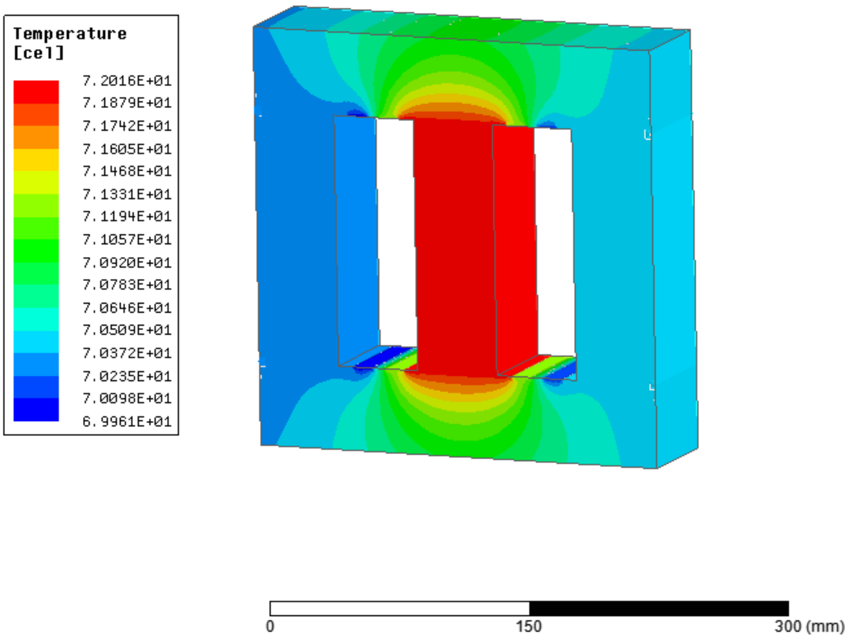


**Figure 3.7 Thermal analysis on transformer core (3 kVA)**

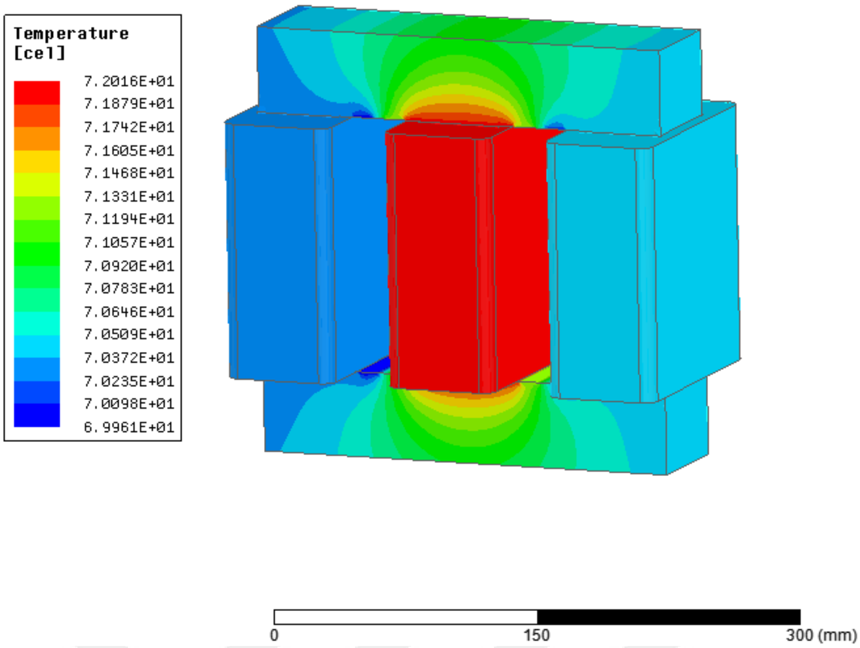


**Figure 3.8 Thermal analysis on low voltage winding of the transformer (3 kVA)**

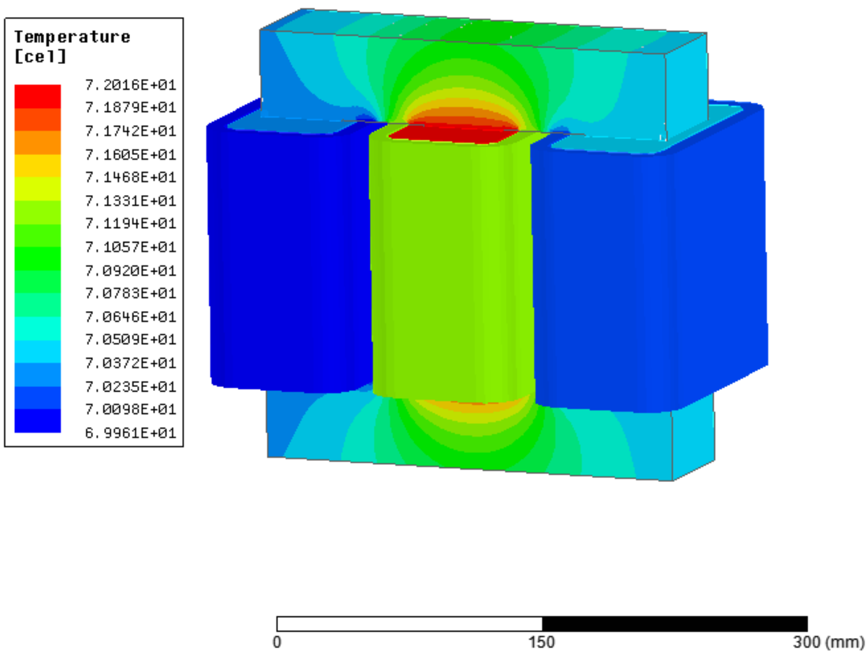


**Figure 3.9 Thermal analysis on high voltage winding of the transformer (3 kVA)**

Temperature distribution on 5 kVA dry type transformer core, the primary winding and the secondary winding is shown in Figure 3.10, Figure 3.11 and Figure 3.12.

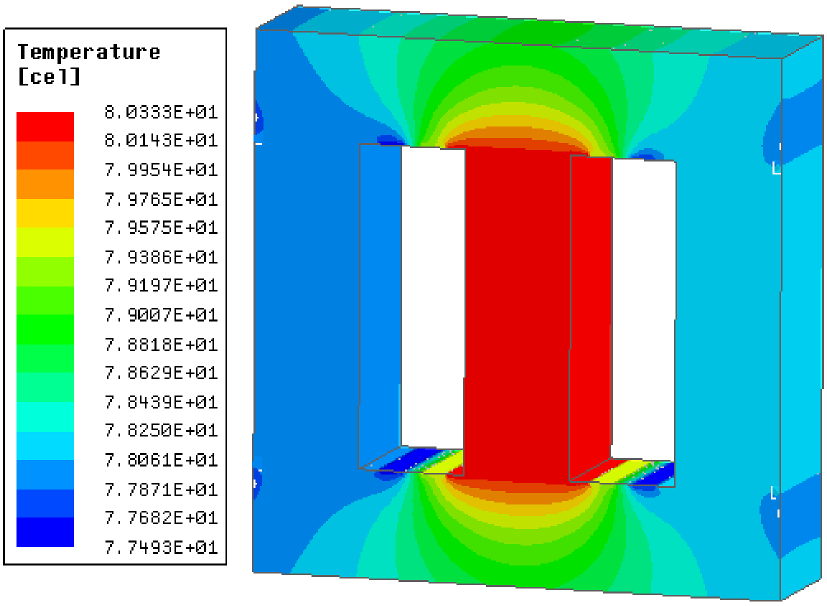


**Figure 3.10 Thermal analysis on transformer core (5 kVA)**

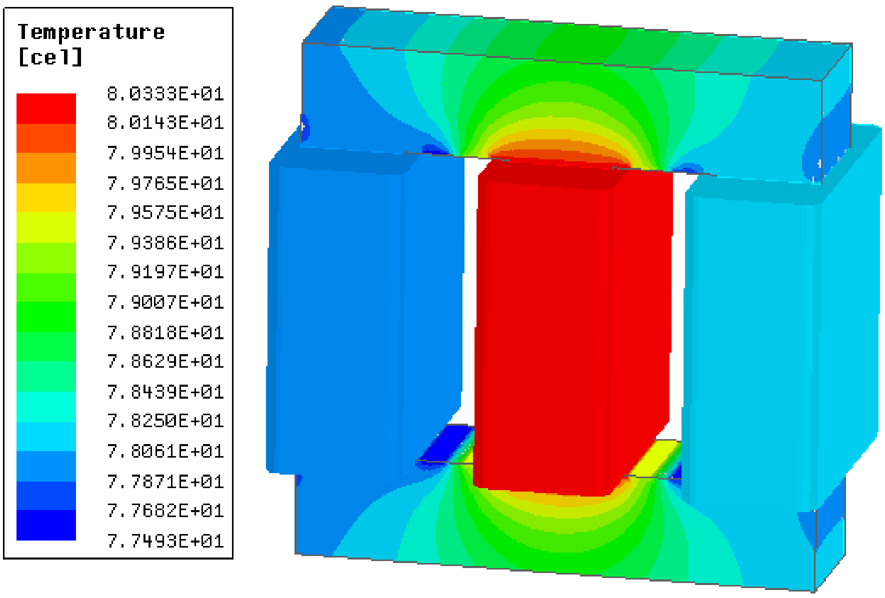


**Figure 3.11 Thermal analysis on low voltage winding of the transformer (5 kVA)**

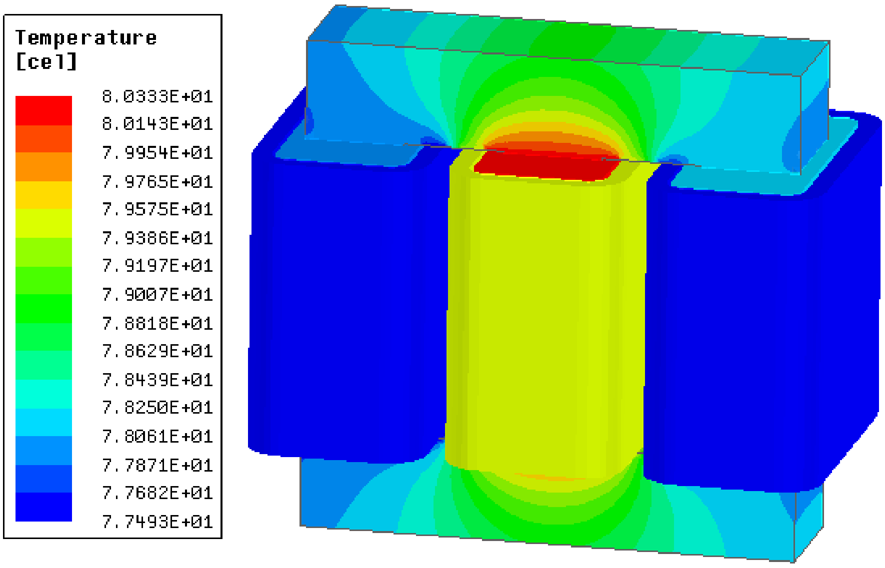


**Figure 3.12 Thermal analysis on high voltage winding of the transformer (5 kVA)**

## 3.5. Temperature measurement of transformers

In this section, winding and core temperature measurement tests and modeling of two dry-type transformers of different powers will be explained. As is known, the life of the dry type transformer is directly related to the insulation life. The sum of the temperature and time factors causing the transformer's insulation to deteriorate gives us great insight into the lifetime of the transformer. We must also consider the ambient temperature when determining the load capacity of the transformer. In addition, short-time loads above the rated load reduce the isolation life of the transformer.

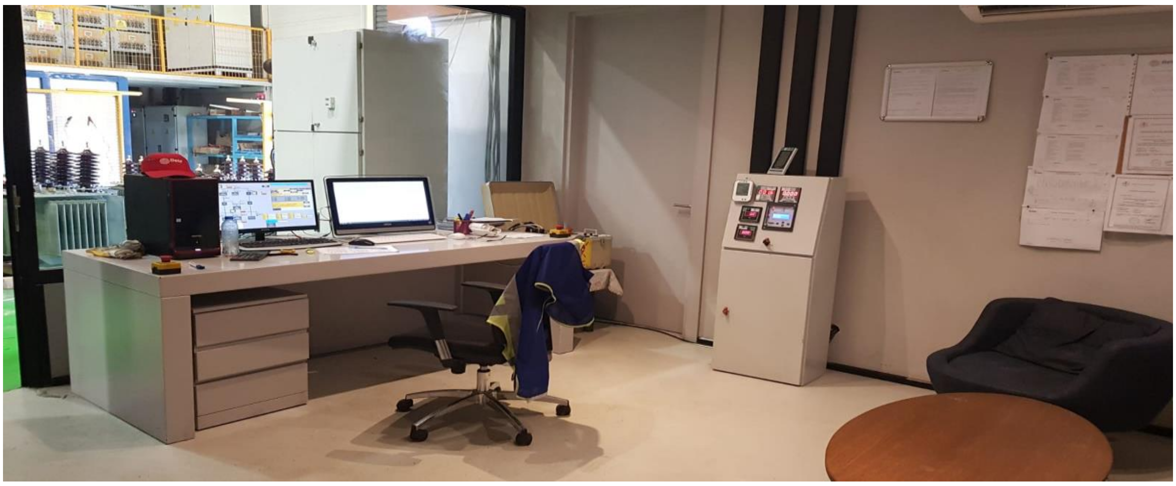

**Figure 3.13 Beta test laboratory**

Experimental data were obtained with a set created in the Beta transformer test laboratory shown in Figure 3.13. Test equipments were provided by Beta transformer as shown in Figure 3.14 and Figure 3.15. Also, the test took place under the supervision of laboratory engineers. Full and half-load current is supplied from the energy source in the laboratory to ensure full and half-load of the transformer. When the load is ensured, the information of protection distance must be considered by employees.


**Figure 3.14 Beta test laboratory warning lamp**

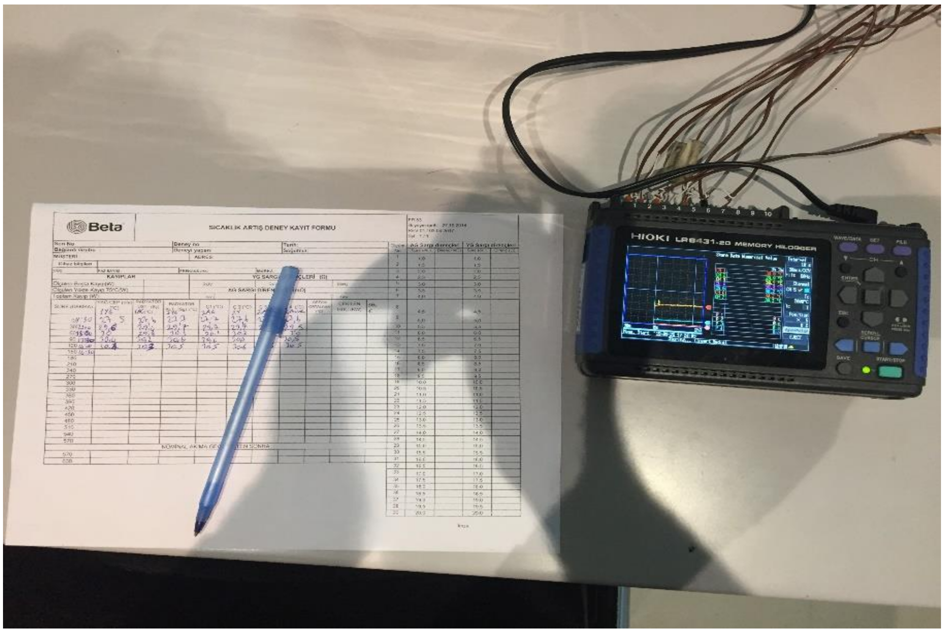


**Figure 3.15 Measuring device**

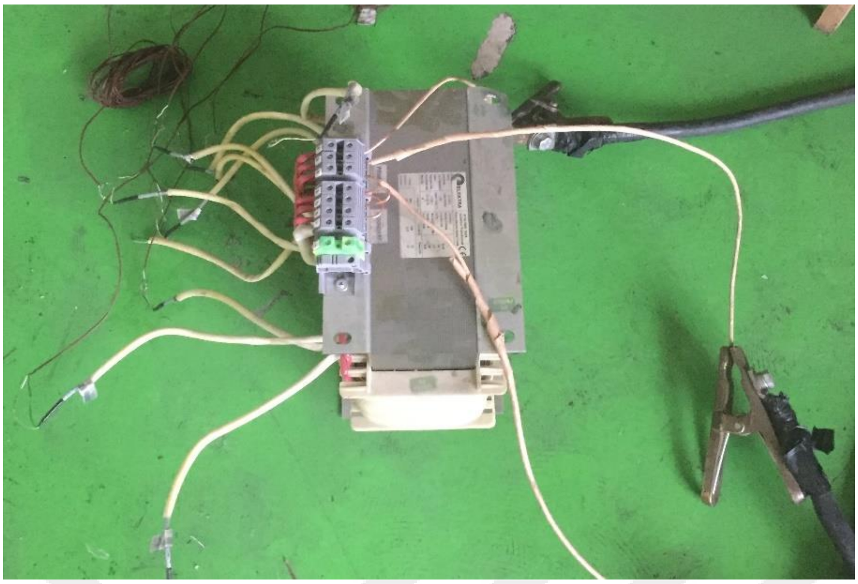

**Figure 3.16 Cable connections of 5 kVA transformer**

In order to measure the winding and core temperature of the transformer, 7 thermocouples temperature sensors were installed at a total of 7 points in the windings and the core. The measurement was recorded by using the measuring device to which the temperature sensors were connected as shown in Figure 3.16. By using the measuring device, the temperature was recorded during the measurement period, also the average temperature value and graph were presented to us as shown in Figure 3.18. Protection distance to the transformer is provided during the test process as shown in Figure 3.17.

**Figure 3.17 Cable Connections of 3 kVA transformer**

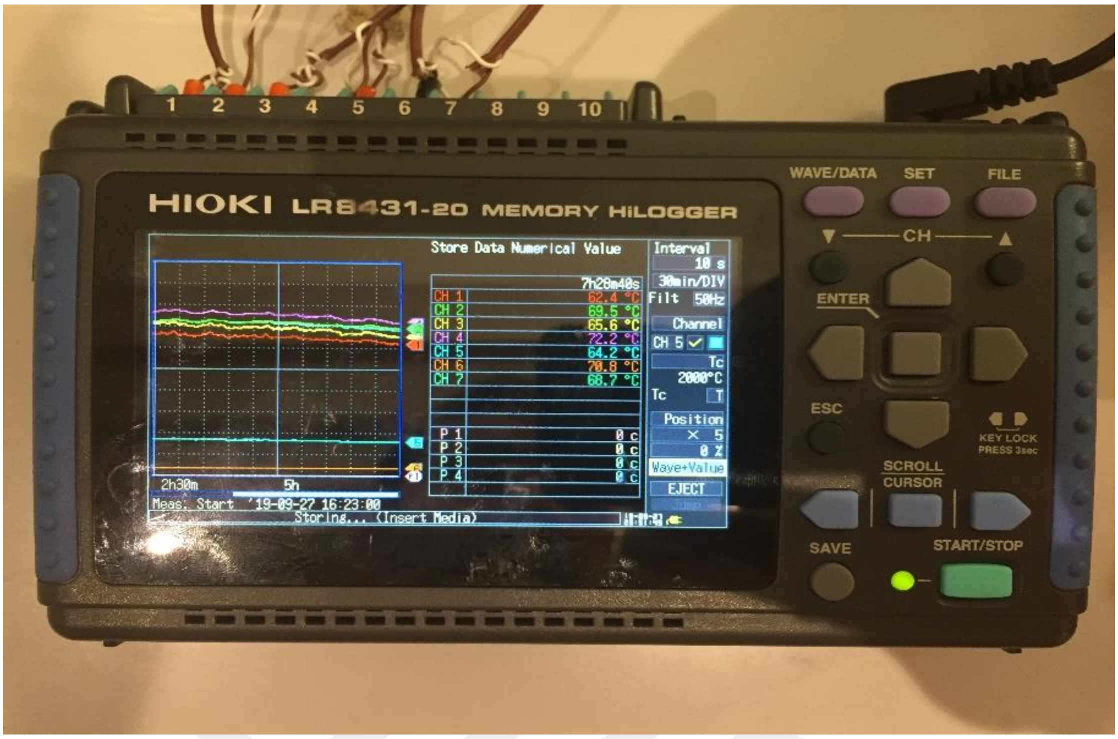


**Figure 3.18 Temperature graph**

In this thesis, measurement techniques and some information in the process have been benefited. (Esenboğa., 2019)

# 4. RESULTS AND DISCUSSIONS

3 kVA and 5 kVA 380/220 Dyn11 connected 3-phase dry-type transformers are analyzed thermally at Beta test laboratory conditions. Firstly, the transformer models are analyzed by ANSYS/Maxwell program. According to the results of the program are compared with real test results which are taken at the test laboratory.

## 4.1. Thermal measurement test of the transformers

Cable connections between the measurement devices and transformers are shown in Table 4.1.

**Table 4.1. Cable connections between the measurement device and transformers**

| | |
|---|---|
| Channel 1<br>CH-1 | The measurement device is connected with the transformer's left leg and secondary side. |
| Channel 2<br>CH-2 | The measurement device is connected with the transformer's left leg and primary side. |
| Channel 3<br>CH-3 | The measurement device is connected with the transformer's right leg and secondary side. |
| Channel 4<br>CH-4 | The measurement device is connected with the transformer's right leg and primary side. |
| Channel 5<br>CH-5 | The measurement device is connected with the transformer's middle leg and secondary side. |
| Channel 6<br>CH-6 | The measurement device is connected with the transformer's middle leg and primary side. |
| Channel 7<br>CH-7 | The measurement device is connected with the transformer's middle leg and middle core. |

### 4.1.1. At %100 load short circuit test

The first experiment was a short circuit test at %100 load for transformers. For 3 kVA 4,5 ampere load was given to the primary side when the secondary side was a short circuit and the same case for 5 kVA and 7,5 ampere load was given. The results for 3 kVA are given in Figure 4.1 and Table 4.2, the results for 5 kVA are given in Figure 4.2 and Table 4.3.

**Table 4.2. Measurement results for 3 kVA for the short circuit test**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 34,7 | 34,1 | 36 | 35 | 35,4 | 34,7 | 34,1 |
| 30 min | 57,5 | 54,4 | 61,9 | 58,7 | 59,1 | 56 | 55,3 |
| 60 min | 64 | 59,8 | 69,1 | 64,9 | 66,4 | 62 | 62,5 |
| 90 min | 67,1 | 61,8 | 71,9 | 66,8 | 69,6 | 64,3 | 66,1 |
| 120 min | 69,9 | 64,8 | 72,6 | 68,7 | 72,8 | 66,9 | 69,5 |
| 150 min | 71,4 | 65,2 | 75,1 | 69,8 | 74,3 | 67,6 | 71,3 |
| 180 min | 73 | 65,6 | 77,6 | 70,9 | 75,9 | 68,7 | 73,1 |
| 210 min | 72,8 | 65,8 | 77 | 70,6 | 75,5 | 68,6 | 72,9 |
| 240 min | 72,5 | 65,7 | 76,3 | 70,1 | 74,9 | 68,2 | 72,3 |
| 270 min | 72,4 | 65,6 | 76,1 | 69,9 | 74,5 | 68,1 | 72,2 |
| 300 min | 72,1 | 65,4 | 75,9 | 69,5 | 74,6 | 68,3 | 72 |
| 330 min | 71,9 | 65,1 | 75,4 | 69,1 | 73,8 | 67,2 | 71,2 |
| 360 min | 71,2 | 64,3 | 75,3 | 68,8 | 73,3 | 66,7 | 70,9 |
| 390 min | 70,2 | 63,6 | 73,6 | 67 | 72,2 | 65,7 | 70,1 |

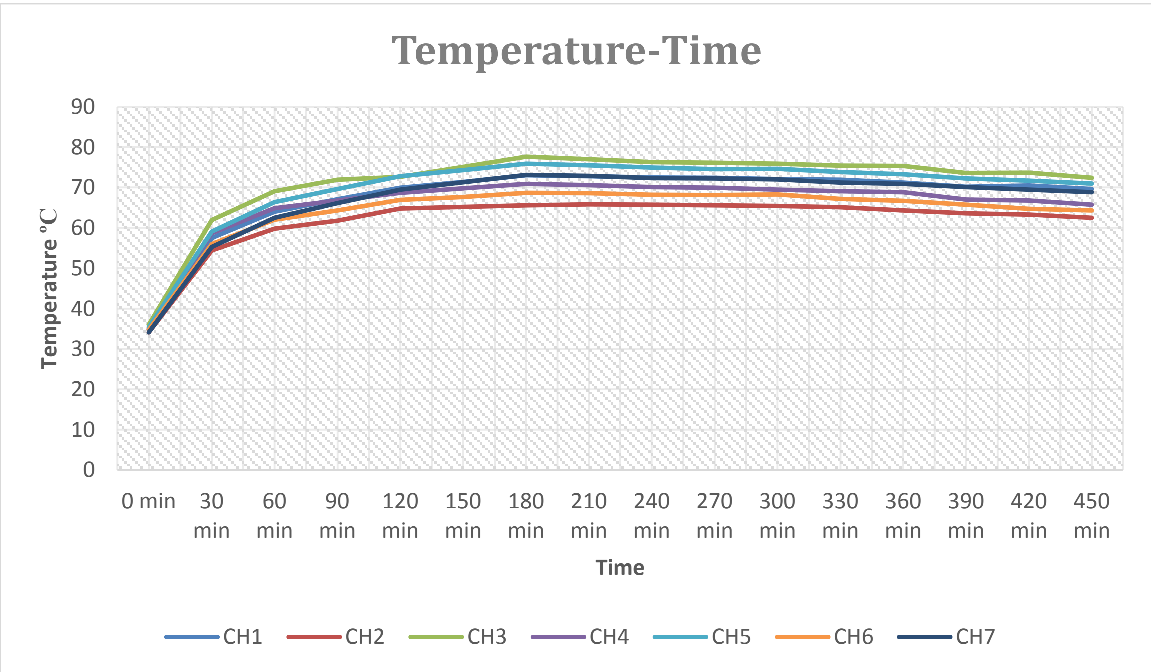


**Figure 4.1 Temperature-time graph for 3 kVA at %100 load short circuit test**

**Table 4.3. Measurement results for 5 kVA for the short circuit test**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 38,65 | 30,95 | 40,6 | 35,55 | 42,55 | 35,6 | 29,2 |
| 30 min | 52,6 | 40,6 | 56 | 48,5 | 58,9 | 48,4 | 38 |
| 60 min | 58,8 | 45,2 | 63,2 | 54,9 | 66,5 | 55,2 | 43,4 |
| 90 min | 61,05 | 47,7 | 65 | 57,05 | 68,6 | 57,3 | 46,55 |
| 120 min | 63,3 | 50,2 | 66,8 | 59,2 | 70,7 | 59,4 | 49,7 |
| 150 min | 65,6 | 52,7 | 69,8 | 62,3 | 73,5 | 62,1 | 53 |
| 180 min | 67,3 | 53,3 | 70,8 | 62,8 | 75,2 | 63,5 | 55,1 |
| 210 min | 71,3 | 57,3 | 74,2 | 66 | 79,2 | 67,1 | 57,9 |
| 240 min | 73,1 | 57,7 | 75,4 | 66,9 | 80,6 | 68,2 | 59,8 |
| 270 min | 72,2 | 56,6 | 75,2 | 65,5 | 80,9 | 68,1 | 61,4 |
| 300 min | 70,6 | 54,4 | 73 | 63,2 | 78,6 | 66,1 | 60,1 |
| 330 min | 65,1 | 49,6 | 67,7 | 57,4 | 71,6 | 60,5 | 57,8 |
| 360 min | 52,8 | 40,8 | 55,7 | 47,8 | 60 | 51,1 | 49,9 |
| 390 min | 51,2 | 39,4 | 54,2 | 46,5 | 58,3 | 49,1 | 47,7 |

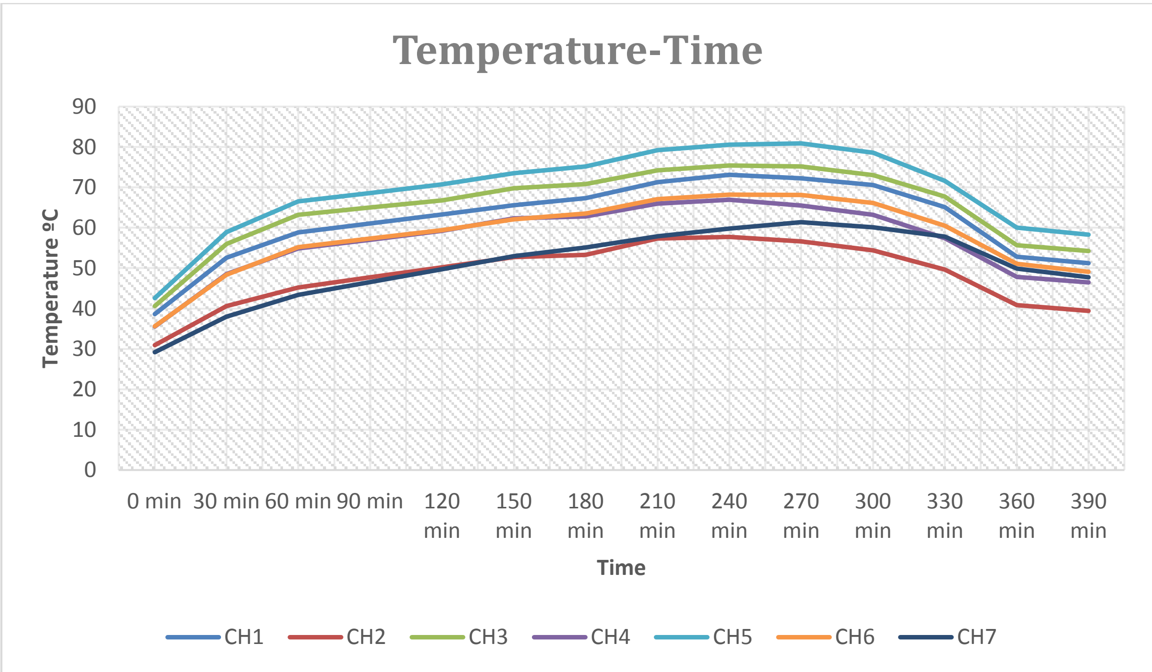


**Figure 4.2 Temperature-time graph for 5 kVA at %100 load short circuit test**

### 4.1.2. At %100 load open circuit test

The second experiment was an open circuit test at %100 load for transformers. For 3 kVA 4,5 ampere load was given to the primary side when the secondary side was open circuit and the same case for 5 kVA and 7,5 ampere load was given. The results for 3 kVA are given in Figure 4.3 and Table 4.4, the results for 5 kVA are given in Figure 4.4 and Table 4.5.

**Table 4.4. Measurement results for 3 kVA for the open circuit test**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 31,4 | 30,35 | 31,2 | 30,55 | 31,25 | 30,35 | 32,65 |
| 30 min | 37,8 | 34,65 | 37 | 34,85 | 37,55 | 34,65 | 40,55 |
| 60 min | 46 | 41,5 | 44,6 | 41,4 | 45,8 | 41,6 | 49,3 |
| 90 min | 51,8 | 46 | 49,9 | 45,7 | 51,6 | 46,3 | 55,7 |
| 120 min | 55 | 48,2 | 52,8 | 48 | 54,2 | 48,4 | 58,8 |
| 150 min | 59,8 | 52,2 | 54 | 52,4 | 61 | 53,4 | 65 |
| 180 min | 61,5 | 53,9 | 55,9 | 53,9 | 62,5 | 55,1 | 67,2 |
| 210 min | 63,7 | 54,9 | 60,9 | 54,3 | 64 | 55,8 | 68,9 |
| 240 min | 63,35 | 54,65 | 60,8 | 54,4 | 63,6 | 55,55 | 68,75 |

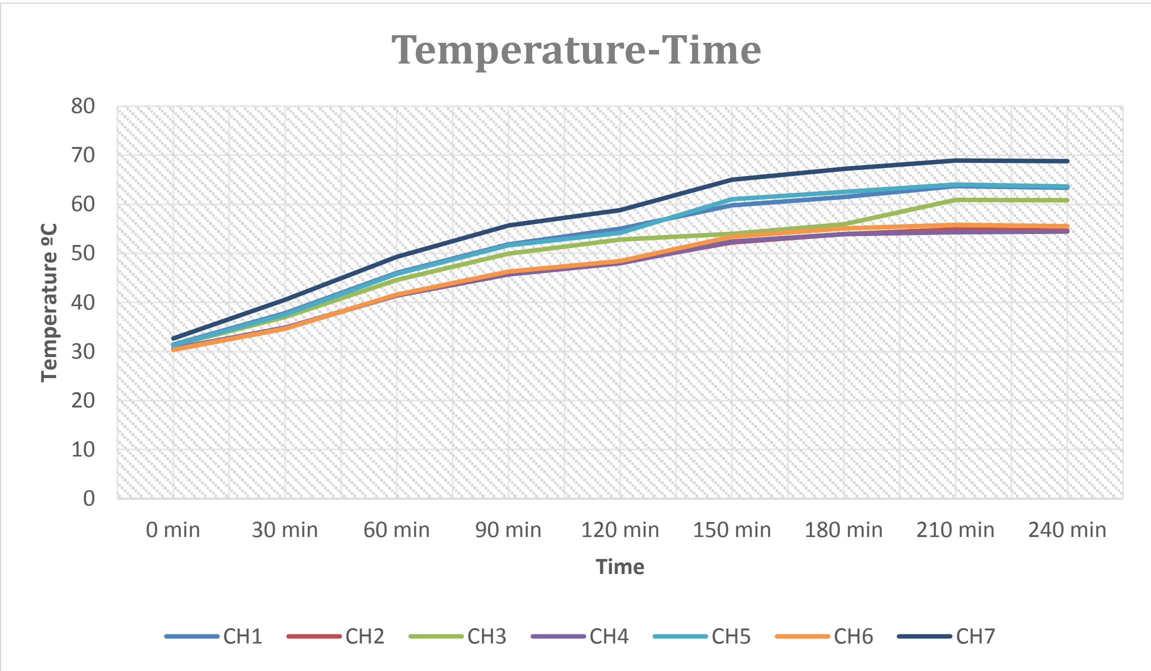


**Figure 4.3 Temperature-time graph for 3 kVA at %100 load open circuit test**

**Table 4.5. Measurement results for 5 kVA for the open circuit test**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 13,9 | 14 | 14 | 14 | 13,8 | 14,1 | 15,8 |
| 30 min | 20,9 | 19,6 | 21,8 | 21,3 | 23,1 | 23,6 | 35,4 |
| 60 min | 28,9 | 25,8 | 25,9 | 28,7 | 32,8 | 32,6 | 48 |
| 90 min | 35,1 | 30,1 | 35,7 | 33,7 | 40,1 | 38,8 | 56 |
| 120 min | 40,8 | 34,5 | 41,8 | 38,6 | 46,6 | 44,8 | 63,6 |
| 150 min | 44,65 | 37,1 | 45,7 | 42,1 | 51,4 | 48,85 | 63,4 |
| 180 min | 48,5 | 39,7 | 49,6 | 45,6 | 56,2 | 52,9 | 63,2 |
| 210 min | 49,6 | 41 | 50,6 | 46,4 | 57,4 | 54,2 | 70,2 |
| 240 min | 50,7 | 42,3 | 51,6 | 47,2 | 58,6 | 55,5 | 77,2 |
| 270 min | 50,4 | 40,9 | 51,8 | 46,9 | 58,5 | 54,9 | 78,1 |
| 300 min | 49,8 | 38,1 | 52,2 | 46,3 | 58,3 | 53,7 | 79,9 |
| 330 min | 49,95 | 40,5 | 51 | 46 | 57,65 | 54,05 | 77,4 |
| 360 min | 49,85 | 40,4 | 50,65 | 45,55 | 57,3 | 53,8 | 77,2 |
| 390 min | 50,05 | 40,9 | 50,65 | 45,9 | 57,5 | 54,15 | 77,15 |

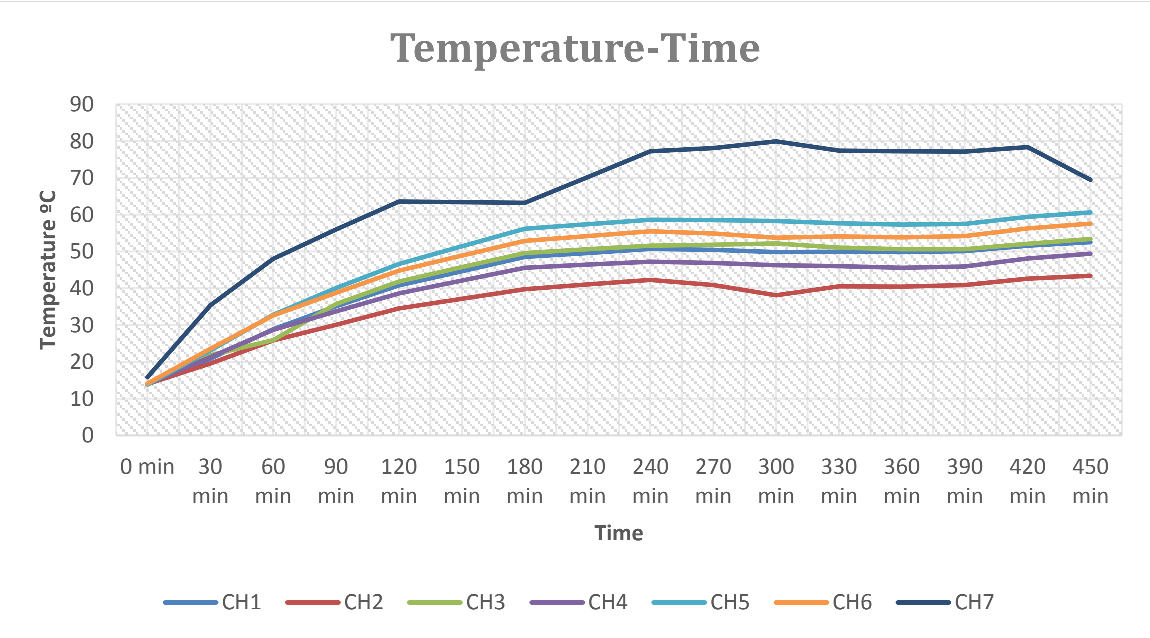


**Figure 4.4 Temperature-time graph for 5 kVA at %100 load open circuit test**

### 4.1.3. At %50 load short circuit test

The third experiment was a short circuit test at %50 load for transformers. For 3 kVA 2,25 ampere load was given to the primary side when the secondary side was a short circuit and the same case for 5 kVA and 3,75 ampere load was given. The results for 3 kVA are given in Figure 4.5 and Table 4.6, the results for 5 kVA are given in Figure 4.6 and Table 4.7.

**Table 4.6. Measurement results for 3 kVA for the short circuit test at %50 load**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 27,5 | 26,6 | 28,5 | 28 | 27,6 | 26,9 | 27,2 |
| 30 min | 33,1 | 31,6 | 35,8 | 34,1 | 34,2 | 32,4 | 32,7 |
| 60 min | 34,9 | 33,3 | 37,9 | 36,1 | 36,2 | 34,5 | 34,6 |
| 90 min | 36,1 | 34,4 | 39,2 | 37,3 | 37,5 | 35,7 | 35,9 |
| 120 min | 37,3 | 35,5 | 40,5 | 38,5 | 38,8 | 36,9 | 37,2 |
| 150 min | 37,75 | 35,7 | 40,95 | 39,15 | 39,4 | 37,3 | 38 |
| 180 min | 38,2 | 35,9 | 41,4 | 39,8 | 40 | 37,7 | 38,8 |
| 210 min | 38 | 35,8 | 41,1 | 38,7 | 39,7 | 37,4 | 38,5 |
| 240 min | 38,0 | 36,2 | 41,2 | 39,0 | 39,8 | 37,6 | 38,7 |
| 270 min | 39 | 37,05 | 42,25 | 40 | 40,85 | 38,6 | 39,55 |
| 300 min | 40,35 | 38,35 | 43,85 | 41,6 | 42,2 | 39,95 | 40,8 |
| 330 min | 42,05 | 40,05 | 45,95 | 43,8 | 43,8 | 41,65 | 42,4 |
| 360 min | 43,95 | 41,55 | 50 | 47,15 | 47,65 | 44,85 | 46 |
| 390 min | 44,25 | 41,65 | 48,2 | 45,45 | 46,75 | 43,75 | 45,4 |
| 420 min | 43,8 | 40,9 | 46,45 | 43,7 | 45,35 | 42,3 | 44,3 |
| 450 min | 42,6 | 39,3 | 44,75 | 41,9 | 43,45 | 40,5 | 42,7 |

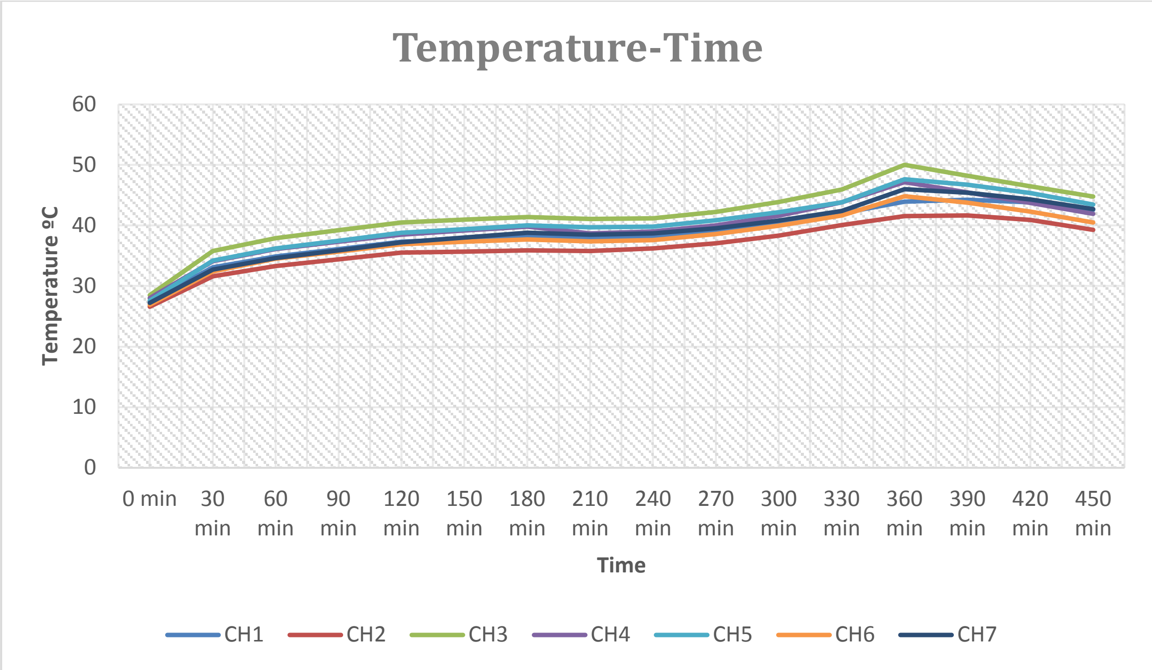


**Figure 4.5 Temperature-time graph for 3 kVA at %50 load short circuit test**

**Table 4.7. Measurement results for 5 kVA for the short circuit test at %50 load**

| Time | CH-1 | CH-2 | CH-3 | CH-4 | CH-5 | CH-6 | CH-7 |
|---|---|---|---|---|---|---|---|
| 0 min | 30,63 | 24,14 | 32,14 | 28,44 | 33,17 | 27,60 | 23,29 |
| 30 min | 30,28 | 23,58 | 32,39 | 28,17 | 34,08 | 28,00 | 22,47 |
| 60 min | 32,06 | 25,17 | 34,66 | 30,54 | 36,25 | 30,72 | 24,03 |
| 90 min | 32,85 | 26,55 | 35,44 | 31,86 | 36,96 | 31,81 | 25,28 |
| 120 min | 33,78 | 27,50 | 37,26 | 33,18 | 37,68 | 32,76 | 26,60 |
| 150 min | 34,68 | 28,86 | 38,06 | 34,94 | 38,98 | 34,27 | 28,25 |
| 180 min | 35,22 | 29,17 | 37,77 | 35,25 | 39,63 | 34,85 | 29,25 |
| 210 min | 37,22 | 31,18 | 39,61 | 36,18 | 41,65 | 36,58 | 30,58 |
| 240 min | 38,31 | 31,75 | 40,66 | 37,22 | 42,78 | 37,60 | 31,97 |
| 270 min | 38,89 | 31,97 | 41,75 | 37,48 | 44,36 | 38,60 | 33,63 |
| 300 min | 39,51 | 31,90 | 42,17 | 37,83 | 44,46 | 38,66 | 34,06 |
| 330 min | 38,07 | 30,51 | 41,26 | 36,38 | 42,49 | 37,50 | 34,42 |
| 360 min | 32,59 | 26,36 | 36,99 | 32,76 | 39,00 | 34,36 | 32,38 |
| 390 min | 32,27 | 25,80 | 35,50 | 31,54 | 37,75 | 32,70 | 30,89 |

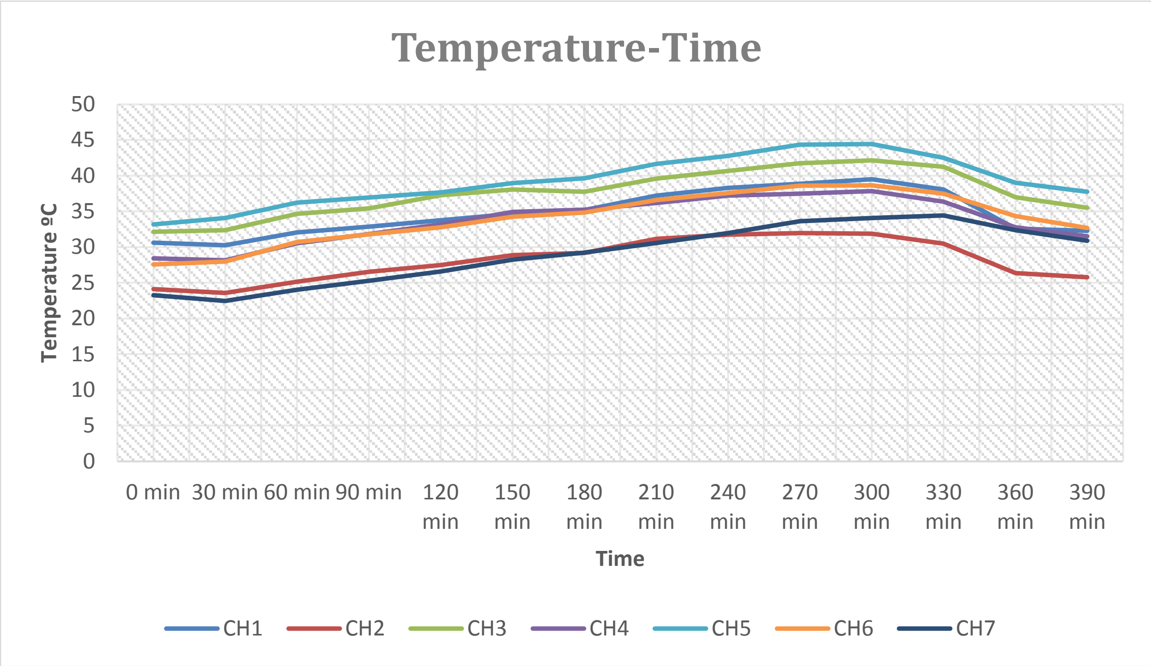


**Figure 4.6 Temperature-time graph for 5 kVA at %50 load short circuit test**

In this section test results which are taken at the laboratory are shown in tables and figures to compare with ANSYS/Maxwell program analyse results.

# 5. CONCLUSIONS

The exact life of the transformers at various operating temperatures is not known. When calculating the effects of the operating temperature on the insulation life, temperatures higher than the normal operating temperature caused by overloads or high ambient temperature will damage the insulation of the transformer and hence reduce the life of the transformer.

In this study, the transformer model has designed with the help of a mathematical model and HS algorithm, the thermal analyses were conducted by Ansys/Maxwell program. Thanks to those algorithms and analyses the optimum transformer had been produced. The transformer which was produced according to the mathematical model, HS algorithm and ANSYS/Maxwell was tested at the laboratory conditions. According to the program, the temperature values were verified with test results which is approximate value varying with environmental conditions.

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# CURRICULUM VITAE

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