ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DETERMINATION OF HOT-SPOT TEMPERATURE FOR ONAN DISTRIBUTION TRANSFORMERS WITH DYNAMIC THERMAL MODELLING

M.Sc. THESIS

Oluş SÖNMEZ

Department Of Electrical Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

ONAN SOĞUTMALI DAĞITIM TRANSFORMATÖRLERİNİN EN-SICAK NOKTA SICAKLIĞININ DİNAMİK ISIL MODELLEME İLE BELİRLENMESİ

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Oluş Sönmez, a **M.Sc.**student of ITU **Graduate School of Science Engineering and Technology** student ID 504081042, successfully defended the **thesis**entitled "Determination of Hot-spot Temperature For ONAN Distribitution Transformers with Dynamic Thermal Modelling ", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my grandfather; Mr. Süreyya Sönmez,

FOREWORD

I would like to thank to my supervisor Ass. Prof. Dr. Güven Kömürgöz for showing such confidence on my abilities. I am very grateful for her continuous support, encouragement and guidance.

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May 2012

Oluş SÖNMEZ
Electrical Engineer

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ABBREVIATIONS AND SYMBOLS

B1	: Mixed bottom oil thermocouple location
B2	: Lowest part of tank thermocouple location
$\mathbf{C_{el}}$	: Electrical capacitance
$\mathbf{C_{th}}$	: Thermal capacitance
$\mathbf{C_{th\text{-}oil}}$	: Thermal capacitance of oil
D	: Constants for oil physical characteristics
DC	: Direct current
$\mathbf{f_1(t)}$	: Relative increase of the top-oil temperature rise over ambient in per-unit value
$\mathbf{f_2(t)}$	: Relative increase of the hot-spot temperature rise to top-oil temperature in per-unit value
$\mathbf{f_3(t)}$	: Relative decrease of the top-oil temperature over ambient in per-unit value
G	: Constants for oil physical characteristics
$\mathbf{g_r}$	: Rated average winding to average oil temperature gradient
H	: Hot spot factor
I	: Current during that loading time period
$\mathbf{I_{rated}}$	: Rated current of transformer for full load
IEC	: The Institute of Electrical and Electronics Engineers
i	: Electrical Current
j	: Index for each time step during temperature rise test
K	: Load factor
k	: Measured variable
$\mathbf{k_{11}}$	: Thermal Constant
$\mathbf{k_{21}}$	: Thermal Constant
$\mathbf{k_{22}}$	: Thermal Constant
kg	: Kilogram
kV	: Kilovolt
kVA	: Kilovoltampere
LV	: Low voltage
m	: A constant
min	: Minute
$\mathbf{M_{ap}}$	: Weight of active part (core and coil assembly)
$\mathbf{M_{fe}}$	: Weight of magnetic steel core
$\mathbf{M_w}$	: Weight of windings
$\mathbf{M_{tank}}$	: Weight of tank and other steel parts which have direct contact to oil
$\mathbf{M_{oil}}$	: weight of oil
$\mathbf{n_{IEEE}}$	: An exponential constant for IEEE model
$\mathbf{n_{Susa}}$	: A costant for D. Susa Model
ONAN	: Oil natural – air natural cooling
P	: Total losses at rated load
$\mathbf{P_{DC}}$	: DC losses (I^2R losses)

$\mathbf{P_{DC,pu}}$: DC losses (I^2R losses) in per unit
$\mathbf{P_{eddy}}$: Eddy losses
$\mathbf{P_{eddy,pu}}$: Eddy losses in per unit
$\mathbf{P_{fe}}$: No-load losses
$\mathbf{P_{l}}$: Total load losses
$\mathbf{P(\theta_{hs})_{pu}}$: Load loss varies on temperature change in per unit
$\mathbf{P_{stray}}$: Stray losses
pu : Per unit
q : Generated heat
$\mathbf{q_{fe}}$: Generated heat by no-load losses
$\mathbf{q_{cu}}$: Generated heat by load losses
$\mathbf{q_{tot}}$: Generated heat by total losses
R : Ratio of load losses at rated power to the no-load losses
$\mathbf{R_{i}}$: Cold resistance (initial measured value)
$\mathbf{R_{el}}$: Electrical resistance
$\mathbf{R_{hv}}$: High voltage winding resistance
$\mathbf{R_{lv}}$: Low voltage winding resistance
$\mathbf{R_{th}}$: Thermal resistance
$\mathbf{R_{th\text{-}oil}}$: Non-linear oil to air thermal resistance
$\mathbf{R_{u}}$: Calculated resistance (ultimate measured value)
sec : Second
t : Time
Temp. : Temperature
T1 : Thermometer pocket location
T2 : Top of the cooling fins thermocouple location
T3 : Outlet of the winding cooling channel (duct) thermocouple location
u : Electrical voltage
W : Watt
x : An oil thermal constant
y : A thermal constant
z : Vector varies with thermal time constant
$\boldsymbol{\mu}$: Viscosity of oil
$\boldsymbol{\mu_{pu}}$: Viscosity of oil in per unit
$\boldsymbol{\theta}$: Temperature
$\boldsymbol{\theta_{amb}}$: Ambient Temperature
$\boldsymbol{\theta_{bo}}$: Bottom oil temperature
$\boldsymbol{\theta_{bo,i}}$: Initial bottom oil temperature
$\boldsymbol{\theta_{hs}}$: Hot-spot temperature
$\boldsymbol{\theta_{hs,hv}}$: Hot-spot temperature for high voltage winding
$\boldsymbol{\theta_{hs,i}}$: Initial hot-spot temperature
$\boldsymbol{\theta_{hs,lv}}$: Hot-spot temperature for low voltage winding
$\boldsymbol{\theta_{oil}}$: Top-oil temperature
$\boldsymbol{\theta_{oil,average}}$: Average oil temperature
$\boldsymbol{\theta_{oil,i}}$: Initial top-oil temperature
$\boldsymbol{\theta_{oil,bottom\text{-}surfece}}$: Oil temperature at the bottom of tank
$\boldsymbol{\theta_{oil,top\text{-}surfece}}$: Oil temperature at the top of tank
$\boldsymbol{\theta_{i}}$: Cold temperature (calculated temperature)
$\boldsymbol{\theta_{k}}$: Temperature factor for calculation
$\boldsymbol{\theta_{u}}$: Calculated temperature (ultimate temperature)
$\boldsymbol{\theta_{w,average}}$: Average winding temperature

$\Delta\theta_{bo,rated}$	: Rated bottom-oil temperature rise at rated power
$\Delta\theta_{hs}$	: Hot-spot temperature rise over top-oil temperature
$\Delta\theta_{hs,I}$	: Initial winding temperature rise over top-oil temperature
$\Delta\theta_{hs,rated}$	: Rated hot-spot temperature rise over top-oil temperature at rated load
$\Delta\theta_{hs,U}$	: Ultimate winding temperature rise over top-oil temperature
$\Delta\theta_{oil,I}$	: Initial top oil temperature rise over ambient
$\Delta\theta_{oil,rated}$	: Rated bottom-oil temperature rise at rated power
$\Delta\theta_{oil,U}$	: Ultimate top oil temperature rise over ambient
$\Delta\theta_{w/A,R}$	: Average winding temperature rise over ambient at rated load
τ_{oil}	: Oil time constant
$\tau_{oil,rated}$	: Rated oil time at rated load
τ_{w}	: Winding time constant

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DETERMINATION OF HOT-SPOT TEMPERATURE FOR ONAN DISTRIBUTION TRANSFORMERS WITH DYNAMIC THERMAL MODELLING

SUMMARY

Transformers are one of the largest capital investment part of distribution networks. Transformers' reliability is very important for electrical networks considering cost impact of power outages.

High temperature rise problem, one of the most serious problems for transformers. Loading cycles and ambient conditions of transformers can be different than design conditions. Transformer top-oil temperature and winding hot spot temperatures are most critical parameters for transformer because it causes aging and therefore affects life time of transformer. It is very important to determine hot-spot temperature and oil temperature accurately which depends on ambient conditions and loading conditions to avoid loss of life on transformer.

One solution to determine top-oil temperature and winding hot-spot temperature is to use on-line monitoring devices like fiber optical measurement devices. Other solution is to use dynamic thermal models to define top-oil temperature and winding hot-spot temperatures. Considering that fiber optical measurement solutions are very costly for distribution transformers, generally thermal models are mandatory to define critical temperatures of distribution transformers.

IEEE C57.91-1995 and IEC 60076-7 standards present thermal models for defining critical temperatures in transformers. These models are widely used in industry. On the other hand these methods are solved with exponential equations and they do not take into account the affects of change on oil temperature. Dynamic thermal model which is proposed by D. Susa, requires similar input parameters with IEEE C57.91-1995 model and IEC 60076-7 model, in addition to this, this thermal model takes into account the effects of change on oil temperature.

Scope of this study is to verify three differenttemperature rise models for distribution transformers to allow optimum loading of natural oil cooled transformers by using the data which could be obtained from manufacturer.

In this study, on a 1000 kVA 33/0.4 kV ONAN cooled distribution transformer, two temperature rise tests are realized. In first test, total losses are injected and necessary data to determine transformers specific parameters for thermal models obtained. In the second test, a varying load test is realized. Three different thermal models are used for same varying loading characteristic and results are compared with measurement results.

Significant advantage of this study is, necessary parameters for all thermal models are determined with proper measurements of tested unit, therefore all three models are compared under same conditions.

ONAN SOĞUTMALI DAĞITIM TRANSFORMATÖRLERİNİN EN-SICAK NOKTA SICAKLIĞININ DİNAMİK ISIL MODELLEME İLE BELİRLENMESİ

ÖZET

Transformatörler, elektrik dağıtım ve iletim şebekelerindeki en değerli elemanlardandır. Günümüzde enerji kesintileri, elektrik enerjisi dağıtım firmalarına büyük maliyetler doğurmaktadır, transformatörlerin güvenilebilir olması, enerji kesintilerinin asgariye indirilebilmesi için büyük önem taşır.

Transformatör kayıpları yükte kayıplar ve boşta kayıplar olarak ikiye ayrılır. Boşta kayıplar, transformatörün anma geriliminde ve yüksüz şekilde çalışması durumunda ortaya çıkan kayıplardır. Yükte kayıplar ise, transformatörün anma gücünde çalışması durumunda oluşan kayıplardır. Bu kayıplar, transformatörün ısıl davranışına farklı şekilde etki etmektedirler.

Transformatörlerin aşırı ısınması, transformatörler için en ciddi sorunlardan biridir. Transformatörler tasarım aşamasında belirli koşullarda çalışmak üzere tasarlanırlar.Transformatörlerin pratikte çalışma koşulları, tasarlanan çalışma koşullarından farklı olabilir. Transformatörün çalışma koşulları hem yüklenme karakteristiğine hem de ortam sıcaklığı gibi ortam şartlarına bağlıdır. Transformatörlerin aşırı ısınmasının engellenmesi için transformatörlerin tepe yağ sıcaklığı ve sıcak nokta sıcaklıkları çok önemlidir, çünkü transformatörün yaşlanmasına doğrudan etki etmektedir. Yağlı tip transformatörlerde yaygın olarak A sınıfı izolasyon malzemeleri kullanılmaktadır. A sınıfı izolasyon malzemelerinin, sistem sıcaklığı 105 ºC’dir ve genel olarak selülozik içerikli maddelerden üretilmektedir. Bu tip izolasyon malzemeleri, sıcaklık 110ºC’yi aştığında çok hızlı bir şekilde yaşlanmakta ve ömür kaybına uğramaktadır. Transformatörün planlanandan erken yaşlanması ise öngörülen ömrünün kısalmasına neden olacaktır.

Tepe yağ sıcaklığını ve sargı sıcak nokta sıcaklığını belirlemenin bir yöntemi, sürekli çevrimiçi ölçüm yapılmasıdır. Fakat sargı sıcak nokta sıcaklığının sürekli çevrimiçi ölçülebilmesi için sargı içine fiber optik ölçüm cihazlarının monte edilmiş olması gerekir. Büyük güç transformatörlerinde bu yöntem uygulanabilir olsa da dağıtım transformatörleri için bu çözüm çok yüksek maliyetli olacaktır. Bu nedenle dağıtım transformatörlerinin kritik sıcaklıklarının belirlenebilmesi ve öngörülebilmesiiçin dinamik ısıl modeller gereklidir.

IEEE C57.91-1995 standardı ve IEC 60076-7 standardı, değişken yük durumları için transformatörlerin tepe yağ ve en sıcak nokta sıcaklarının belirlenmesine yardımcı olan ısıl modeller sunmaktadır. Bu modeller, transformatör kullanıcıları tarafından yaygın olarak kullanmaktadır. Böylece transformatörün kritik sıcaklıkları belirlenmektedir. Öte yandan, bu modeller, yağ sıcaklık değişiminin kayıplara ve yağın özelliklerine olan etkilerini dikkate almayan göreceli olarak basit modellerdir. D. Susa tarafından önerilen model ise, temel ısıl prensipler ve temel elektriki

prensipler arasındaki benzerliği kullanarak, transformatörlerin ısıl analizi için direnç ve kapasite içeren bir devre sunar. Bu devrede, direnç, yağ sıcaklığına bağlı olarak değişkendir. Bu devrenin çözümü ile bir diferansiyel denklem elde edilir. Sonuç olarak karmaşık ısıl problem, bir elektrik devresine benzetilerek, diferansiyel denklem ile çözülür. Bu yöntemde, standartlarda önerilen yöntemden farklı olarak, yağ sıcaklığı değişiminin yükte kayıplara ve yağ viskozitesine etkisi dikkate alınmıştır.

Bu çalışmanın kapsamı, yukarıda belirtilen üç farklı ısıl modelin, üreticiden alınabilecek veriler kullanılarak, doğal soğutmalı dağıtım transformatörlerinin optimum olarak yüklenebilmesinin sağlanması amacı ile doğrulanmasıdır.

Bu çalışmada, 1000 kVA gücünde 33/0.4 kV değiştirme oranına sahip, ONAN soğutmalı (doğal yağ soğutmalı) bir dağıtım transformatörü kullanılmıştır. Transformatör ülkemizde yaygın olarak kullanılan aynı güçteki transformatörlere eşdeğer nitelikte seçilmiştir. Söz konusu transformatörün dışında ve içinde sıcaklık ölçümü için ısı sensörleri monte edilmiştir. Transformatör içindeki sensörler, her bir sargının alçak gerilim ve yüksek gerilim kısımlarına konulmuştur. Sargı içindeki sensörlerin yerlerinin seçiminde, daha önce yapılan çalışmalar ve tecrübeler dikkate alınarak en sıcak noktaların oluşması beklenen bölgeler seçilmiştir. Özellikle en sıcak noktanın beklendiği sargılara, ilave olarak ikişer sensör daha konulmuştur. Sargı içindeki ısı sensörlerine ek olarak, çeşitli noktalardaki yağ sıcaklıklarını ölçebilmek için, transformatör kapak ve kazanına da ısı sensörleri yerleştirilmiştir. Bu sensörler ile tepe yağ sıcaklığı üç farklı noktadan ölçülebilmiştir. Dip yağ sıcaklığı ise iki farklı noktadan sensörlerin yardımı ile ölçülmüştür. Toplamda on beş sensör kullanılmıştır. Bu sensörler, görüntüleme ve kaydetme cihazlarına bağlanmıştır. Ölçümler sırasında sürekli olarak ortam sıcaklığı da ölçülerek kaydedilmiştir. Ortam sıcaklığının değişimi etkisi, transformatörün kritik sıcaklıklarını doğrudan etkileyeceği için bütün modellerde, ortam sıcaklığı etkisi dikkate alınmıştır. Testler sırasında ısıl kamera kullanılarak, ısı dağılımı gözlenmiştir. Isıl kamera ile transformatörün kazanın içinde yağın etkisi ile beklenen dengeli sıcaklık dağılımı doğrulanmıştır.

Transformatör üzerinde iki farklı sıcaklık artış deneyi uygulanmıştır. Birinci deneyde, toplam kayıplar transformatör üzerinden geçirilmiştir ve söz konusu transformatörün ısıl modelleri için gerekli değişkenler ve sabitler elde edilmiştir. Transformatörün ısıl özelliklerinin belirlenmesi için bu test kullanılmıştır. Sensörler yardımı ile yapılan ölçümlere ek olarak, transformatörün alçak gerilim ve yüksek gerilim sargılarının doğru akım dirençleri soğuk ve sıcak durumlarda ölçülerek ortalama sargı sıcaklık artış değerleri belirlenmiştir.

İkinci test sırasında ise farklı akımlar transformatöre uygulanarak değişken yük durumu deneyi gerçekleştirilmiştir. Bu test sırasında transformatör üç saat boyunca anma gücü ile yüklenmiştir ardından 105 dakika boyunca iki katı yük ile yüklenmiştir.Ardındam transformatör iki katı yüklenmesi kesilerek, son yarım saat transformatör yüksüz durumda bırakılarak ölçümlere devam edilmiştir.Testler transformatörün sekonder tarafı kısa devre edilmek sureti ile primerden akım uygulanması şeklinde gerçekleştirilmiştir. İkinci test sonucunda elde edilen tepe yağ sıcaklığı ve alçak gerilim ve yüksek gerilim sargıları için en sıcak nokta sıcaklıkları, matematiksel model ile elde edilen sonuçlarla karşılaştırılmıştır.

Bu çalışmada, üç farklı matematiksel model kullanılmıştır.Bunlardan ilki IEEE C58.91 standardında belirtilen modeldir, ikincisi IEC 60076-7 standardında belirtilen modeldir. Bu iki modele ek olarak, D. Susa tarafından geliştirilen model kullanılmıştır. Bu modelde ısıl devre ile elektrik devreleri arasındaki benzerlik kullanılmıştır. Bu benzerliğe göre ısı kaynağı, akım kaynağı olarak; sıcaklık, gerilim olarak; ısıl direnç, elektriksel direnç olarak ve ısıl kapasite; elektriksel kapasite olarak modellenmiştir. Bu şekilde karmaşık ısıl problem, basit bir R-C elektrik devresine indirgenmiştir. Bu devre, devre analizi yöntemleri ile çözülerek diferansiyel denklemler elde edilmiştir. Tepe yağ sıcaklığı ve en sıcak nokta sıcaklıkları ise bu diferansiyel denklemler çözüşerek elde edilmiştir. Bu modelde, standartlarda verilen modellerden farklı olarak sıcaklıkla, yağın fiziksel özelliklerindeki değişim de dikkate alınmıştır. Yağın fiziksel değerlerindeki en etkin değişim viskozite değerinde olduğu için, modelde viskozitenin sıcaklık ile değişim etkisi kullanılmıştır. Buna ek olarak, transformatör kayıplarının da sıcaklık ile değişimi modelde dikkate alınmıştır. Standartlarda verilen modeller kullanılırken, gerekli olan değişkenler, deneyler ile elde edilen veriler ve optimizasyon yöntemleri kullanılarak belirlenmiştir.

Testte uygulanan ile aynı değişken yük durumu, söz konusu üç ısıl modelde gerçeklenmiştir. Modeller ile hem tepe yağ sıcaklığı hem de alçak gerilim ve yüksek gerilim sargıları için sıcak nokta sıcaklıkları hesaplanmıştır. Elde edilen sonuçlar, ölçüm sonucu ile elde edilen sonuçlar ile karşılaştırılmıştır.

Bu çalışmanın önemli bir üstünlüğü, uygulanacak ısıl modeller için değişkenler, gerçekleştirilen test sayesinde, doğru bir şekilde elde edilmiştir. Isıl modellerin karşılaştırılması için gerekli olan ölçümler yapılmıştır. Bu nedenle her üç model de aynı şartlar altında karşılaştırılabilmiştir.

1. INTRODUCTION

Transformer history starts from the early 1880s. It is based on induction principle which is discovered by Faraday in 1831 [1]. Modern transformers are widely used in transmission, distribution systems and also industrial systems. Transformers are one of the most expensive equipments of electrical systems. Efficiency of transformers are relatively high compared to different electrical machines. Except no load and load losses, output power is approximately equal to input power. On the other hand, these losses causetemperature rises on transformers.

Transformer losses are categorized as no-load losses and load-losses[2]. No-load losses are losses, which occurs during rated voltage and no-load operation. Load losses are consists from DC (I^2R) losses, stray losses and eddy losses. DC load losses are calculated from measured winding resistance values. Stray losses and eddy losses are calculated by subtracting DC losses from measured load losses. Load losses are measured with short-circuit test method which is described in IEC 60076-1 standard [3]. No-load losses, DC losses and stray losses have different affects on transformers thermal behavior.

High temperature rise problem , one of the most serious problems for all kind of transformers[4]. Loading cycles and ambient conditions of transformers can be different than design conditions. Transformer top-oil temperature and winding hot spot temperatures are most critical parameters for transformer because it causes aging and therefore affects life time of transformer. In oil filled distribution transformers A class insulation which of system temperature is 105˚C is commonly used [5]. A class insulation contains mainly cellulosic based materials. For cellulosic insulation materials rate of aging will rapidly increase above 110˚C, this affects aging rate of distribution transformer directly. In Figure 1.1, aging acceleration rate changes with hot-spot temperature change is plotted according to equations given in IEEE standard C57.91-1995 [6,7].

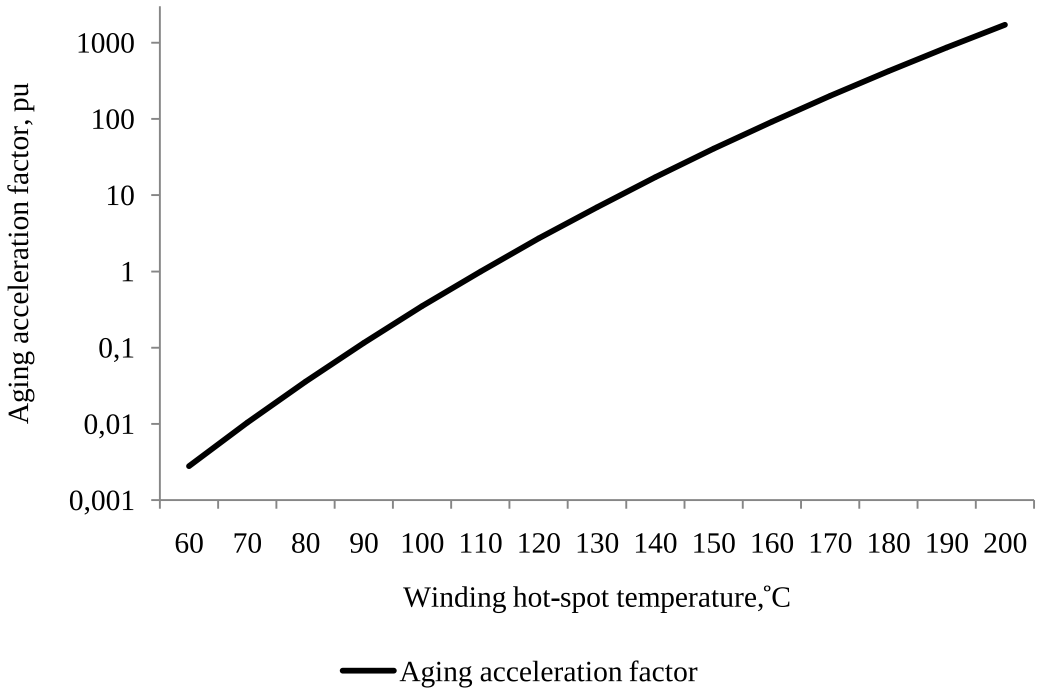

Figure 1.1 : Aging acceleration rate.

Top-oil temperature is the temperature, measured at top layer of the oil in transformer. Hot-spot temperature is the hottest point temperature of conductor part of transformer, which is in contact with oil[6]. Transformers loading beyond nameplate can be defined by respecting limits of the top-oil and hot-spot temperatures of transformer. Therefore, it is very important to define hot-spot temperature properly.

Many on-line and off-line monitoring systems have been developed [8-12]. However on-line monitoring by direct measurement of winding temperature by using fiber optic probes, is a very costly method for distribution transformers. Therefore, thermal models should be used for distribution transformers to define loading capability.

These thermal models are based on conventional heat transfer theory [13], transformer thermal tests [14-27], application for the lumped capacitance method, thermal electrical analogy [27] .In previous studies, it has been noticed that hot-spot temperature rise over top-oil temperature for load changes is a function which depends on time [24,27]. Present IEC and IEEE standards recommends thermal models to determine top-oil temperature and hot-spot temperatures [6-7,28]. These models are widely used in industry to determine temperatures. In addition to this, an investigation performed on a 2500 kVA transformer without external cooling showed accurate results [24]. Author was highly motivated to make a study to verify this method with measured values of a smaller distribution transformer and compare results with IEC and IEEE standards which are very widely used in market [6,28].

Scope of this study is to verify different thermal models for distribution transformers to allow optimum loading of natural oil cooled transformers by using the data which could be obtained from manufacturer.In this thesis, two different temperature rise tests are realized on a 1000 kVA ONAN cooled distribution transformer, installed with measurement thermocouples. First temperature rise test is constant load test. From the data obtained from the first test, parameters required for thermal modelsare determined by using optimization methods.In the second temperature rise test, varying step loads are applied as given in Table 3.2. Temperature values for top-oil and hot-spots are determined by three different thermal models for same loading condition which is realized during Test 2. Results obtained from variable load tests for tested distribution transformer is compared with calculated temperature values. For calculations of hot-spot and oil temperatures, three different models are used and results are compared.

Primary aim of this thesis is to verify different models which could be applied for distribution transformers by using input data which could be obtained by manufacturer.Therefore various thermal models are compared with measured values for a standard ONAN cooled distribution transformer which means without external cooling.

Three models which will be used in this study is explained in Chapter 2 with details. Two of the methods are given in generally accepted standards and other method is developed by D. Susa [24,26]. Experimental study which realized with a 1000 kVA 33/0.4 kV ONAN cooled distribution transformer is explained with details in Chapter 3. In this chapter, measured values and calculated values are plotted and compared. Conclusions and comments obtained from this study are given in Chapter 4.

2. THERMAL MODELLING OF DISTRIBUTION TRANSFORMERS

Transformer life is very dependent on condition of insulation materials. High oil temperature and high hot-spot temperature affects condition of insulation materials. Therefore it is very important to determine oil temperature and hot-spot temperature of transformers according to load conditions and ambient conditions. Determinations of these temperatures are possible with dynamic thermal models. In this study, three different thermal models are used to determine top-oil temperature and hot-spot temperature of both high voltage and low voltage windings. Methods which are given in IEEE Standard C57.91-1995 and in IEC 60076-7, are widely used in industry to determine top-oil and hot-spot temperatures [6,28]. Affects of temperature change on oil viscosity and losses are taken into account in dynamic thermal model which is developed by D. Susa.

In this section, three different method for thermal modeling is described. Definition of methods are as following;

- IEEE Standard C57.91-1995 (Cor.2002)[6,7]

- IEC Standard 60076-7 ed1.0[28]

- D. Susa's thermal model [24]

2.1 IEEE Standard C57.91-1995 Model

IEEE standard C57.91-1995 provides two different methods for predicting thermal behavior of transformers. One of them is explained in Clause 7 of related standard and other method is given in Annex G of this standard. The Annex G method, provides a non-linear model, however it requires, more input data for model, and for distribution transformers required data for Annex G method could not be easily found in the market for all distribution transformers[6,30]. Special temperature rise tests like bottom temperature rise measurement required to obtain requested input data to model. Considering that this study is mainly targeting distribution transformers, only Clause 7 model is used in this study. Normally, according to Clause 7 model, variable ambient temperature affects are not considered, however in this study, affects of ambient changes applied in model to obtain more accurate results.

According to this thermal model, first top-oil temperature over ambient is calculated. For this calculations, oil time constant should be defined. Following, winding hot-spot rise over top-oil rise is calculated.

2.1.1 Top-oil temperature rise over ambient

In standard, top-oil temperature rise at a time after a step load change is given with following equation [28];

$$\Delta\theta_{oil} = (\Delta\theta_{oil,U} - \Delta\theta_{oil,I})(1 - \exp^{\frac{-t}{\tau_{oil}}}) + \Delta\theta_{oil,I} \tag{2.1}$$

Where;

$\Delta\theta_{oil,I}$ initial top oil temperature rise over ambient (in K) $\Delta\theta_{oil,U}$ ultimate top oil temperature rise over ambient (in K) τ_{oil} oil time constant (in hour).

In case of multi step loading cycles, equation 2.1 is used for each load step and in each step top-oil rise calculated for the previous load step is used as initial top-oil rise of next step.

Ultimate top oil temperature rise over ambient is calculated with following equation;

$$\Delta\theta_{oil,U} = \Delta\theta_{oil,rated}\left[\frac{K^2R+1}{R+1}\right]^{n_{IEEE}} \tag{2.2}$$

Where; K is theratio of load to nominal load (in pu), R is the ratio of load losses at rated power to the no-load losses and n_{IEEE} is exponential constant, which is 0.8 for ONAN cooled transformers.

2.1.2 Oil time constant

In IEEE C57.91 standard, rated oil time constant is given with an equation which uses thermal capacity value, rated temperature rise value and total losses. Formula is given in equation 2.3.

$$\tau_{oil,rated} = \frac{C_{th-oil}\Delta\theta_{oil,rated}}{P} \qquad \textbf{(2.3)}$$

Thermal capacity value ($C_{th\text{-}oil}$) is calculated with following equoation

$$C_{th-oil} = 0.1323M_{AP} + 0.0882M_{tank} + 0.40M_{oil} \qquad \textbf{(2.4)}$$

Where; M_{AP} is the weight of active part (core and coil assembly) (in kg) , M_{tank} is the weight of tank and other steel parts which have direct contact to oil (in kg) and M_{oil} is weight of oil (in kg).

Top oil time constant for each interval calculated with following equation;

$$\tau_{oil} = \tau_{oil,rated} \frac{(\frac{\Delta\theta_{oil,U}}{\Delta\theta_{oil,rated}}) - (\frac{\Delta\theta_{oil,I}}{\Delta\theta_{oil,rated}})}{(\frac{\Delta\theta_{oil,U}}{\Delta\theta_{oil,rated}})^{\frac{1}{n_{IEEE}}} - (\frac{\Delta\theta_{oil,I}}{\Delta\theta_{oil,rated}})^{\frac{1}{n_{IEEE}}}} \qquad \textbf{(2.5)}$$

where

n_{IEEE} is constant exponential defined 0.8 for ONAN cooled transformers [6].

2.1.3 Winding hot-spot temperature rise over top-oil rise

Winding hottest-spot temperature over top-oil rise for each step load cycle is given by following equation;

$$\Delta\theta_{hs} = (\Delta\theta_{hs,U} - \Delta\theta_{hs,I})(1 - \exp^{\frac{-t}{\tau_w}}) + \Delta\theta_{hs,I} \qquad \textbf{(2.6)}$$

where;

$\Delta\theta_{hs,I}$ initial winding temperature rise over top-oil temperature (in K)

$\Delta\theta_{hs,U}$ ultimate winding temperature rise over top-oil temperature (in K)

τ_w winding time constant (in min.)

Ultimate winding temperature rise over top-oil temperature calculated with following equation;

$$\Delta\theta_{hs,U} = \Delta\theta_{hs,rated} K^{2m} \tag{2.7}$$

Where $\Delta\theta_{hs,rated}$ is rated winding temperature rise over top oil temperature (in K) and m is the exponential constant which is 0.8 for ONAN cooled transformers.

2.2 IEC Standard 60076-7 Model

IEC standard provides two thermal models. One of them is given as an exponential equation solution, this method is more suitable for load cycles which are changing with steps [28,31]. The other method which is given as a differential equation solution, is suitable for randomly changing load cycles. Second method is mainly applicable for on-line monitoring [31]. In this study, exponential equation solution model is used.

In this model, primarily, top oil temperature rise over ambient is calculated by defining necessary variables and constants. Afterwards, hot-spot temperature rise over top-oil temperature rise is calculated by defining necessary variable and constants.

2.2.1 Top-oil temperature rise over ambient

According to IEC 60076-7 standard, oil temperature rise over ambient temperature is given with an equation depends on a function. This function includes exponential constants. IEC 60076-7 has recommended some values for constants [28].

Equation given in 2.8 is applied at load increase. Equation which is given in 2.9 is applied at load decrease.

$$\Delta\theta_{oil} = (\Delta\theta_{oil,U} - \Delta\theta_{oil,I})\, f_1(t) + \Delta\theta_{oil,I} \tag{2.8}$$

$$\Delta\theta_{oil} = (\Delta\theta_{oil,I} - \Delta\theta_{oil,U})f_3(t) + \Delta\theta_{oil,U} \quad \textbf{(2.9)}$$

Ultimate temperature rise value is calculated from equation 2.10

$$\Delta\theta_{oil,U} = \Delta\theta_{oil,rated}\left[\frac{K^2R+1}{R+1}\right]^x \quad \textbf{(2.10)}$$

where;x is the oil exponent, $f_1(t)$ indicates the relative increase of the top-oil temperature rise in per-unit value. $f_3(t)$ indicates the relative decrease of the top-oil temperature rise value in per-unit value.$f_1(t)$ and $f_3(t)$ fuctions are solved with following equations which are given in equation 2.11 and equation 2.12;

$$f_1(t) = (1 - \exp^{\frac{-t}{k_{11}\tau_{oil,rated}}}) \quad \textbf{(2.11)}$$

$$f_3(t) = \exp^{\frac{-t}{k_{11}\tau_{oil,rated}}} \quad \textbf{(2.12)}$$

where, k_{11} is the thermal model constant.

It is recommended by IEC Standard to use standard values for thermal constants [28]. These values are given in related standard. For x value it is recommended to use 0.8 value for ONAN cooled distribution transformers. For k_{11}, it is recommended use 0.8 for ONAN cooled distribution transformers. Recommended constants are given in Table 2.1.

Table 2.1 : Recommended constants for ONAN cooled distribution transformers.

Oil exponent x	0.8
Winding exponent y	1.6
Constant k_{11}	1.0
Constant k_{21}	1.0
Constant k_{22}	2.0
Oil time constant τ_{oil}	180 minutes
Winding time constant τ_w	4 minutes

However more accurate results had been obtained by estimating this constant from top-oil temperature rise curve which is plotted by realizing temperature rise test according to IEC 60076-2 standard [32].

Measured relative increase of the top-oil temperature rise of the steady state value is calculated as per unit value with following equation [31]

$$kf_{1_j} = \frac{k\theta_{oilj} - k\theta_{ambj}}{\Delta\theta_{oil,rated}} \tag{2.13}$$

where

k	measured variable
j	number of each step
f_{1j}	relative increase of oil temperature rise over ambient for related step

After relative increase of top-oil temperature rise is obtained, non-linear regression method is used to define the constant to minimize the sum of squares between differences f_{1j} and kf_{1j}.

Equation is given following;

$$\min : \sum_{j=1}^{N} [f_{1j}(z) - kf_{1j}]^{2} \tag{2.14}$$

where;

k	measured variable
z	vector varies with thermal time constant k_{11}
j	index for each time step during temperature rise test

Recommended k_{11} value in IEC 60076-7 which is given in Table 2.1 is used for initial value of minimization [28].

2.2.2 Hot-spot temperature rise over top-oil temperature

Hot-spot temperature rise over top-oil temperature is calculated with a similar formula to the top-oil temperature rise.

Equation given in 2.15is applied at load increase.Equation given in 2.16 is applied at load decrease.

$$\Delta\theta_{hs} = (\Delta\theta_{hs,U} - \Delta\theta_{hs,I})f_2(t) + \Delta\theta_{hs,I} \tag{2.15}$$

$$\Delta\theta_{hs} = \Delta\theta_{hs,U} \tag{2.16}$$

Ultimate winding temperature rise over top-oil temperature rise is calculated with following equation.

$$\Delta\theta_{hs,U} = \Delta\theta_{hs,rated}K^{y} \tag{2.17}$$

Where y is the winding exponent.

$f_2(t)$ indicates the relative increase of the hot-spot temperature rise to top-oil temperature rise value in per-unit value.Equations is shown in Equation 2.18.

$$f_2(t) = \left[k_{21}x(1-\exp^{\frac{-t}{k_{22}x\tau_w}}) - (k_{21}-1)(1-\exp^{\frac{\frac{-t}{\tau_{oil,rated}}}{k_{22}}}) \right] \tag{2.18}$$

Where; k_{21} is thermal model time constant, k_{22} is the thermal model time constant and τ_w is the winding time constant (min.).

It is recommended to use defined values for thermal constants by IEC Standard [28]. These values are given inthe related standard. k_{21} is given as 1.0 for ONAN cooled distribution transformers. $k_{22}$is given as 2.0 for ONAN cooled distribution transformers as shown in Table 2.1. For y value it is recommended to use 1.6 for ONAN cooled distribution transformers.

2.2.3 Winding time constant

According to IEC standard, the winding time constant value which is used in equation 2.18 is calculated with equation 2.19 which is given below [28].

$$\tau_w = \frac{M_w c g_r}{60 P_l} \qquad \textbf{(2.19)}$$

Where

c	specific heat of the conductor material in Ws/kg.K. It is 390 for copper and 890 for aluminum
g_r	average winding to average oil temperature gradient in K
M_w	weight of the windings in kg
P_l	total winding losses at rated load in W

2.3 D. Susa's Thermal Model

Dejan Susa's method is based on thermal-electrical analogy [24,27,29].In this study, top-oil temperature model and hot-spot temperature model is used. According to developed model's circuit theory, capacitance value is taken as constant and resistance value is taken as variable which depends on oil viscosiy changes and loss value changes with temperature changes. Basically input variables of model are load pu value, oil viscosity value and ambient temperaeture, and main input constants are, losses, time constants, rated temperature rise values. As a result of model, output variables will be top oil temperature and hot-spot temperatures.

2.3.1 Thermal electrical analogy

One of the most used heat transfer law; Fourier theory's equation form is with the same form of Ohm's law which is one of the most-well known electrcal law. Therefore mathematical solution of a thermal system is usually similar to mathematical soluation of an electrical system. By using this similarity, an equivalent electrical circuit can be obtained to solve a thermal problem [20]. In Figure 2.1, a basic electrical RC circuit is given.

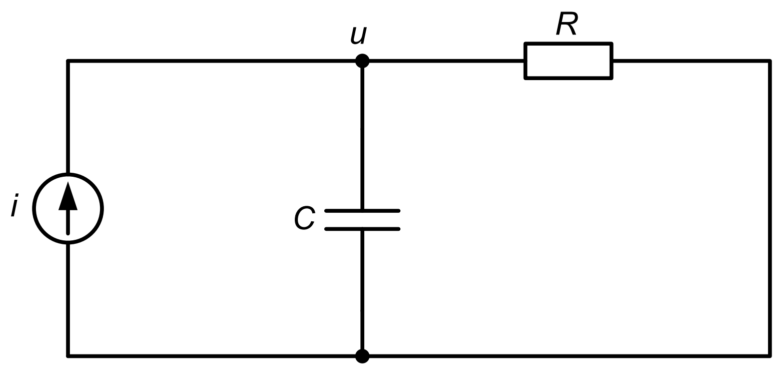

Figure 2.1 : Basic electrical RC circuit.

It will be noticed that thermal analogy could be replaced as in Table 2.2 into electrical analogy parameters based on basic heat transfer principles [13,20,25,27].

Table 2.2 : Parameters for Thermal and Electrical Analogy

Thermal	Electrical
Heat Value, q (W)	Current, i (A)
Temperature, θ (˚C)	Voltage, u (V)
Thermal Resistance R_{th}(˚C / watt)	Electrical Resistance, R_{el} (ohm)
Thermal Capacitance C_{th} (j /˚C)	Electrical Capacitance, C_{el}(f)

Accordingly, new RC circuit is defined for thermal analogy which is given in Figure 2.2;

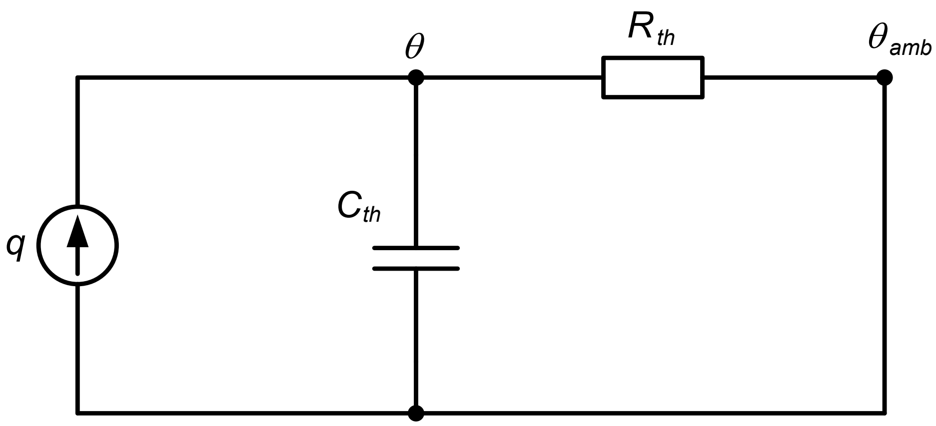

Figure 2.2 : Basic thermal RC circuit.

Thermal capacitance and resistance values can be defined as material's thermal characteristics. This is a common method for transformers thermal analysis. Because, it allows to make mathematical solutions for complex heat transfer problems.Past studies about lumped capacitance method are given in [17,20,21,23,33].

In Susa's method, thermal characteristic's of materials are not considered as constant as they were in previous studies. Therefore a non-linear thermal resistance is introduced[27]. Because transformer oil characteristics like density, specific heat, thermal conductivity, coefficient of thermal cubic expansion and viscosity values are strongly dependent to oil temperature [22].

The change of viscosity with oil temperature change is significantly higher than the change on other parameters [15,22,27]. This is shown in Figure 2.3 by plotting all major oil physical parameter changes, which depends on temperature. Therefore, only viscosity value of oil is variable in the model and other parameters are constant. Oil physical parameters' equations are taken from [15,27].

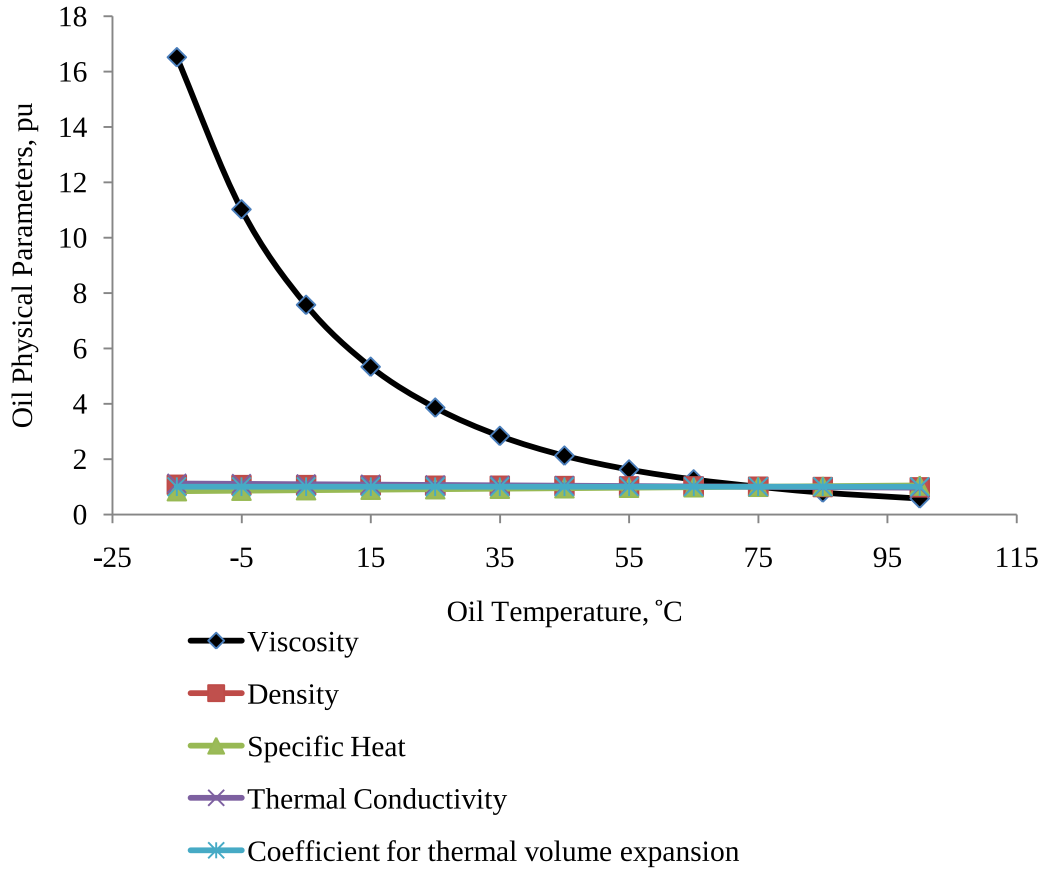

Figure 2.3 : Oil physical parameter changes with varying temperature.

The viscosity of oil is dependent on oil temperature and formula is given in Equation 2.20.

$$\mu = D \exp^{\left[\frac{G}{\theta_{oil}+273}\right]} \qquad \textbf{(2.20)}$$

D and Gparameters are constants related with transformer oil characteristic and they are given in IEEE standard which is shown in Table 2.3. In the Table 2.3, viscosity constants for two different insulation fluids are given[6].

Table 2.3 : Viscosity calculation constants [6,7]

Insulation Fluid	D	G
Mineral Oil	0.0013573	2797.3
Silicone Fluid	0.12127	1782.3

2.3.2 Top oil temperature rise over ambient model

From basic RC circuit which is given in Figure 2.2, thermal circuit is defined for top-oil temperature as shown in Figure 2.4;[17, 24]. In this model, no-load losses and load losses are defined as current sources in circuit diagram [25,26]. No-load losses are constant and load losses are dependent on load factor.Because load losses varies with load factor.For top oil temperature rise model, both no load and load losses are heat sources since oil temperature is affected from heat of both losses. Capacitance of oil is indicated as constant and calculation equation is given in Equation 2.4. Thermal resistance value is variable of the circuit and depends on oil viscosity change with temperature. Ambient temperature is indicated as voltage source, since it is constant and added on top-oil temperature rise value to determine top-oil temperature.

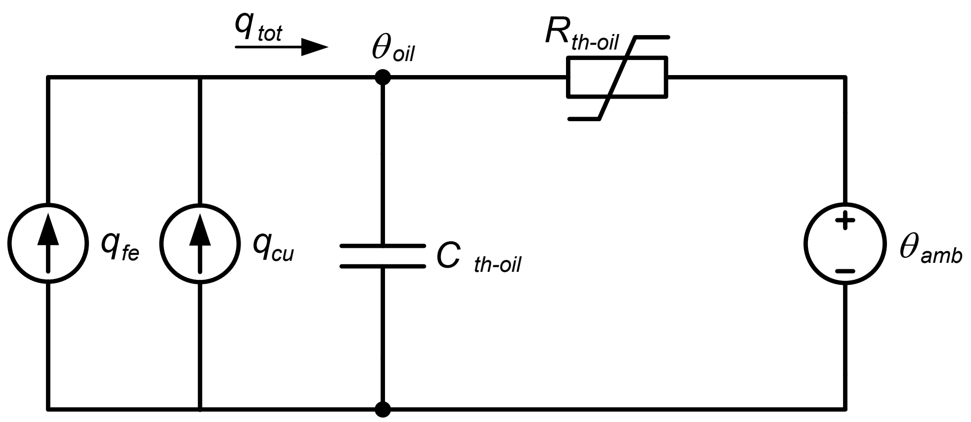

Figure 2.4 : Top-oil temperature rise over ambient model.

Where; $q_{tot}$is total heat generated with affect of losses (in W), $q_{fe}$is heat generated with affect of only no load losses (in W), $q_{cu}$is heat generated with affect of load losses (DC losses, eddy and stray losses) (in W) and $R_{th\text{-}oil}$is non-linear oil to air thermal resistance.

This circuit is solved with circuit analysis theory and differential equation which is given Equation 2.21 is found [6,7,27-28].

$$\frac{1+RK^2}{1+R}\mu_{pu}^{n_{Susa}}\Delta\theta_{oil,rated} = \mu_{pu}^{n_{Susa}}\tau_{oil,rated}\frac{d\theta_{oil}}{dt} + \frac{(\theta_{oil}-\theta_{amb})^{n_{Susa}+1}}{\Delta\theta_{oil,rated}^{n_{Susa}}} \tag{2.21}$$

Where,

R	ratio of load losses to no-load losses
K	load factor
μ_{pu}	oil viscosity (pu)
θ_{amb}	ambient temperature (°C)
$\Delta\theta_{oil,rated}$	rated top-oil temperature rise over ambient temperature (K)
$\tau_{oil,rated}$	rated oil time constant (minutes)

In Susa’s method, rated oil time constant is calculated according to IEEE Std. C57.91-1995(Cor.2002)[7]. It is noticed that in IEEE method constant is used in hours, however in Susa’s method it is used in minutes.

Oil viscosity is calculated from Equation 2.20 for each oil temperature value, however in model it is used in per unit.

Ratio of load losses to no-load losses is calculated with following equation

$$R = \frac{P_l}{P_{fe}} \tag{2.22}$$

Load factor is calculated with Equation 2.23.

$$K = \frac{I}{I_{rated}} \tag{2.23}$$

where;

I	current during that loading time period (A)
I_{rated}	rated current of transformer for full load. (A)

In this model, different than other two models, which are described in the previous sections, both thermal resistance and oil time constants are affected from change of oil viscosity [27].

2.3.3 Hot-spot temperature rise over oil temperature model

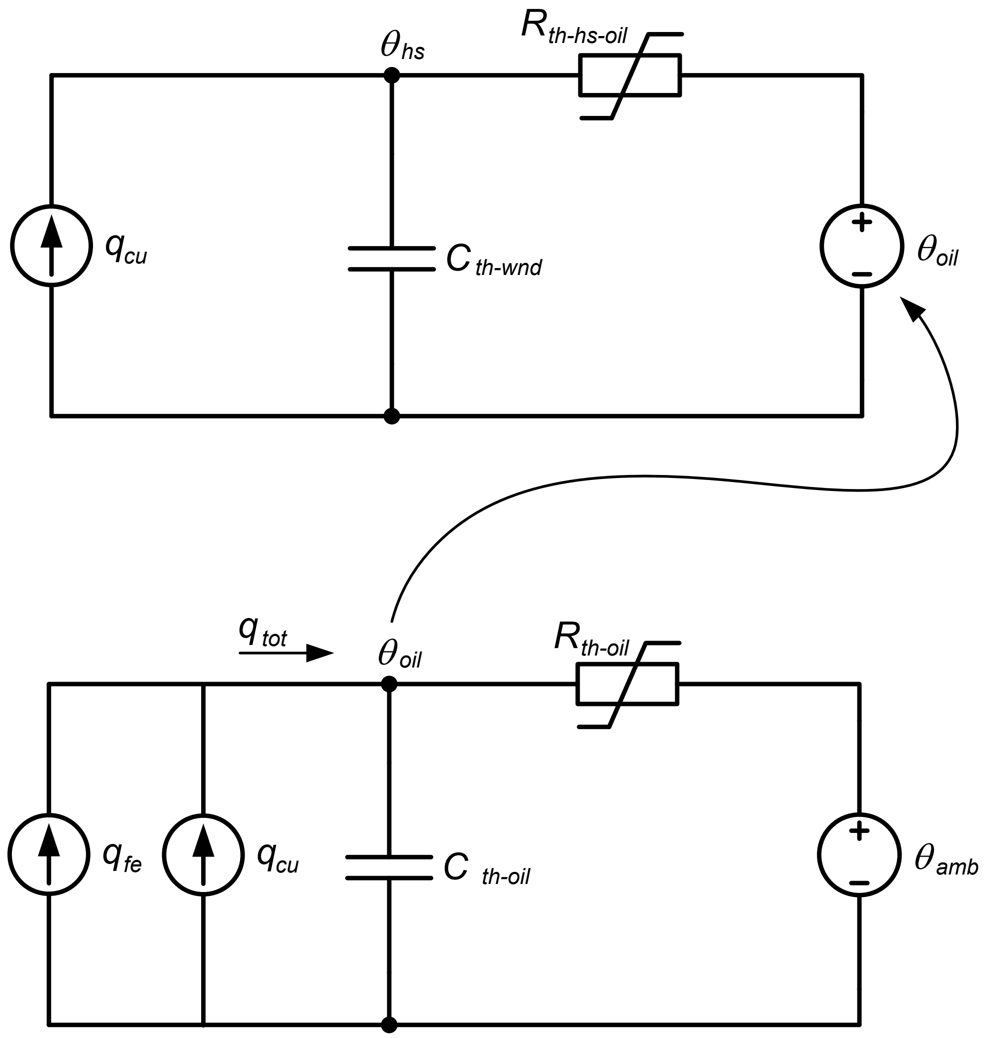

Figure 2.5 : Hot-spot temperature circuit model together with top-oil model circuit.

Where, $q_{cu}$is heat generated with affect of load losses (DC losses, eddy and stray losses) (W) , $R_{th\text{-}hs\text{-}oil}$ isnon-linear hot-spot to oil thermal resistance, $\theta_{hs}$is hot-spot temperature (˚C).

Model for hot-spot temperature rise over oil temperature is based on thermal model which is using thermal electrical analogy similar to oil temperature rise model [13].

RC circuit which is developed for hot-spot temperature is given in Figure 2.5. In developed thermal model, different than oil temperature rise model, only load losses are taken into account. Load losses are given as a current source which varies with load factor since it is heat source. Thermal capacitance of winding is given as constant. Thermal resistance of winding is a variable value which depends on oil viscosity. Top oil temperature is given as voltage source and value of top oil temperature is taken from top-oil temperature model which equation is given in Equation 2.21.

This circuit is solved with similar way with top-oil model with circuit analysis theory and differential equation which is given Equation 2.24 is found [6-7, 29].

$$K^2 P(\theta_{hs})_{pu} \mu_{pu}^{n_{Susa}} \Delta\theta_{hs,rated} = \mu_{pu}^{n_{Susa}} \tau_w \frac{d\theta_{hs}}{dt} + \frac{(\theta_{hs} - \theta_{oil})^{n_{Susa}+1}}{\Delta\theta_{hs,rated}^{n_{Susa}}} \qquad \textbf{(2.24)}$$

where

$\Delta\theta_{hs,rated}$ rated hot-spot temperature rise over top-oil temperature (K)

τ_w rated winding time constant (minutes)

$P(\theta_{hs})_{pu}$ load loss pu value varies on temperature change (pu)

n_{Susa} constant (given as 0.25 for ONAN transformers)

Load losses' change depending on temperature is calculated with Equation 2.25.

$$P(\theta_{hs})_{pu} = P_{DC,pu}\left(\frac{\theta_{hs} + \theta_k}{\theta_{hs,rated} + \theta_k}\right) + P_{eddy,pu}\left(\frac{\theta_{hs,rated} + \theta_k}{\theta_{hs} + \theta_k}\right) \qquad \textbf{(2.25)}$$

$P_{DC,pu}$ DC losses (I^2R losses) (in pu)

$P_{eddy,pu}$ eddy losses (in pu)

θ_k temperature factor for calculation, equal to 225 for aluminum and 235 for copper;

Differential equations which are obtained in Equation 2.21 and 2.24 are solved with a numerical analysis method to determine the temperature for both oil and hot-spot for windings.

3. EXPERIMENTAL STUDY

An experimental study is realized with a 1000 kVA 33/0.4 kV ONAN cooled distribution transformer. One goal of this experimental study is determine necessary parameters for thermal models explained in Section 2. Other goal is to compare and verify results of thermal models with measured values. During the measurements, oil temperatures, winding temperatures and ambient temperatures are recorded. Two different test is done. One of the test is constant load test with the aim of determination of thermal model parameters. Second test is varying load test to compare and verify results with dynamic thermal models which are given in Section 2.

Unit, which tests have been performed is a distribution transformer without external cooling (ONAN cooled). Fifteen Thermocouples has been installed during manufacturing of transformer. Location of thermocouples have been determined according to past experiment results to measure hottest points [23-24]. Thermocouples installed to same locations in all three coils to compare temperature differences between each coil.Measurement devices and thermocouples data is given in Appendix A. Considering tolerance of thermocouple and monitoring device, total accuracy of measurements expected ±2%.In this section, experimental study is explained with three subsections.In first part, realized test unit and realized tests are explained. In the second part, calculations, which are realized with thermal models, are given. In the third subsection, measured and calculated values are compared.

3.1 Measurements From Temperature Rise Tests

Two different tests are realized with 1000 kVA distribution transformer. Results of tests are plotted and necessary parameters for thermal models are determined from this test. Tested unit details, realized tests and results of tests are given in following subsections.

3.1.1 Tested unit design parameters

Table 3.1 : Nameplate data of tested transformer.

Rated Power	1000 kVA
Primary Voltage	33000 V
Secondary Voltage	400 V
Frequency	50 Hz
Short Circuit Voltage %	6.2 %
Cooling	ONAN
Vector Group	Dyn11
No-load Losses	1648 W
Load Losses	10177 W
Manufacturing Standard	IEC 60076-1

Table 3.1 shows the nameplate data of the tested transformer. These values are taken from test report of manufacturer.

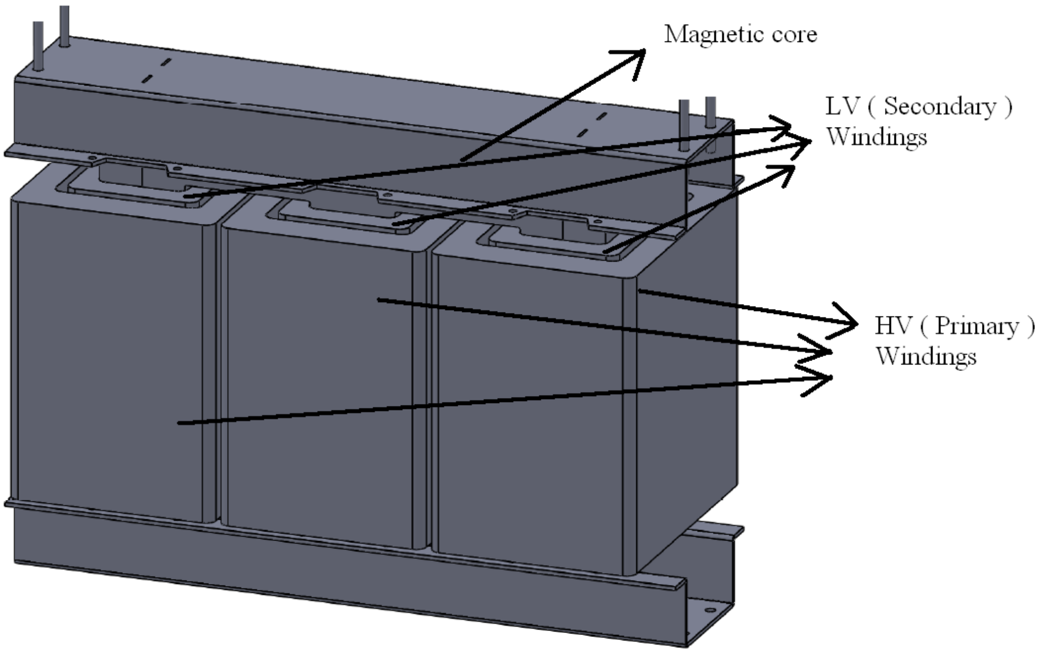

Figure 3.1 : Active part of transformer.

In Figure 3.1 , basic transformer active part schema is given . There are fifteen Aluminum foil windings in the secondary winding (LV winding). There are two cooling channels between the layers, one of them is located between layer five and layer six and the other channel is located between layer ten and layer eleven. The distance between secondaryconductor to the core yoke is 58 mm from top. It is also the same for the bottom of winding. 45 mm of this space is pressboard insulation material.

Primary winding has 14 layers, and total number of turns are 2142.Enameled isolated aluminum conductor is used as primary winding conductor. There are three cooling channels in primary winding. First cooling channel is located immediately after secondary winding and before the start of the primary winding. Second cooling channel is located between layer 4 and layer 5 and third cooling channel is located between layer 8 and layer 9. The distance between primary conductor to the core yoke is 58 mm from top. It is same for bottom. 45 mm of this space is pressboard insulation material. Internal view of transformer is given in Figure 3.2 and Figure 3.3. In figure 3.3, thermocouples inside of tank are shown.

Figure 3.2 : Internal view of tested transformer.

Figure 3.3 : Internal view of tested transformer with thermocouples.

Transformer tank is corrugated wall design which consists from total of 112 cooling fins. 25 of this fins are located in each short side of transformer tank and 31 of fins are located in each long side of transformer. Figure 3.4 and Figure 3.5 shows the transformer’s exterior view.Quantities of cooling fins and locations are shown in Figure 3.7.

Transformer is breathing type with conservator. In addition to thermocouples on transformer, pressure relief device and Buchholz Relay are installed.

In Figure 3.5, thermocouples which are coming inside of tank to outside of tank is shown. In same figure, monitoring devices for temperature is also shown. During tests, these monitoring devices are not installed on transformers fins, they are installed in a separate area.

Figure 3.4 : Exterior view of tested transformer from HV side.

Figure 3.5 : Exterior view of tested transformer from LV side.

3.1.2 Location of thermocouples

There are total of 15 thermocouples installed on transformer. Locations of thermocouples are as following:

Five thermocouples are installed in secondary (low voltage) windings. In A and C coils, two thermocouples are installed. In B coil, three thermocouples installed since it was expected that hottest temperature occurs in this winding. In figure 3.10, locations of thermocouples are shown. All thermocouples are installed approximately 5 mm inside from foils, since it was expected to get hottest temperature at this location [24]. Thermocouples on windings are shown in Figure 3.6.

Four thermocouples are installed in primary (high voltage) windings. In each coil, one thermocouple is installed. All thermocouples are installed approximately 5 mm depth from aluminum conductor material, since it was expected to get hottest temperature at this location [24]. In addition to this, one thermocouple is installed to outlet of cooling channel.

One thermocouple is located on the magnetic core of transformer.

One thermocouple is located in oil pocket on transformer cover. One thermocouple is located on the top of cooling fin Thermocouple on cooling fin is located on the long side of fins and on the centerline. Locations of thermocouples for oil temperatures are shown in Figure 3.9.

Transformers top view drawing is given in Figure 3.7. Location of bushings and thermometer pocket can be seen in that figure. In addition cooling fins of transformer tank is shown on the drawing which is given in Figure 3.7.

Two thermocouples are installed in the bottom part of the tank. One of them is located in the bottom part of phase insulation pressboard to measure the mixed bottom oil temperature and other thermocouple is installed in the lowest part of the bottom of the tank. Locations of thermocouples are shown in Figure 3.9.

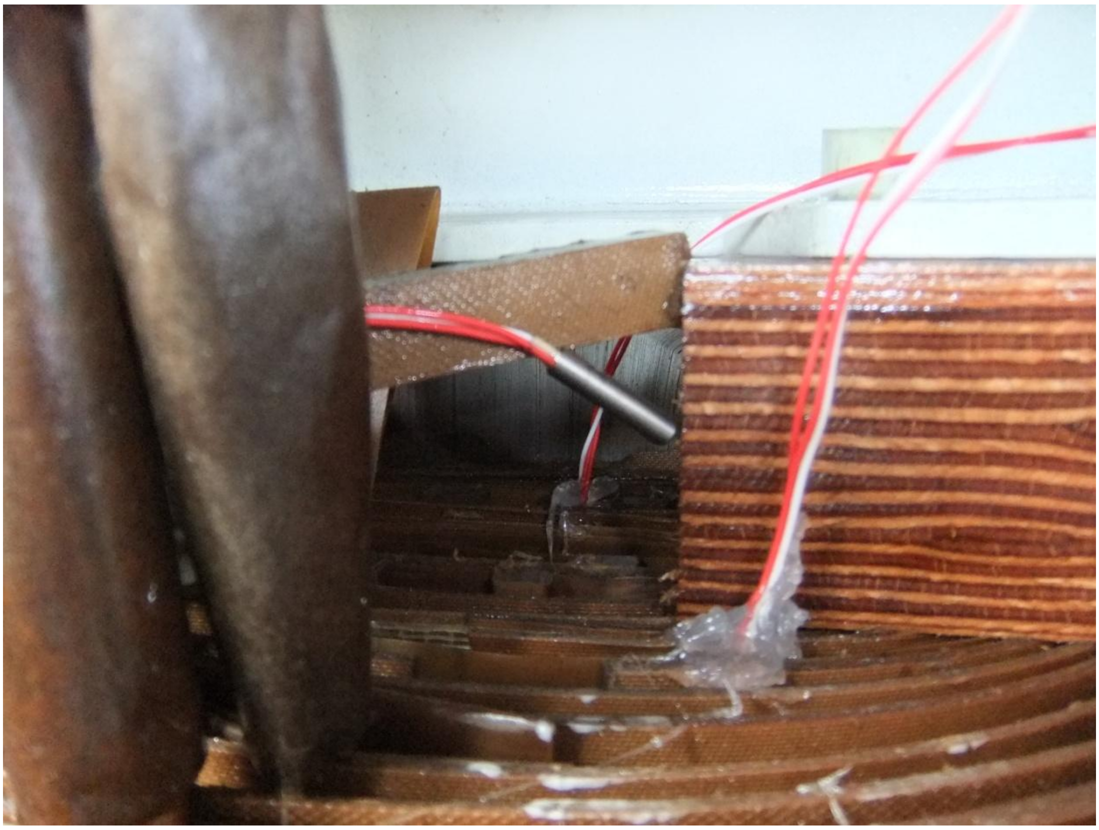

Figure 3.6 : Positions of thermocouples on phase B winding.

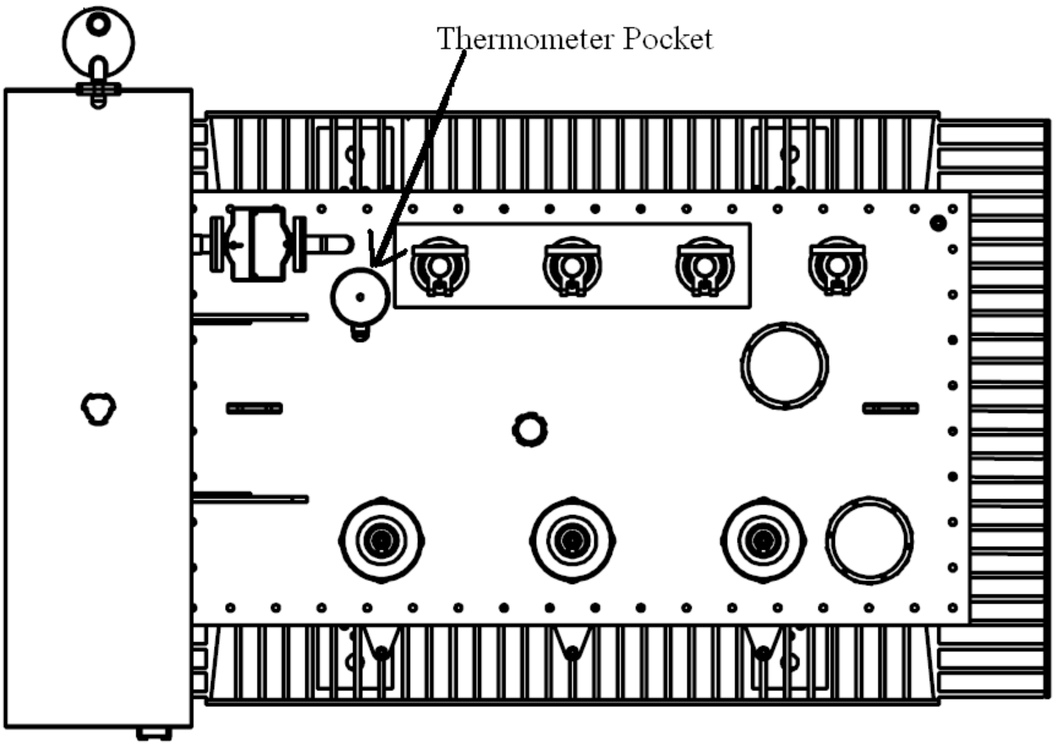

Figure 3.7 : Top view of transformer showing thermometer pocket.

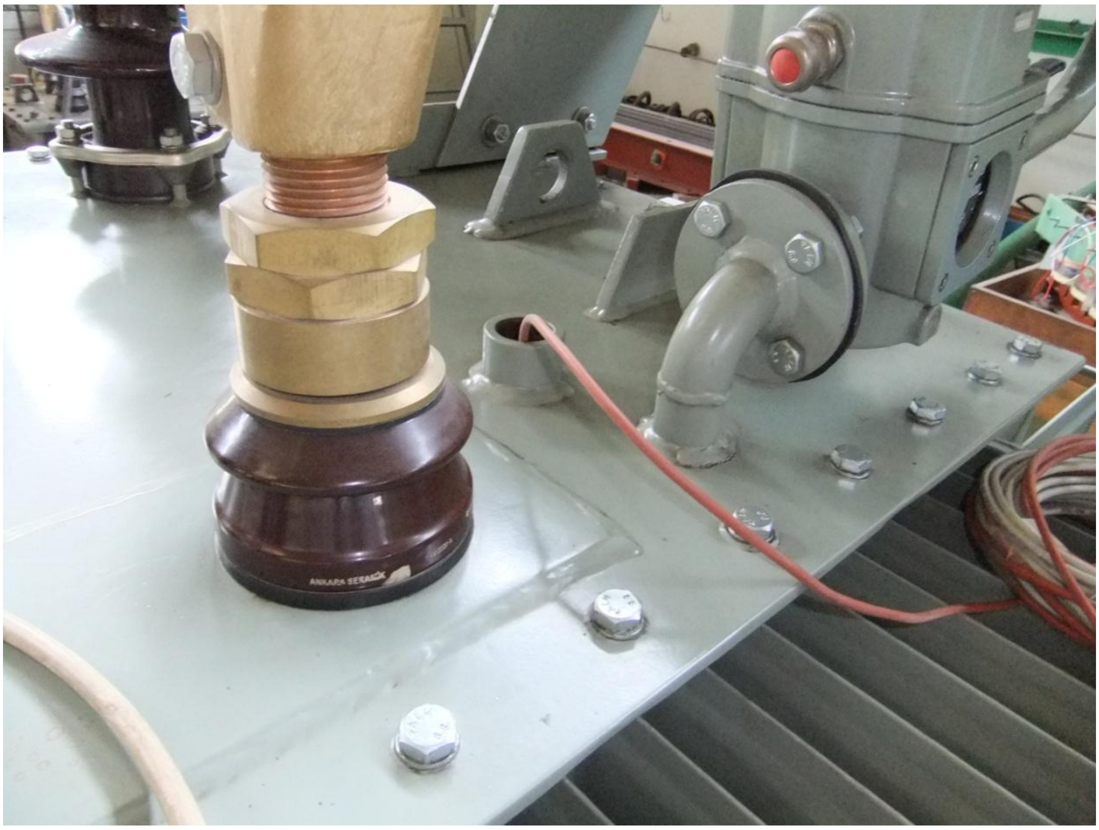

Figure 3.8 : Thermocouple in thermometer pocket.

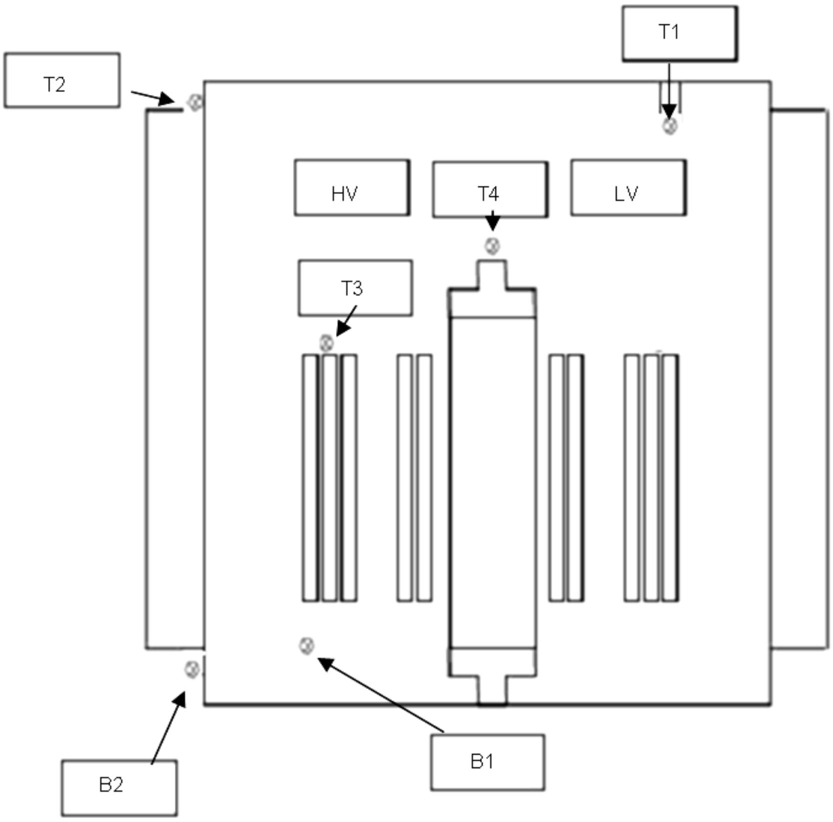

Figure 3.9 : Location of thermocouples in transformer.

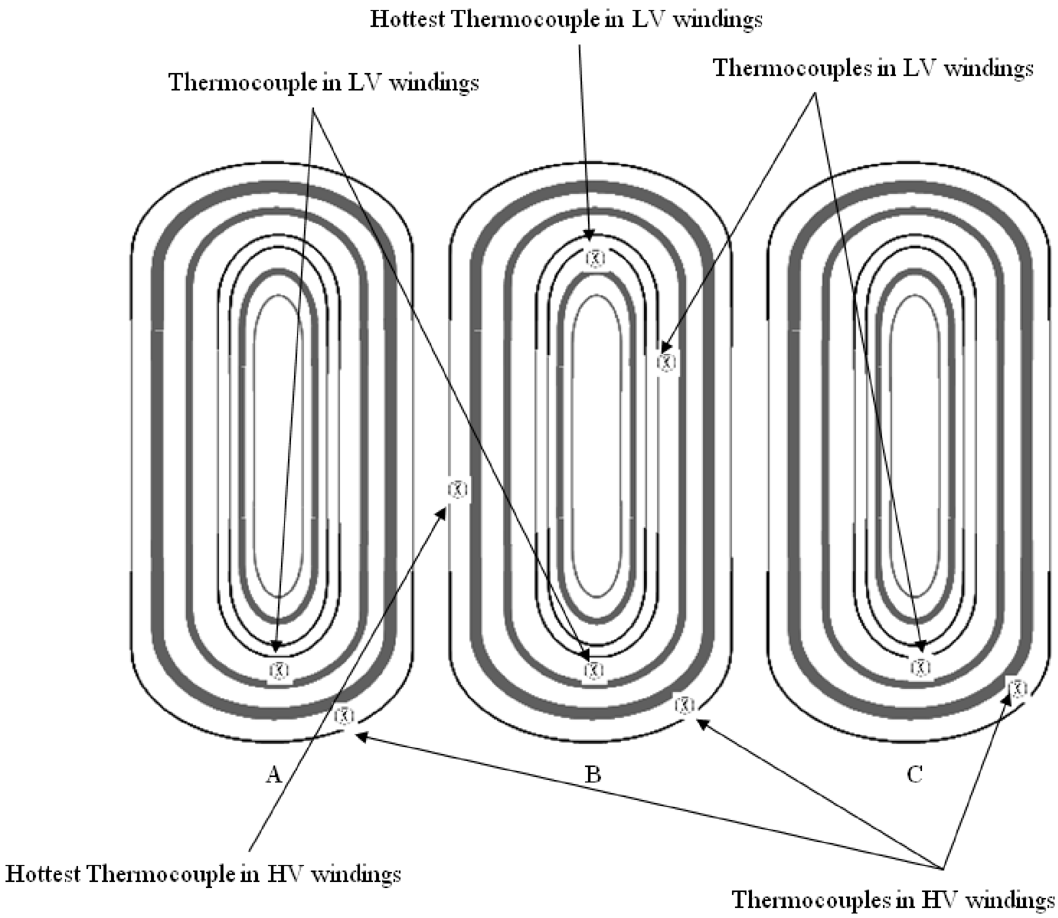

Figure 3.10 : Location of thermocouples in windings.

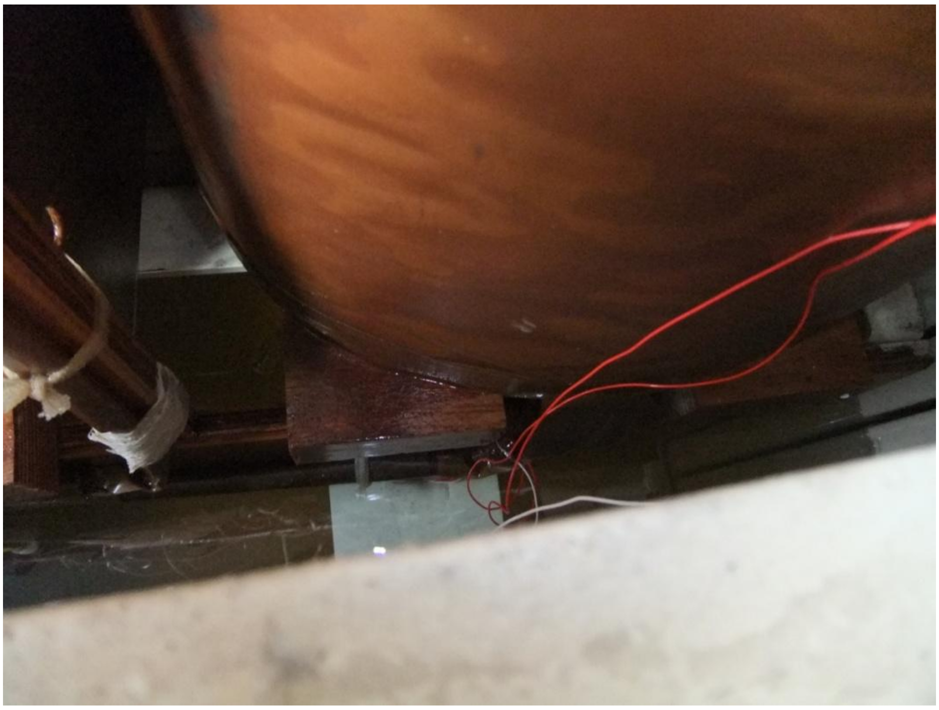

Figure 3.11 : Thermocouples for bottom oil temperature.

To measure the ambient temperature during the tests, two opposite side located thermocouples are installed in the test room with a distance of 1 m from transformer.

During the tests, six of the thermocouples which are installed outtterpary of the tank are connected to a data logger, which records temperature readings continuously with 15 second intervals. Details of data logger, which designed for measurement and recording of temperatures are given in Appendix A.

In addition, thermal images of transformer during tests has been taken with thermal camera which is data is given in Appendix A. However, thermal photos are only taken to observe distribution of temperature on transformer tank , these data is not used neither in calculation nor plotting..

Figure 3.12 : Thermocouples located inside of transformer tank.

3.1.3 Applied temperature rise tests

Two different temperature rise tests applied to the transformer. In the first test, constant nominal load applied. This test realized according to total loss injection method which is givenin standard IEC 60076-2[32]. According to this method, rated current and rated voltage is not applied to transformer simultaneously, total losses which are written on routine test report of transformer is injected. Injection method is to short-circuit transformers secondary side and apply necessary current from primary side to inject total losses to transformer. This test has two steps. In first step, total losses (both no-load and load losses) are injected to transformer till rate of change of top oil temperature rise has fallen below 1 K per hour. After this period, in the second step, only nominal current is applied to transformer from primary side while secondary is short-circuit condition for 1 hour. At the end of the hour, connections are removed in shortest time possible and DC resistance measurement for windings is done. Average winding temperature rise for both high voltage and low voltage side is determined by using DC resistance measurements after test and before test in cold condition [32]. Temperature difference is defined by comparing change on the DC resistance values. DC resistance values are measured with specially designed test device for this application which applies high currents to obtain resistance measurement in short time and accurately. Detail of device is given in Appendix A. In figure 3.13, transformer is shown during first test. As described, transformer's secondary is in short-circuit condition and current is applied from primary side as seen in Figure 3.13.

Figure 3.13 : Transformer during constant load test.

In the second test, varying load test is realized. First nominal current (1.00 pu) is applied for three hours, and following double current (2.00 pu) is applied for 1.45 hours. Load steps are given in Table 3.2. this load steps arechosenrandomly by aiming to obtain a sudden change on loading., and extreme overloading conditions is applied to transformer during double current step.

Table 3.2 : Load steps of the second test.

Time Period (minutes)	Load (pu)
0.0 - 180.0	1.0
180.0 - 285.0	2.0
285.0 - 317.0	0.0

All assembled thermocouple's measurements have been recorded for both tests.

Both tests are realized in main tap position which is 4^{th} tap with 33000 V rating.

Total fifteen unit thermocouples are used during tests. These thermocouples are three wire type Pt100 resistance temperature detectors (RTD).Six of these thermocouples are connected to a continuous data monitoring and recording device and rest of the thermocouples are connected to three separate Pt100 monitoring device. thermocouples. Considering tolerance of thermocouple and monitoring device, total accuracy of measurements expected ±2%. Details of measurement devices are given in Appendix A.

Continuous data monitoring and recording device has recorded temperature values for six thermocouples continuously with 15 second intervals. For the other thermocouples only monitoring devices are used and values are recorded manually.Taken thermal images during tests are given in Figure 3.14 and Figure 3.15. In Figure 3.14, narrow side of transformer cooling fins are shown during test. In Figure 3.15, longer side of transformer cooling fins are shown.

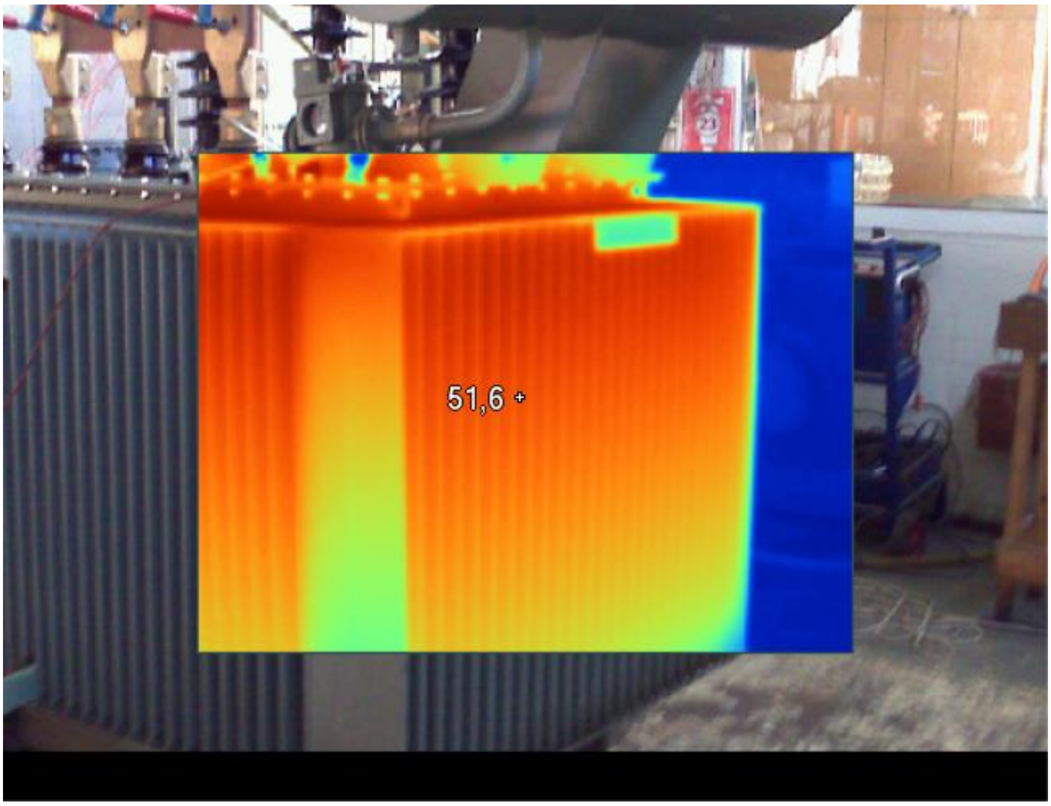

Figure 3.14 : Thermal camera view from narrow side.

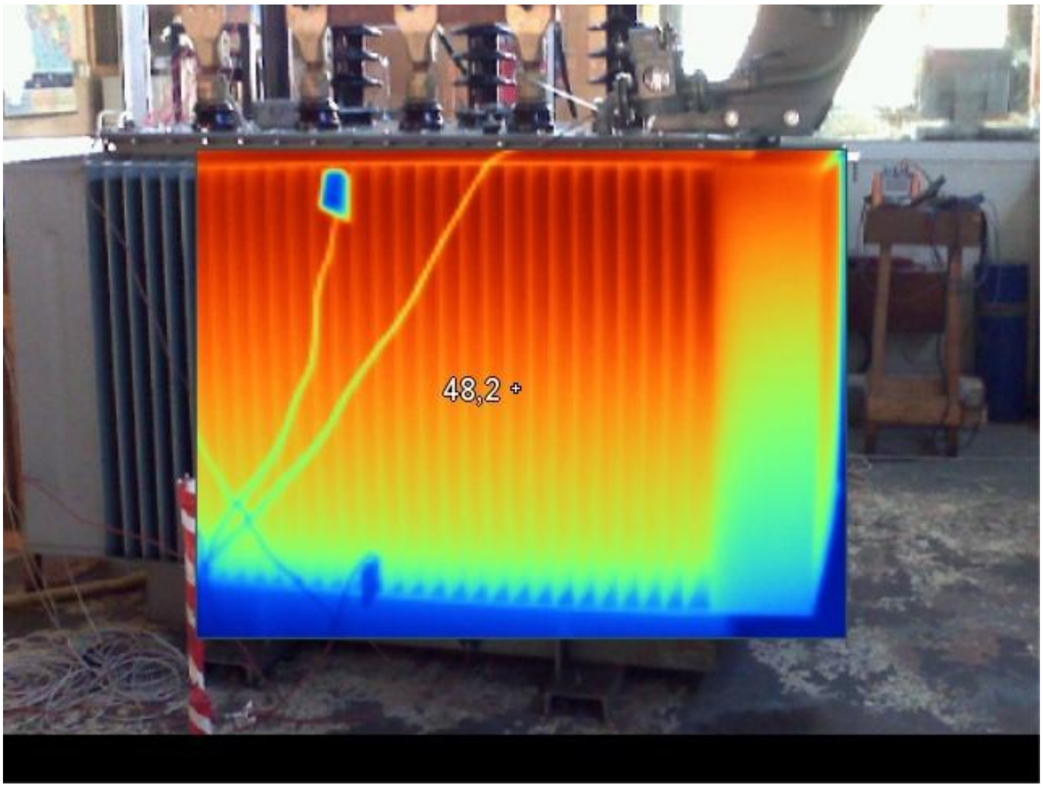

Figure 3.15 : Thermal camera view from long side.

3.1.4 Results of tests

Measurements recorded during both tests are analyzed. Top oil temperatures and bottom oil temperatures which are measured from different locations are compared. Hot-spot temperatures for both high voltage and low voltage side is determined. Measured values for both top-oil temperature and winding hot spot temperatures are plotted. Average winding temperature rise is calculated according to data which is obtained from temperature rise test. Average oil over ambient temperature rise values are defined according to different methods which are explained in IEC 60076-2 standard, IEEE C57.12.90 standard and D. Susa's study [2,24,32]. Results are compared. Gradients are calculated according to different methods. Results calculated for gradients are compared.

3.1.4.1 Top-oil temperature

Top oil temperaturesare measured and recorded from three different locations. Most common measurement method is thermometer pocket measurement since most of the transformers in market has thermometer pocket and thermometers installed on existing transformers are assembled in thermometer pockets. In addition to this, measurements are recorded from thermocouples assembled on top radiator and oil cooling channel outlet in tank.

Measured values in constant load test (Test 1) are plotted in Figure 3.16. Measured values in varying load test (Test 2) are plotted in Figure 3.17.For both tests, measurement results from different top oil temperature locations are given in Figures 3.16 and Figures 3.17. According to measurements, highest top oil temperature is obtained from the thermocouple, located on outlet of cooling channel.Although highest top oil temperature is obtained from outlet of cooling channel, these values are not used in calculations and models. In industry usually no thermocouples are located inside of distribution transformers' tank therefore measurement of top oil at the outlet of cooling channel is not common [24].

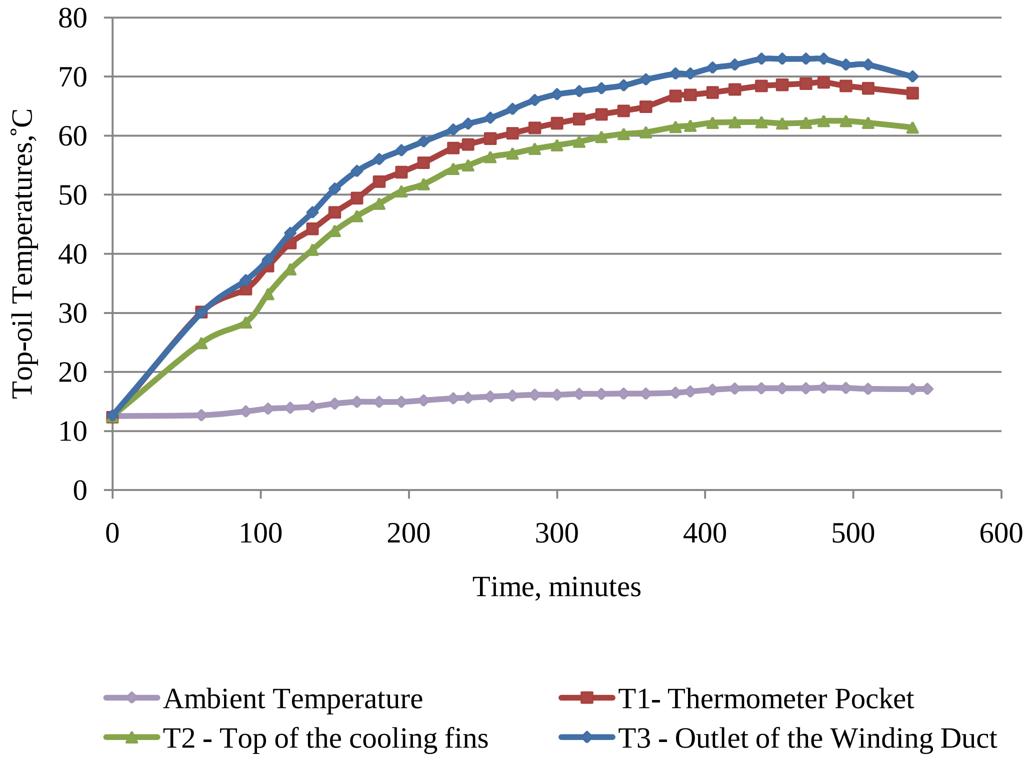

Figure 3.16 : Measured top-oil temperatures at three different locations in first test.

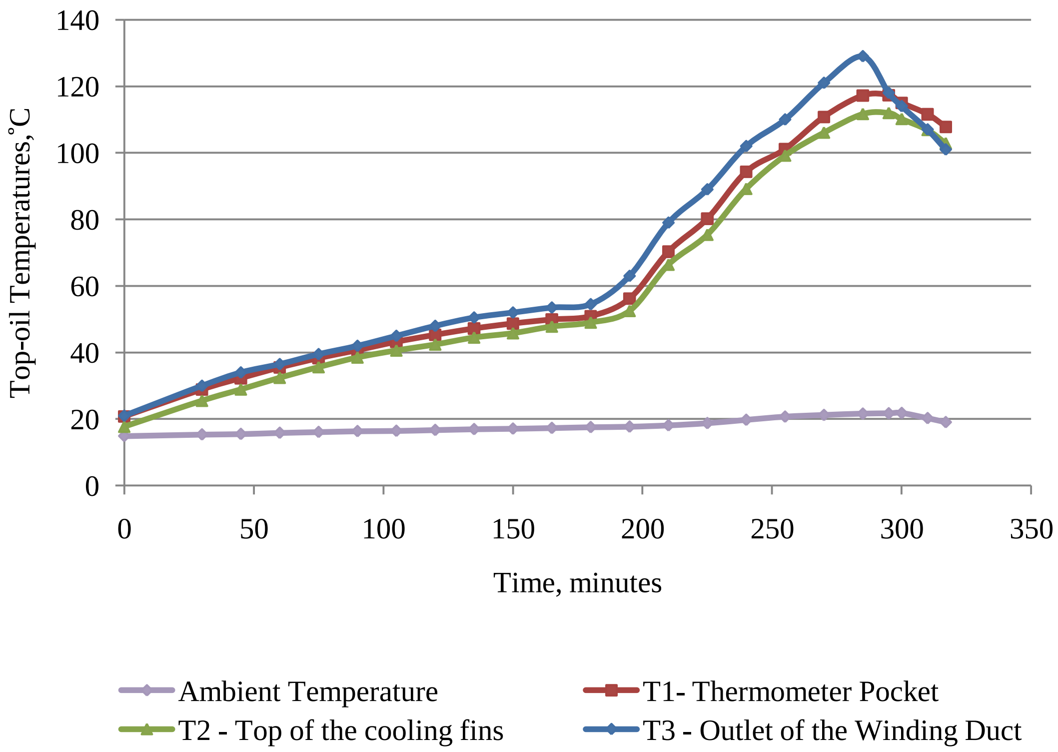

Figure 3.17 : Measured top-oil temperatures at different locations in second test.

In Table 3.3, highest measured values in different locations are given for both test 1 and test 2. As also shown in Figure 3.16 and Figure 3.17,hightest top oil temperature is obtained from thermocouple, which is located in the outlet of winding,'s cooling channel. In Table 3.3 T1, T2 and T3 locations are indicating thermocouples at following locations; T1 is thermometer pocket, T2 is top of the cooling fins and T3 is outlet of the winding cooling channel (duct).

Table 3.3 : Measured highest top-oil temperatures.

Test	Load	Time , min	Location	θ_{oil} , °C
Test 1 (Constant Load)	1.0 pu	480	T1	69.0
			T2	62.5
			T3	73.0
Test 2 (Variable Load)	1.0 pu	180	T1	50.9
			T2	49.0
			T3	54.5
	2.0 pu	285	T1	117,2
			T2	111.7
			T3	129.0

3.1.4.2 Bottom-oil temperature

Bottom oil temperatures are measured and recorded from two different locations. One of them is installed inside of the tank to measure mixed bottom oil temperature and other thermocouple was installed on the lowest bottom part of transformer tank.

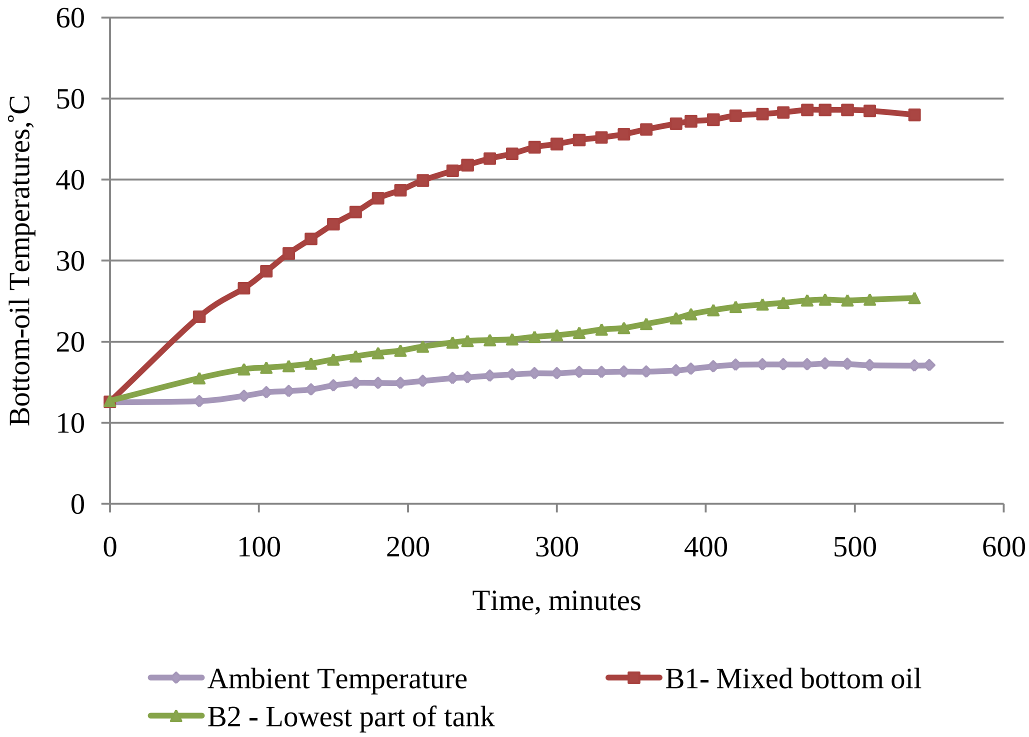

Figure 3.18 : Measured bottom-oil temperatures at different locations in first test.

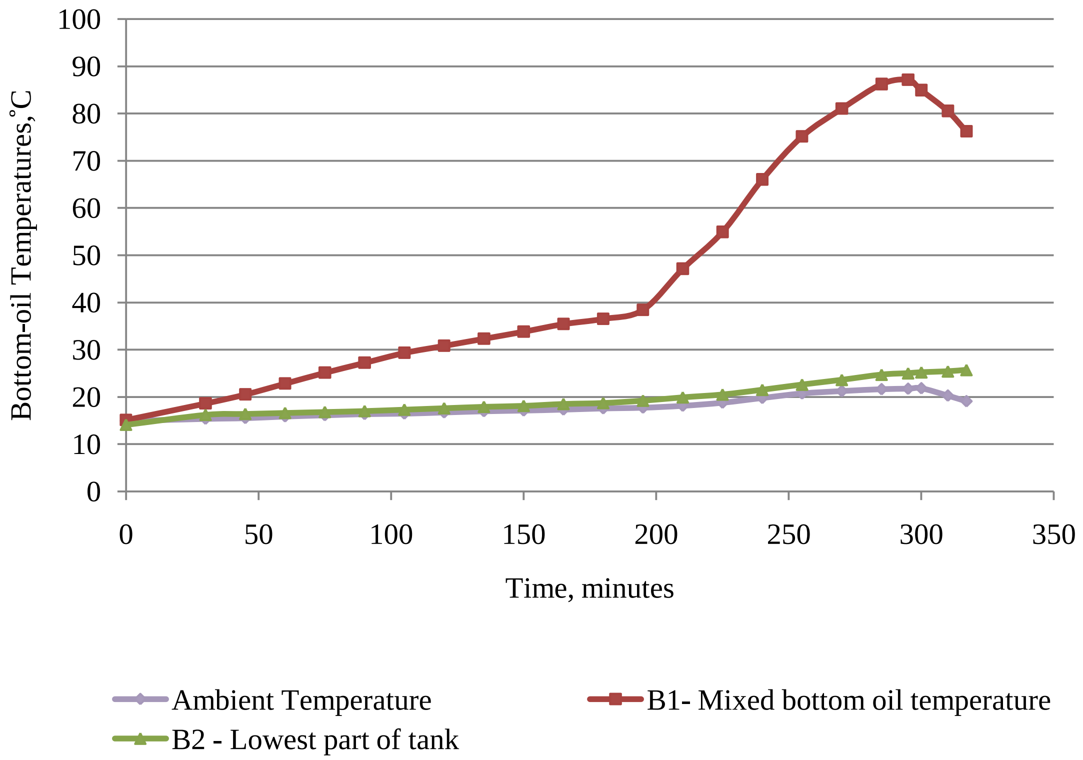

Figure 3.19 : Measured bottom-oil temperatures at different locations in second test.

The Figure 3.18 shows the bottom oil temperatures measured from different locations in first test. Figure 3.19 shows the top oil temperatures measured from different locations in test 2.

In Table 3.4 highest measured values of bottom oil temperatures in different locations are given for both Test 1 and Test 2.

Hottest bottom oil temperature is measured in mixed bottom oil temperature thermocouple. It has been observed that mixed bottom oil temperature has responded to load changes analogous with the top oil temperature. In addition, measurements on thermocouple located in the bottom of the tank has shown that, oil in the lowest part of tank, has not been changed significantly in both of the tests as clearly shown in Figure 3.18 and Figure 3.19. This is a result of low natural oil circulation under active part and under the cooling fins. Therefore, measurement data, which is received from the thermocouple, located in the lowest part of tank is not used in calculations and analyzes.

Table 3.4 : Measured highest bottom-oil temperatures

Test	Load	Time , min	Location	θ_{bo} , ˚C
Test 1 (Constant Load)	1.0 pu	480	B1	48.6
			B2	25.2
Test 2 (Variable Load)	1.0 pu	180	B1	36.5
			B2	18.7
	2.0 pu	285	B1	86.2
			B2	24.7

where;B1 is indicating the location of thermocouple for mixed bottom oil temperature and B2 is indicating location of thermocouple for lowest part of the tank inside transformer.

3.1.4.3 Hot-spot to top-oil temperature rise

Hottest spot temperatures are defined by comparing the hottest measurement values. For both primary (high voltage) and secondary (low voltage) windings, highest temperature measured in phase B which is the mid located phase. This result is reasonable since mid located phase windings are affected from both other two windings temperature raises. On the other hand, the difference is not significant.Measured values in constant load test are plotted in Figure 3.20. In figure 3.21, varying load test results for hot-spot temperatures are given. It also noted that low voltage winding hot spot temperatures are higher than high voltage winding's hot spot temperatures. This result is as expected since low voltage winding is internal located between magnetic core and primary windings, therefore oil circulation and heat transfer is expected less than high voltage windings.Location of thermocouples which measured the hottest points are shown in Figure 3.10.

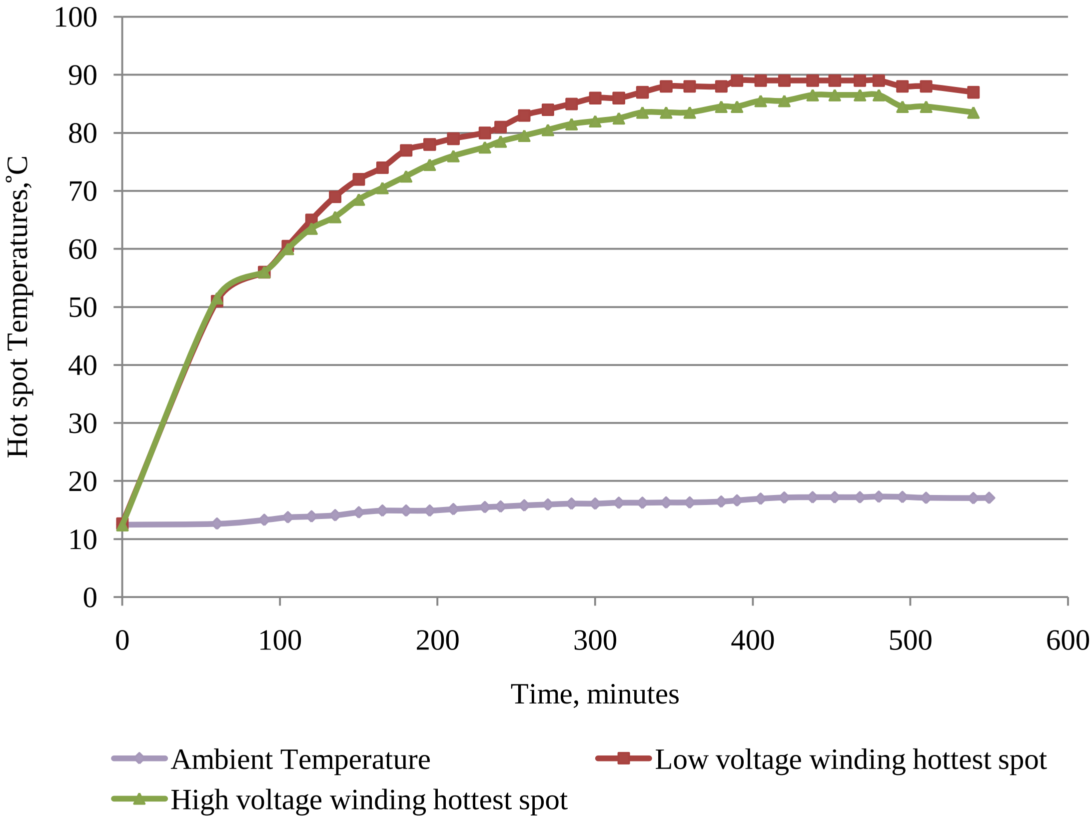

Figure 3.20 : Winding hot spot temperatures in the first test (constant load test)

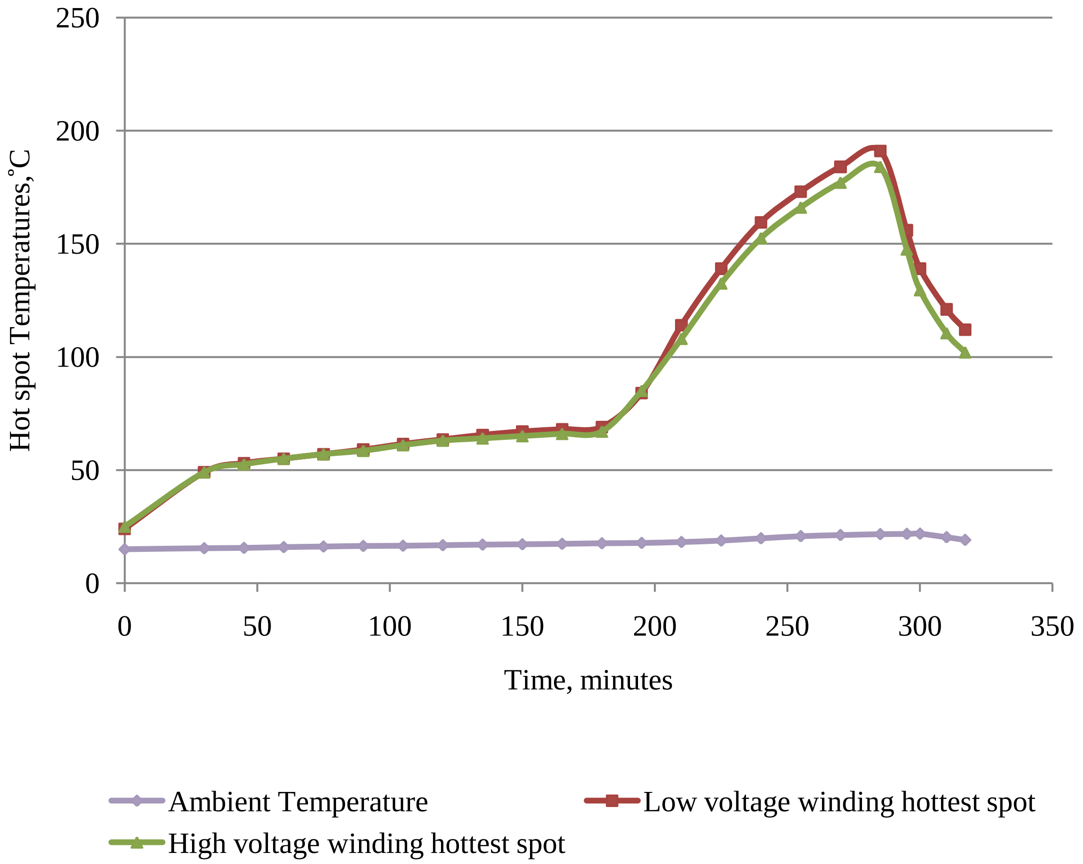

Figure 3.21 : Winding hot spot temperatures in the second test (varying load test)

Hottest spot rise above top oil temperature is calculated for both high voltage and low voltage winding. During this calculation top oil temperature has been taken from different locations and results are compared in Table 3.5.

Table 3.5 : Hot-spottemperatıre rises to top oil temperatures

Time, min.	Load	Location	$\Delta\theta_{hs,\ rated}$, K	
			LV	HV
180	1 pu	T1	24.3	21
		T2	27.3	24
		T3	20	17
285	2 pu	T1	73	66
		T2	79	70
		T3	62	56

In this study rated hot-spot to top oil temperature rise is take by using oil temperature in thermometer pocket. Reason of this is, oil thermometer pocket is most common measurement location for top oil temperature in industry as already explained in

Section 3.1.4.1. Hottest spot rise over top oil pocket temperature is plotted in Figure3.22. It had been observed that the hot-spot temperature rise over top-oil temperature had not experienced with overshoot. This were expected since it had been verified in the past studies that in transformers without external cooling , a function with overshootshould not be observed [23,28].

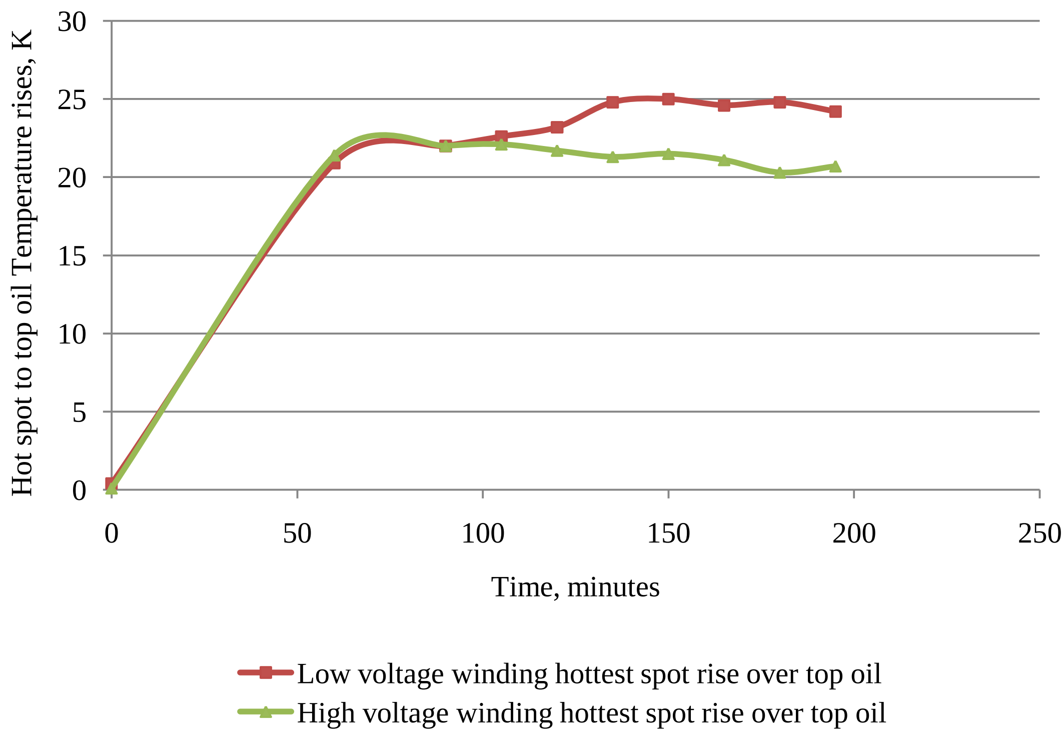

Figure 3.22 : Hot-spot to top-oil temperature rises

3.1.4.4 Average temperature rises

As a part of constant load test, resistance values are measured immediately after tests as per related IEC standard [32]. Measured values and cold resistance values are given Table 3.6 and Table 3.7.

Average winding temperatures are defined with extrapolation graph.Average winding temperature was defined with following formula from resistance values[32].

$$\theta_u = \frac{R_u}{R_i}(\theta_i + \theta_k) - \theta_k \qquad \textbf{(3.1)}$$

Where;θ_u is calculated temperature(in ˚C);θiiscold temperature (initial measured value) (in ˚C) ;$\theta_k$is temperature factor for calculation, equal to 225 for aluminum; 235 for copper;$R_i$is the cold resistance (initial measured value) (in ohm) and R_u is thecalculated resistance (in ohm).

Before starting temperature rise test, during transformer is in cold condition, initial resistance values are measured and recorded. These values are given in Table 3.7. After completing test, during transformer in warm condition, resistance measurement test of same winding is repeated. Measured values are given in Table 3.6. Since transformer winding is cooling down during measurement, more than ten measured resistance values are recorded. It is shown in Table 3.6 that resistance values are continuously reducing.Measurement is realized with a sensitive resistance measurement device which is data is given in Appendix A. Considering that, an amount of time is lose during removing connections of test and connecting test device for resistance measurement, resistance at the end of the test is determined with an extrapolation. This extrapolation is realized by plotting measured values and finding equation of this function from graph.

Table 3.6 : Measured warm resistances

Time sec.	R_{hv} ohm	R_{lv} μohm
45	11.665	-
60	11.517	1255
75	11.423	1251
90	11.364	1246
105	11.322	1243
120	11.284	1242
135	11.250	1240
150	11.225	1240
165	11.200	1239
180	11.181	1238
195	11.166	1237
210	11.166	1236

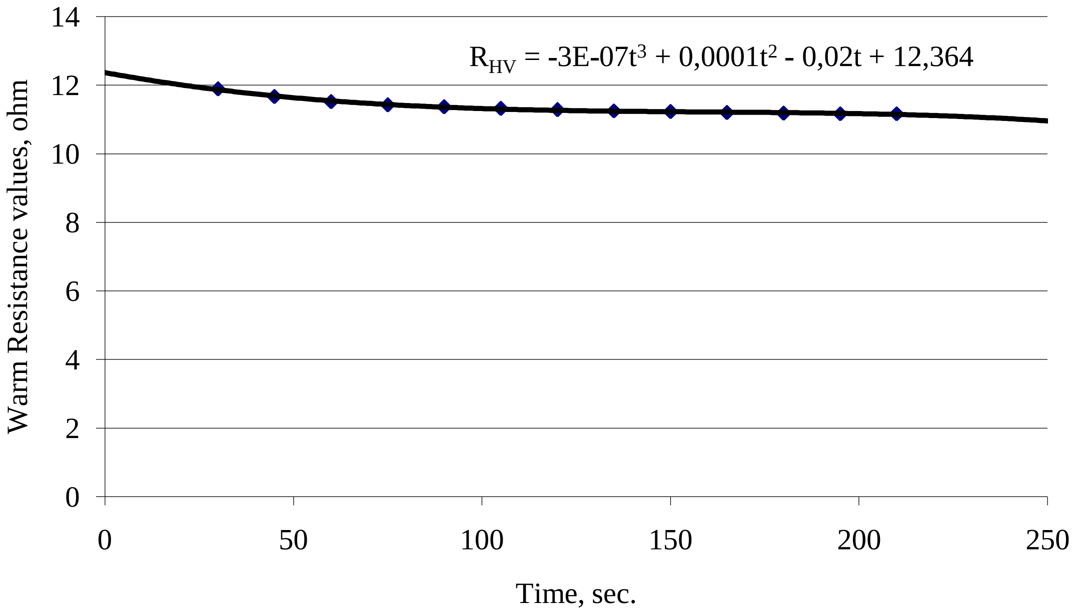

Figure 3.23 : Warm resistance values for high voltage winding.

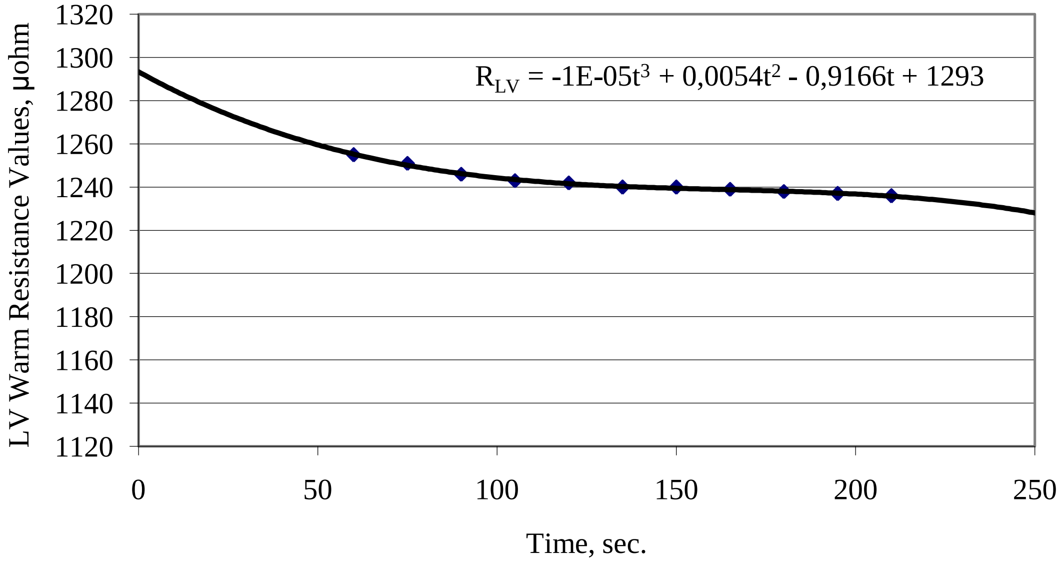

Figure 3.24 : Warm resistance values for low voltage winding.

According to extrapolation, values from plotted graphs which are given in Figure 3.23 for high voltage winding and given in Figure 3.24 for low voltage winding, warm resistance values were defined. From warm resistance values, average winding temperatures are calculated by using Equoation 3.1. Calculated values are given in Table 3.7.

Table 3.7 : Calculated resistance and average winding temperatures

Cold Resistances		$\theta_{w,average}$,˚C		Warm Resistances		$\theta_{w,average}$,˚C	
HV	LV	HV	LV	HV	LV	HV	LV
9.92 ohm	1028 μohm	17	17	12.364 ohm	1293 μohm	76.62	79.38

It is very important to define average oil temperature correctly to determine average winding to average oil temperature rise (g_r) correctly. It is relatively difficult to define average temperature rise for the transformer without external cooling compared to transformers with external cooling. Because, in transformer without external cooling, there is a complex natural oil circulation inside of tank[24].

In this study, average oil temperature rises are defined with different methods and results are compared.

Gradients calculated according to IEC 60076-2

According to IEC standard, average oil temperature is calculated only using top oil temperature. Equation is given in Equation 3.2 [32].

$$\theta_{oil,average} = 0.8(\theta_{oil} - \theta_{amb}) + \theta_{amb} \tag{3.2}$$

According to equaiton which is given in Equation 3.2, average oil temperature is calculated. Calculated average oil temperature's difference between hottest spot winding temperatures for both high voltage and low voltage windings are given in Table 3.8.

Table 3.8 : Average winding – average oil temperature rise according to IEC method

According to IEC 60076-2					
Location	$\theta_{oil,\ average}$, ˚C	g_r, K		H, pu	
		LV	HV	LV	HV
T1	58.66	20.72	17.96	1.17	1.17

H is the hot spot factor and it is calculated with following equoation;

$$H = \frac{\Delta\theta_{hs}}{g_r} \tag{3.3}$$

Gradients calculated according to IEEE C57.12.90

According to IEEE standard, average oil temperature is calculated with following equotation [2].

$$\theta_{oil,average} = \theta_{oil} - 0.5(\theta_{oil,top-surface} - \theta_{bottom,surface}) \tag{3.4}$$

Average winding to average oil tempeatureis calculated with following equotaiton;

$$g_r = \theta_{w,acerage} - \theta_{oil,average} \tag{3.5}$$

$\theta_{w,average}$is calculated from resistance measurements with Equation 3.1 and results are shown inTable 3.7.

H is the hot spot factor and it is calculated with Equoation 3.3.

From this equation, calculated average oil temperature values are given in Table 3.9.

Table 3.9 : Average winding- average oil temperature rise according to IEEE

According to IEEE					
Location	$\theta_{oil, average}$, ˚C	g_r, K		H, pu	
		LV	HV	LV	HV
T1	50.35	29.03	26.27	0.84	0.80

Gradients calculated according to bottom oil temperature measured in tank

Considering that , measured top oil temperature and bottom oil temperatures are for mixed oil temperatures, average mixed oil temperature is calculated with following equotaiton [24];

$$\theta_{oil,average} = \frac{\theta_{oil} + \theta_{bo}}{2} \tag{3.6}$$

Top oil temperature is taken 69˚C from first test (constant load test) results which is shown Table 3.3. Bottom oil temperature is taken 48.6˚C from Table 3.4.

Average winding to average oil tempeatureis calculated with Equation 3.6.H is the hot spot factor and it is calculated from equoation 3.3.

Calculated values are given in Table 3.10.

Table 3.10 : Average winding – average oil temperature rise according to D. Susa

According to D. Susa Method					
Location	$\theta_{oil,\ average}$, ˚C	g_r, K		H, pu	
		LV	HV	LV	HV
T1	58.80	20.58	17.82	1.18	1.18

It is observed that the difference between average winding to average oil temperature rise values calculated according to IEC standard and calculated according to bottom oil temperature measurements in tank (D.Susa Method) gives similar results. On the other hand, values had been calculated according to IEEE method, are notably higher than the calculated values according to bottom oil temperature measurements in tank.

3.2 Results Obtained With Thermal Models

Top oil temperature and hot-spot winding temperatures for both high voltage and low voltage windings are calculated with three different methods which are explained in Section 3. Data required for these models are obtained from test 1 which is constant load test as explained in previous part of study. Optimization is done for defining some parameters which are required in thermal models. Data which are used for calculation of thermal models are given in Table 3.11. Average oil temperature rises and average winding temperature rises are determined according to different methods which are given in IEC, IEEE standards and Susa's study [6,7,24,28]. Results are compared between each other and between measured values during test 2 which is varying load test.

Table 3.11 : Data which is used in thermal models

Quantity	Windings		Unit
	LV	HV	
kVA Base	1000	1000	kVA
Temp. Base	75	75	˚C
P_{DC}	9550		W
$P_{eddy}+P_{stray}$	627		W
P_{fe}	100		W
pu Base	1000	1000	kVA
$\Delta\theta_{w/A,R}$	62.08	59.32	K
$\Delta\theta_{hs,rated}$	24.3	21	K
$\Delta\theta_{oil,rated}$	51.7		K
$\Delta\theta_{bo,rated}$	31.3		K
H	1.181	1.178	
g_r	20.58	17.82	K
$\tau_{oil,rated}$	199.04		min
τ_w (IEEE)	5	5	min
τ_w (IEC)	8.2	8.6	min
k_{11}	0.822		
k_{21}	1.0		
k_{22}	2.0		
x	0.8		
y	1.6		
n_{IEEE}	0.8		
m	0.8		
n_{Susa}	0.25		
M_{ap}	1810		kg
M_{fe}	1205		kg
M_w	114	192	kg
M_{tank}	550		kg
M_{oil}	930		kg
$\theta_{hs,i}$	24	25	K
$\theta_{oil,i}$	20.8		K
$\theta_{bo,i}$	15.1		K

For all models; power rating base is taken as 1000 kVA since transformer rated power is 1000 kVA, temperature base is taken as 75 ˚C. Temperature base is important to define load losses correctly since load losses depends on temperature changes. It is very important especially in D. Susa method, since affect of temperature change on losses are considered, base temperature value is very important.

No-load losses are taken reduced since Test 2 (varying load test) is realized with short-circuit method which is already explained in Section 3.1.3. Other loss values are obtained from manufacturer's test report. It is confirmed that, given load losses on test report are with the same temperature base which is 75˚C as given in Table 3.11.

$\Delta\theta_{w/A,R}$ which indicated rated average winding temperature increase over ambient is calculated by using average winding temperature rise values which are given in Table 3.7 and ambient temperature during test.

Ambient temperature during test is measured averagely 17.3˚C as shown in Figure 3.16, Figure 3.16 and Figure 3.18.

Top-oil temperature rise over ambient which is taken from Table 3.3 by using ambient temperature which is explained in previous paragraph.$\Delta\theta_{hs,rated}$is taken from Table 3.5 by using oil temperature in thermometer pocket (T1).

Top oil temperature rise over ambient temperature which is shown with $\Delta\theta_{oil,rated}$ in Table 3.11 is calculated by using top oil temperature value in Table 3.3 and ambient temperature. Similarly bottom oil temperature rise over ambient ($\Delta\theta_{bo,rated}$) is calculated from Table 3.4 by using ambient temperature.

Hot spot factor (H) is calculated from Equation 3.3 by using rated hot-spot temperature rise over top oil temperature which is given in Table 3.5 and gradient which is calculated according to in Table 3.10.

Rated oil temperature time constant ($\tau_{oil,rated}$) is calculated from Equation 2.3. Winding time constants for both high voltage and low voltage windings for IEEE model, are taken as 5 minutes as per recommendation of the standard [6]. Winding time constants for IEC and Susa's models arecalculated according to equation which is given in section 2.2.3 , Equation 2.19.

Constants required for IEC thermal model is indicated as $k_{11,}$ k_{12}, k_{22}, x and y as already explained in Section 2.2. k_{11} value is determined by realizing optimization as described in Equation 2.13 and 2.14. Optimization is realized by minimizing function which is given in Equation 2.14. Other constants are taken from IEC 60076-7 recommendations which are given in Table 2.1.

Constants for IEEE C57.91-1995 method which are shown as n_{IEEE} and m in Table 3.11 are taken from recomandations of this standard[6].

Weight data of transformer's various parts are obtained from manufacturer. These data is indicated as M_{ap}, M_{wdn}, $M_{tank}$and M_{oil} in Table 3.11 .

Initial temperatures for top oil ($\theta_{oil,i}$), bottom oil ($\theta_{bo,i}$) and hot spot temperatures for both high voltage and low voltage windings ($\theta_{hs,i}$)are taken from measurement records of Test 2 which is varying load test. Initial temperatures of hottest spots and top oil were not same with ambient temperature. These temperatures were slightly higher because of the, effect of previous temperature rise test.

All thermal models, are solved for same load cycle which is applied during Test 2 which is given in Table 3.2.

Exponential equations for IEC and IEEE method which are given and explained in Section 2.1 and Section 2.2 are solved for each interval and results are plotted in Figure 3.25 , Figure 3.26 and Figure 3.27.

Differential equations in D. Susa's method which are given and explainedin Section 2.3, are solved with fourth order Runge-Kutta method. Obtained results are plotted on Figure 3.25 , Figure 3.26 and Figure 3.27.

3.3 Comparison Of Measured Values With Results Of Thermal Models

Results obtained by thermal models in Section 3.2 are compared in this part. Both top-oil temperatures and hot-spot temperatures for high voltage and low voltage windings are determined with thermal models. These calculated values are plotted and compared with measured values.Identificaiton of methods on graphs are as following:

“Measurement” refers to results measured during test 2 (varying load test), “IEEE Method” refers to the model which is given in Section 2.1, “IEC Method” refers to the model , which is given in Section 2.2“TM” refers to the model, which is given in Section 2.3

In Figure 3.25, top oil temperature values which are measured and calculated with thermal models are given. It is observed that IEEE method give slightly higher results, IEC method give slightly lower results and D.Susa thermal model give more accurate results compared to measured values.

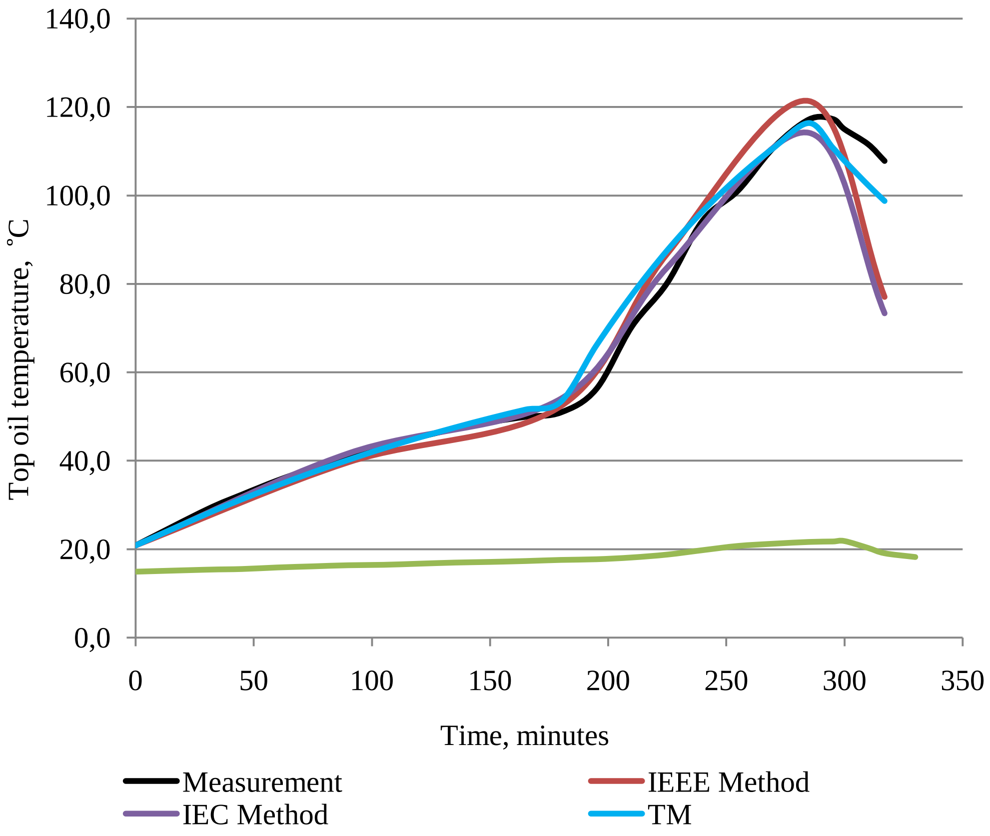

Figure 3.25 : Top oil temperature for varying load test

In Figure 3.26, hot-spot temperatures for low voltage winding’s are plotted. In Figure 3.26, both measured and calculated with thermal models are given. It is observed that IEEE method give significantly higher results, IEC method give slightly lower results and D. Susa thermal model gives more accurate results compared to measured values. On the other hand D. Susa method, does not give accurate results in first minutes of load step change which shows winding time constant is not defined correctly.

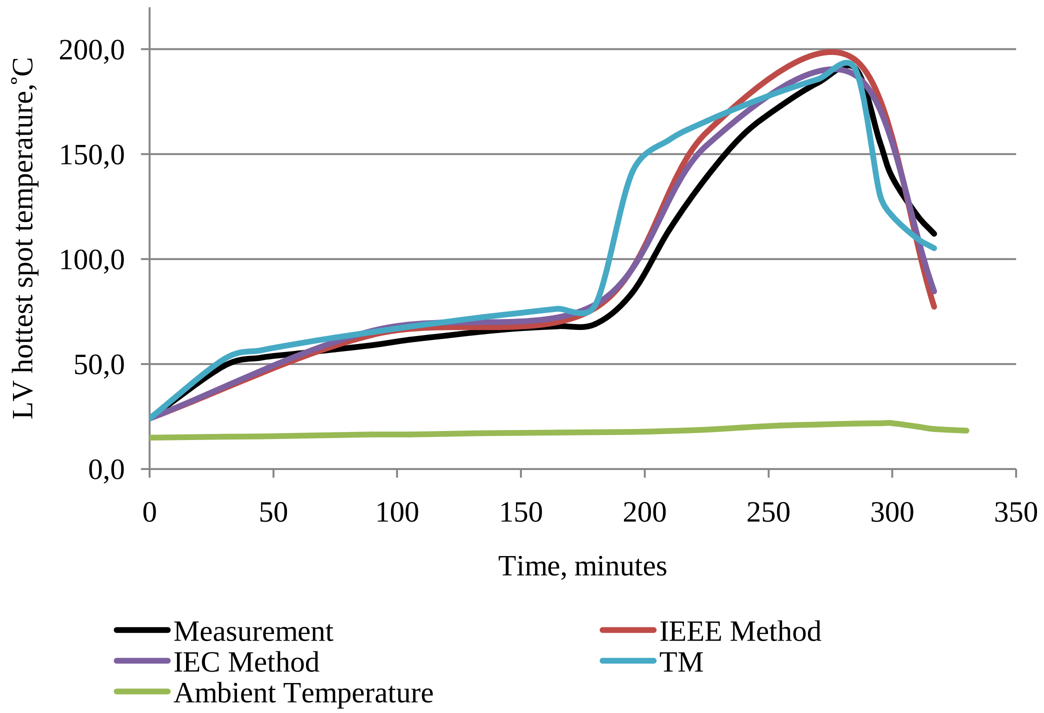

Figure 3.26 : LV hot-spot temperature for varying load test

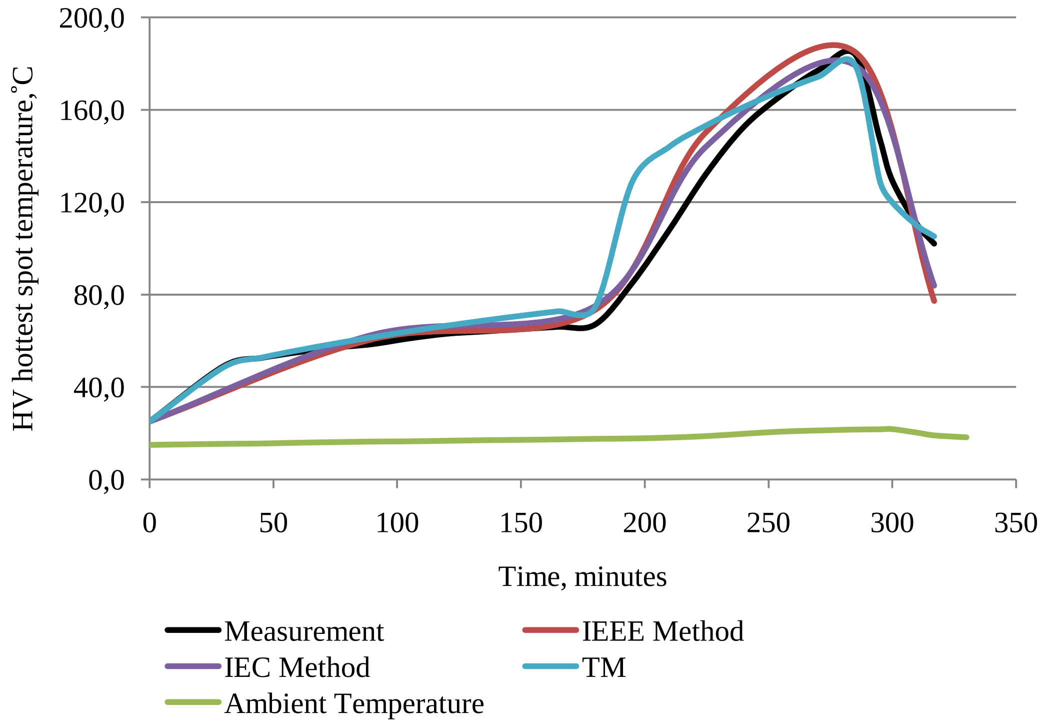

Figure 3.27 : HV hot-spot temperature for varying load test

In Figure 3.27, hot spot temperature values for high voltage winding which are measured and calculated with thermal models are given. It is observed that differences between measured values and calculated values are very similar to differences for low voltage winding which is shown in Figure 3.26. It is noticed that IEEE method give significantly higher results and IEC method gives slightly lower results. D. Susa method gives accurate results especially for the hottest temperature.

4. CONCLUSIONS

Distribution transformers are one of the most important equipmentsin electrical distribution systems. Operation of transformer with higher temperatures, which is why they are designed for, causes increase in aging rate. An aging transformer, could fail before economical life time, this will obviously cause additional costs. The common reason of failures in this case, is insulation material deformations on layer insulations and also turn to turn insulations.

In the industry two basic thermal models are widely used which are proposed by IEC and IEEE. These two models uses exponentials formulas and neglects the affect of viscosity change with oil temperature change. Thermal model which is developed by Dejan Susa, takes into account the oil viscosity changes and loss variations with temperature changes. In addition to oil viscosity and loss variations, it also takes into account the change on time constants.

In this study, average winding to average oil gradients which are calculated according to different methods were compared with each other. It is observed that , IEC method gives very similar results with well established calculations methods. On the other hand, IEEE method, gives significantly higher values compared to well-established calculation methods.

For top oil temperature, three different models' results are compared with measured values. In all models, proper rated oil time temperature rise values are used which were obtained during temperature rise tests with well-established methods. Also affects of ambient temperature changes are adapted on all thermal models. Therefore it is noticed that, all three methods supplied similar results to measured values. Thermal model which is developed by D. Susa, gave the best result for all load cycles except slight difference on cooling down condition. It is observed that values calculated according to IEEE method , are considerably higher from measured values and for IEC method , it is just the opposite and calculated values are considerably lower than measured values.

For hot-spot temperature, three different models' results are compared with the measured values for both high voltage and low voltage windings. As in top oil model, in hot-spot model also, proper rated winding hot-spot temperature rise values are used. It is observed that the values obtained from IEEE method are slightly higher than the measured values and the values obtained from IEC method are slightly lower than measured values. According to results obtained from thermal model which developed by D. Susa, highest hottest-spot temperature is calculated very accurately compared to measured data. On the other hand, a significant difference is noticed during first minutes of step load change. This has shown that winding time constant for this transformer is not defined properly.

According to temperature rise tests, it is observed that, highest winding temperature was occurred in B phase which is located in the mid of active part.

It is observed that, results are very dependent on accurate input data for defined rated load parameters like rated temperature rise values and rated top-oil time constants.

Considering the difficulty of defining, winding time constant with temperature rise tests, further research and development is needed to improved defining the winding time constant for distribution transformers.

Distribution transformers which are feeding non-sinusoidal loads are continuously increasing in the industry. Hot-spot temperature rises are highly affected with the affect of harmonic contents. Considering IEEE C57-110-98 standard is conservative and does not consider real load cycle, further research and developments are needed for ONAN cooled transformers which are without external cooling that areloaded with harmonic contents. This has been left as a further research activity.

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APPENDICES

APPENDIX A: Test Equipment DataAnd Photos

APPENDIX A

In this appendix part, data of measurement devices are given. During this study, mainly following devices are used; thermocouples, temperature monitoring and recording devices, winding resistance measurement device. In this section datasheets for temperature monitoring and recording devices are given in Figure A.1, Figure A.3, and Figure A.4. In addition to this, in Figure A.2, Figure A.5, Figure A.6 , Figure A.7, Figure A.8 and Figure A.9, photos of the test devices which are used in this study are shown.

Figure A.1 : Temperature monitoring and recording device

Table A.1 : Technical datasheet for temperature monitoring and recording devices

Technical data

Analog inputs

Input for DC voltage, DC current

Basic range	Accuracy	Input resistance
-20 to +70mV -3 to +105mV -10 to +210mV -0.5 to +12V -0.05 to +1.2V -1.2 to +1.2V -10 to +12V	±80µV ±100µV ±240µV ±6mV ±1mV ±2mV ±12mV	$R_{IN} \geq 1$ MΩ $R_{IN} \geq 1$ MΩ $R_{IN} \geq 1$ MΩ $R_{IN} \geq 470$ kΩ $R_{IN} \geq 470$ kΩ $R_{IN} \geq 470$ kΩ $R_{IN} \geq 470$ kΩ
Shortest span	5mV	
Range start/end	freely programmable within the limits in 0.01 mV steps	
-2 to +22mA -22 to +22mA	±20µA ±44µA	burden voltage ≤ 1V burden voltage ≤ 1V
Shortest span	0.5mA	
Range start/end	freely programmable within the limits in 0.01 mA steps	
Overrange / underrange	according to NAMUR NE 43	
Sampling cycle	3 or 6 channels 250msec	
Input filter	2nd order digital filter; filter constant adjustable from 0 to 10.0sec	
Test voltage for electrical isolation	350V (via optocoupler)	
Resolution	>14 bit	

Thermocouple

Designation	Type	Standard	Meas. range	Accuracy[1]
Fe-Con	L	DIN 43 710	-200 to +900°C	±0.1%
Fe-Con	J	EN 60 584	-210 to +1200°C	±0.1% from -100°C
Cu-Con	U	DIN 43 710	-200 to +600°C	±0.1% from -150°C
Cu-Con	T	EN 60 584	-270 to +400°C	±0.15% from -150°C
NiCr-Ni	K	EN 60 584	-270 to +1372°C	±0.1% from -80°C
NiCr-Con	E	EN 60 584	-270 to +1000°C	±0.1% from -80°C
NiCrSi-NiSi	N	EN 60 584	-270 to +1300°C	±0.1% from -80°C
Pt10Rh-Pt	S	EN 60 584	-50 to +1768°C	±0.15% from 0°C
Pt13Rh-Pt	R	EN 60 584	-50 to +1768°C	±0.15% from 0°C
Pt30Rh-Pt6Rh	B	EN 60 584	0 to 1820°C	±0.15% from 400°C
W3Re/W25Re	D		0 to 2400°C	±0.15% from 500°C
W5Re/W26Re	C		0 to 2320°C	±0.15% from 500°C
Chromel-Copel		GOST R 8.585-2001	-200 to +800°C	±0.1%
Shortest span			Type L, J, U, T, K, E, N, chromel-copel: Type S, R, B, D, C:	100°C 500°C
Range start/end			freely programmable within the limits, in 0.1°C steps	
Cold junction			Pt100 internal or thermostat external constant	
Cold junction accuracy (internal)			± 1°C	
Cold junction temperature (external)			-50 to +150°C, adjustable	
Sampling cycle			3 or 6 channels, 250msec	
Input filter			2nd order digital filter; filter constant adjustable from 0 to 10.0sec	
Test voltage for electrical isolation			350V (via optocoupler)	
Resolution			>14 bit	
Special features			also programmable in °F	

[1] The accuracy refers to the maximum measuring range. The accuracy is reduced with short spans.

Table A.2 : Technical datasheet of temperature monitoring device

DESCRIPTION

The Temperature Relay TR-42 has been designed for continuous monitoring of the temperature, the cooling fan's control and overheat protection for resin or air insulated three-phase transformers.

Thermal detectors PT100 DIN 43760, three of them located inside the transformer coils and the fourth at the core, detect the temperature.

The TR-42 relay is microprocessor-based equipment designed to satisfy all control requirements and guarantee high reliability.

The TR-42 perform the following functions:

Measurement:

- Coils and core transformer temperatures, automatically each 5 sec or manually.
- Highest temperature indication and storage.

Signaling and programming:

- 7 segment display and led indication.
- Simplified programming through frontal push buttons.
- Display and non volatile storage of: alarm temperature, trip temperature, fan on, start and stop fan temperature, highest RTD temperature, baud rate of serial transmission, and assigned relay address.

Figure A.2 : Temperature monitoring and recording devices in varying load test.

Figure A.3 : Thermal camera

Table A.3 : CPC 100 winding resistance measurement test device datasheet

Resistance Measurement

4-wire measurement with 400 A DC output and 10 V DC input

Current	Resistance	Voltage	Accuracy (full scale)
400 A	10 µΩ	4 mV	Error < 0.70 %
400 A	100 µΩ	40 mV	Error < 0.55 %
400 A	1 mΩ	400 mV	Error < 0.50 %
400 A	10 mΩ	4 V	Error < 0.50 %

4-wire measurement with 6 A DC output and 10 V VDC input

Current	Resistance	Voltage	Accuracy (full scale)
6 A	100 mΩ	0.6 V	Error < 0.35 %
6 A	1 Ω	6 V	Error < 0.35 %
1A	10 Ω	10 V	Error < 0.25 %

2-wire measurement with 10 V VDC input

Current	Resistance	Voltage	Accuracy (full scale)
< 5 mA	100 Ω		Error < 0.60 %
< 5 mA	1 kΩ		Error < 0.51 %
< 5 mA	10 kΩ		Error < 0.50 %

Figure A.4 : CPC 100 winding resistance measurement test device view.

Figure A.5 : Test room while recording temperature reading during test 1

Figure A.6 : Tested transformer view from test laboratory during test

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