ÇUKUROVA UNIVERSITY
INSTITUTE OF NATURAL AND APPLIED SCIENCES

MSc THESIS

Gamze KILAGÖZ

PARAMETRIC DESIGN OF ELECTRICAL AND MECHANICAL STRUCTURE FOR A DISTRIBUTION TRANSFORMER

DEPARTMENT OF MECHANICAL ENGINEERING

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ABSTRACT

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PARAMETRIC DESIGN OF ELECTRICAL AND MECHANICAL STRUCTURE FOR A DISTRIBUTION TRANSFORMER

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INSTITUTE OF NATUREL AND APPLIED SCIENCES DEPARMENT OF MECHANICAL ENGINEERING

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Typically mechanical and electrical designs of distributed transformers are performed by using a 3D software packages. The parametric design modelling is used to create different variations of the same concept design. For this purpose, some special software settings and related features are used. These software features are 3D design program configurations, related i-logic features and visual basic encoding with Excel and some analysis programs.

In this study, a hermetic and oil expansion tank type distributed transformers with a power range between from 25 kVA to 4000 kVA is being parametrically designed and developed. Firstly, parameterization process is performed on the main concept model to make variants of the main model. In order to parameterize a mechanical model, it is necessary to clarify the characteristic parameters of the model and how these parameters should be varied to achieve the variants. Usually, the characteristic parameters are more than one and some of them have a specific range. Therefore, the point to be considered here is that they should be used and examined in such a way that they do not impair the flexibility of the model. Hence, it is necessary to define parameters correctly and add design rules in order to ensure to keep the final product keep within the standards. After drawing the model, all dimensions must be converted into mathematical formulas by using macros and VBA coding for automatically updating for each design case. After entering initial requirements and data analysis stage, firstly dimensions of electrical parts are to be calculated depending upon some rules and formulas.Then, the transformer is drawn in generally to give numerical dimensions on software. Afterwards, the parameters are assigned to each dimension by using Excel data sets. All parameters and rules can be formed easily before drawings just once all necessary details are defined in Excel data. Finally, different variants of the design can be generated automatically just by defining the relevant deign related critical parameters are defined.

Key Words : Parametric design, transformer, electrical power conversion, distribution transformer

ÖZ

YÜKSEKLİSANS TEZİ

DAĞITIM TRAFOLARI İÇİN ELEKTRİK VE MEKANİK YAPININ PARAMETRİK TASARIMI

Gamze KILAGÖZ

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Tipik olarak, dağıtım transformatörlerin mekanik ve elektrik tasarımları, bir 3D yazılım paketleri kullanılarak gerçekleştirilir. Parametrik tasarım modellemesi, aynı konsept tasarımın farklı varyasyonlarını oluşturmak için kullanılır. Bu amaçla bazı özel yazılım ayarları ve ilgili özellikler kullanılır. Bu yazılım özellikleri; 3D tasarım programı yapılandırmaları, ilgili i-mantık özellikleri ve Excel ile görsel temel kodlama ve bazı analiz programlarıdır.

Bu çalışmada, 25 kVA ile 4000 kVA güç aralığında hermetik ve yağlı genleşme tanklı tip dağıtılmış transformatörler parametrik olarak tasarlanmakta ve geliştirilmektedir. İlk olarak, ana modelin varyantlarını yapmak için ana konsept model üzerinde parametreleme işlemi gerçekleştirilir. Mekanik bir modeli parametreleştirmek için, modelin karakteristik parametrelerini ve varyantları elde etmek için bu parametrelerin nasıl değiştirileceğini açıklığa kavuşturmak gerekir. Genellikle karakteristik parametreler birden fazladır ve bazılarının belirli bir aralığı vardır. Bu nedenle burada dikkat edilmesi gereken nokta, modelin esnekliğini bozmayacak şekilde kullanılması ve incelenmesi gerektiğidir. Bu nedenle nihai ürünün standartlar dahilinde kalmasını sağlamak için parametrelerin doğru tanımlanması ve tasarım kurallarının eklenmesi gerekmektedir. Modeli çizdikten sonra, her bir tasarım durumu için otomatik güncelleme için tüm boyutlar makrolar ve VBA kodlaması kullanılarak matematiksel formüllere dönüştürülmelidir. İlk ihtiyaçlar ve veri analizi aşamasına girildikten sonra öncelikle bazı kural ve formüllere bağlı olarak elektriksel parçaların boyutları hesaplanacaktır. Ardından yazılım üzerinde sayısal boyutlar vermek için trafo genel olarak çizilir. Daha sonra Excel veri setleri kullanılarak her boyuta parametreler atanır. Tüm parametreler ve kurallar, Excel verilerinde gerekli tüm ayrıntılar tanımlandıktan sonra çizimlerden önce kolayca oluşturulabilir. Son olarak, tasarımın farklı varyantları, sadece ilgili tasarımla ilgili kritik parametrelerin tanımlanmasıyla otomatik olarak oluşturulabilir.

Anahtar Kelimeler : Parametrik tasarım, transformatör, elektriksel güç dönüşümü, dağıtım transformatörü,

EXTENDED ABSTRACT

Typically, mechanical and electrical designs of distributed transformers are performed by using a 3D software packages. The mechanical and electrical parts of distributed transformers are mainly designed in the 3D software packages. In this study, the task is achieved by using parametric design approach. These design parameters firstly described in Excel then the Excel is link provided to the 3D software package. The parametric design modelling is used to create different variations of design by using software program and coding. These software packages are Autodesk Inventor and its i-logic feature, visual basic encoding with Excel and some analysis packages. In this study, a hermetic and oil expansion tank type distributed transformers with a power range between from 25 kVA to 4000 kVA is being parametrically designed and developed.

One of these reasons why Autodesk Inventor is preferred to make parametric design is it's useful and easy of drawing interface. The I-logic feature of Autodesk Inventor allows easy parameterization of both drawing and mounting parts. In addition, I-logic makes easy to convert them to technical drawings in Autodesk Inventor. However, the parameterization process mentioned above is not the process of manually reordering in this study, but it is a process of returning to the desired variation more easily with coding.

Firstly, a transformer in general form is designed to give numerical dimensions on Inventor. Then the parameters are assigned to each dimension by using Excel. All parameters and rules must be formed before generating the drawings once the necessary data is provided in Excel. Then, these parametric rules and features are then introduced into Inventor by using i-logic environment and its tools. That's why the design is linked to the parameters that are defined in Excel and the design updates itself automatically when each parameter is changed.

In order to parameterize a general mechanical concept model, it is necessary to clarify the characteristic parameters of the model and also necessary to set up how these parameters should be varied. Usually, the characteristic parameters are more than one and some of them have a specific range. Therefore, the point to be considered here is that they should be used and examined in such a way that they do not impair the flexibility of the model. Hence, it is necessary to define parameters correctly and add design rules in order to ensure to keep the final product keep within the standards. After drawing the model, all dimensions must be converted into mathematical formulas by using macros and VBA coding for automatically updating for each design case. After entering initial requirements and data analysis stage, firstly dimensions of electrical parts are to be calculated depending upon some rules and formulas. Then dimensions of mechanical parts are calculated depending on electrical jump distances, mechanical strength of material that we choose based on required quality, additional customer request, working conditions of transformer in Excel. Firstly, the working conditions, power, input and output voltages are to be defined. Then the electrical design based on desired quality and losses are to be made. After the completion of the electrical design stage, the mechanical design is performed with electrical safety distance considerations.

Initial required data is as follows:

- Working conditions (place, temperature, altitude, using aim)
- Required power
- Required quality (low, medium, high)
- Transformer losses

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NOMENCLATURE

CRGO	: Cold Rolled Grain Oriented
LV	: Low Voltage
HV	: High Voltage
AN	: Air Natural
ON	: Oil Natural
Hz	: Frequency
Φ_m	: Magnetic Flux
e1	: Induced Voltage
N	: Number of Turns
V	: Voltage Source
Φ_{mp}	: Magnetic Flux Peak Value
I	: Current
N	: Turn Ratio
a	: Sectional Area
Q	: Apparent Power
A_i	: Sectional Area of Core
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

δ : Permissible Current Density

f : Frequency

$\emptyset_m$: Maximum Flux in the Core

r : Controlling Factor

Ψ_1 : Flux Linkage of Primary Winding

Ψ_2 : Flux Linkage of Primary Winding

K_i : Stacking Factor

E_t : Volt / Turn

K : Constant Value Depend on Step Number

n : Number of Steps

b : Main step thickness

A_w : Window Area

W_w : Width of Window

L : Height of Window

A_y : Yoke Area

D_y : Depth of Yoke

h_y : Height of Yoke

W : Width of the Core

h : Height of the Core

I_c : Core Loss Component of No-Load Current

I_0 : No Load Current

p_y : Specific Iron Loss

p_i : Total Iron Loss

$I_{m,peak}$: Peak Value of the Magnetizing Current

$I_{m,RMS}$: RMS value of the magnetizing current

Cos $\emptyset_0$: No Load Power Factor

L_{mt}	: Length of Mean Turn
$R_{1,dc,75}$	: Resistance of Primary Winding
$R_{2,dc,75}$	: Resistance of Secondary Winding
R_{01}	: Total Copper Loss
M_X	: MMF at Distance x
W_t	: Width of Transformer
W_t	: Width of Transformer
D_e	: External Diameter of HV Winding
b	: Clearance Width
l_t	: Depth of Transformer (Tank)
a	: Clearance Depth
W_t	: Width of Transformer
H_t	: Height of Transformer
h	: Clearance Height
S_t	: Surface Area of Tank
θ	: Temperature Rise of Oil
A_t	: Surface Area of One Cooling Tube
W_i	: Weight of Iron Core
W_c	: Weight of Copper in Windings
CU	: Copper
AL	: Aluminum
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
Υ_{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
Υ_{fe}	: Iron Specific Weight Constant
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
ξ_2	: Loss Factor
p_{10}	: Additional Loss Factor of the Core
G_{total}	: Total Weight of the Transformer
η	: Efficiency
∵	: Because

1. INTRODUCTION

The transformers are especially used to transmission and distribution of electrical energy in energy industry. There are dozens of transformers manufacturers' brands and different types of transformers are available in the sector of the energy industry. When considering that each customer has unique electrical and mechanical design, weight, dimension and cooling system request and each of which has at least two type (hermetic or oil immersed), different types and configurations of transformers needed are available that causes lots of designs in the sector. The transformers manufacturers usually deal with different requirements and designs for each customer. The high diversity of different transformers designs should be executed with minimum design time and effort due to high pressures on the cost, competition and ever increase in demands on urgent supplies coming from customers to manufacturers. This requirement on urgent supplies can be supplied more quickly and efficiently if the design is carried out using computer aided design of transformer based on variable parametric design and assembly methodology.

A transformer is a static or passive electromagnetic device that alternates AC electric power at one voltage level to another AC voltage level through the effect of a magnetic field without any changing in frequency. Hence, the transformers are electrical devices that alternate or convert voltage levels between two independent circuits. A typical transformer consists of two or more coils of wire wrapped around a common ferromagnetic iron core. Typical distribution transformer supplies include laminated iron core. Laminations can be important as they help prevent eddy currents flowing in the core that cause loss of efficiency. The maximum output current is specified at the point where the core is saturated, or the windings current rating is exceeded. Transformer coils are (usually) not directly connected each other. The only connection between the coils is the common magnetic flux present within the iron core (Chapman, 2005). The current values are also converted in the process; however, the power transferred between two independent circuits does not change, except for a typically small loss that occurs in the process. This power only alternating current (AC) power occurs in the transmission or takes place under temporary power conditions.

As it said before, the transformers are static devices that transfer or alternate electrical energy from one electrical circuit to another through electromagnetic induction without changing the frequency. Transformers, which are in the machine group that do not move between electrical machines, transmit most of the energy applied to their inputs to the output side as electrical energy without changing its quality. In other words, there is no energy conversion in transformers. Transformers are used in AC (Alternating Current) circuits, not DC (Direct Current) circuits.

They are generally used for purposes such as increasing and decreasing current and voltage in an electrical circuit, transferring and distribution of electrical energy. It is a tool for universal use of alternating current system in the distribution and transmission of electrical energy.

The basic working principle of transformers was discovered by Michael Faraday in 1831 (Chapman, 2005). Faraday wrapped two insulating wires around the iron ring and connected the ends of one of the windings to a powerful battery and the ends of the other to the galvanometer used to detect electric current. Faraday observed that whenever the battery was switched on or off, the galvanometer flickered slightly, that is, an instantaneous current was induced through the second winding. It also revealed that the current in the second winding is induced only if the current in the first winding changes. This phenomenon determined by Faraday is the main principle on which all transformers are based on. This phenomenon called electromagnetic induction can be explained as follows; when the battery is switched on, a magnetic field occurs around the first winding and this field affects the second winding as well. If there is a wire near this changing magnetic field, this change causes an electric current to flow through the wire. This is why an electric current is generated in the first winding. Just like this, when a coil of the transformer is connected to an alternating current source, rapid direction changes in current create a continuously variable magnetic field and thus a variable voltage between the ends of the second coil. When a variable magnetic flux is connected to a circuit, a voltage or electromotive force (EMF) was induced in the circuit. The induced voltage is proportional to the number of turns associated with the varying flux. Figure 1. 1 shows two circuits with different connected turns and connected by a common flux of an iron core, so different voltages will be induced. One of the transformer windings is connected to an AC electrical power source or input voltage, and the second transformer windings provide electrical power to the loads. The transformer winding connected to the power supply or input voltage is called the primary winding or input winding, and the winding connected to the loads is called the second winding or output winding. If there is a third winding in the transformer, it is called a tertiary winding. Connected turns N1 and N2 are different each other so the induced voltages V1 and V2 will be different. The inductors-like devices that Faraday invented were little more than laboratory curiosity until the advent of AC electrical systems for power distribution in the late nineteenth century.

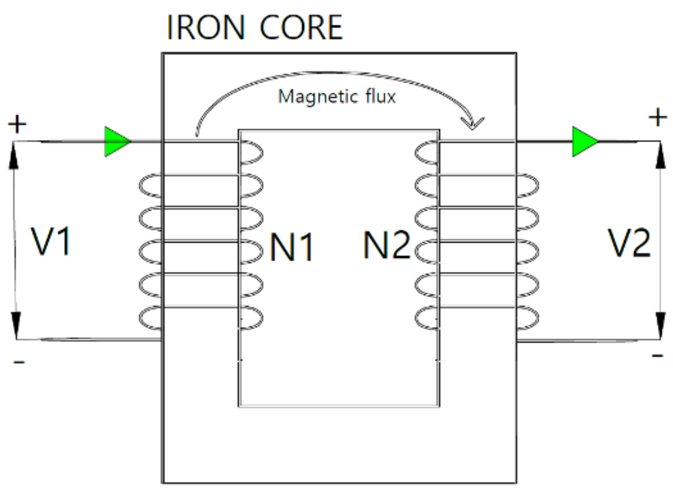


Figure 1.1. Transformer working principle for two circuits connected by a common changing flux.

The Michael Faraday's device that enabled Michael Faraday to invent electromagnetic induction involving two independent windings and a closed iron core, the most basic elements of transformers, was made in 1831. However, 54 years passed before transformers and transformer power distribution systems in use were seen. During this half century, high current transformers and various similar induction devices were made, but they were different in construction and operating methods. Based on these differences, the transformer should be regarded as an independent invention.

Faraday's work was the inspiration for the Danish physicist Hans Cristan Oersted, who had shown in 1820 that electric current flowing through a conductor creates a magnetic field around the conductor (Robert M. Del Vecchio, 2010). Oersted's discovery was crucial for that time. Because until this event, electricity and magnetism were known as unrelated forces. If the electric current could generate a magnetic field, a magnetic field could also produce an electric current. Edison proved that with the electrical system he built in New York in 1882, the wide-field power supply could only occur with a continuous voltage grid, parallel connection and regulation of its devices. He also proved that those large areas can only be provided with high voltage AC and transformer distributions.

The operation of the transformer is based on the principle of induction, which was discovered by Faraday in 1831 (Chapman, 2005). He found that when a variable magnetic flux is connected to a circuit, a voltage or electromotive force (EMF) was induced in the circuit. The induced voltage is proportional to the number of turns associated with the varying flux.

The first useful and practical modern transformer designed by William Stanley in 1885. The core is made up of individual laminated metal sheets. This transformer is shown in Figure 1.2.

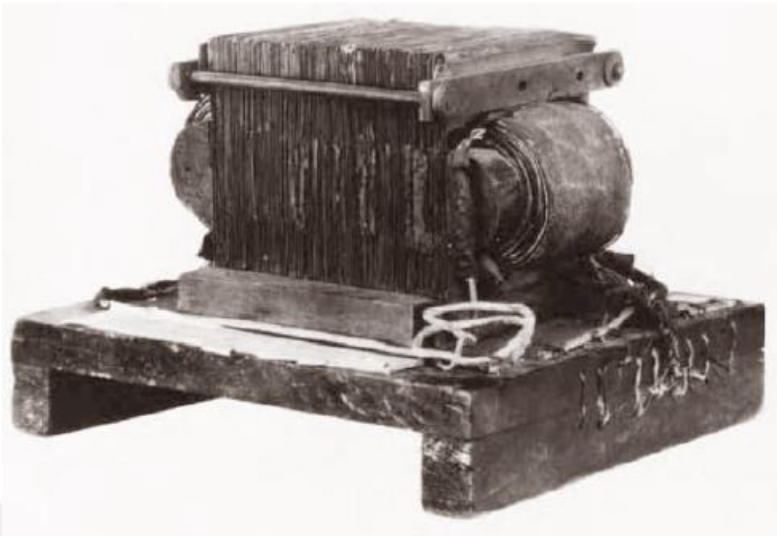


Figure 1.2. The first practical modern transformer made by William Stanley in 1885. Courtesy of General Electric Company (Chapman, 2005).

Development of transformers and AC power systems was carried out in almost the same period, as they were closely connected to each other. Hungarian engineers Karoly Zipernowsky, Otto Blathy and Miksa Deri, working at the Hungarian Ganz factory, invented the first practical transformer in 1885 (Jeszenszky, 1996). This transformer, initially used to provide electrical had lighting, had a closed toroidal core made of iron wire, and its input or primary voltage was just a few kV' s and the output or secondary voltage was about 100 volts.

Although the transformers used today are significantly different from these older models, the basic working principle is still the same. There are many transformers used in the electronics industry, as well as transformers used in power systems ranging in size from small units installed on top of telephone poles to units that are small in size to a house and weigh hundreds of tons.

In real, long-distance power transmission and distribution are carried out up to 100-500 kV voltages, and more recently even up to 1000 kV. But using these high voltages is dangerous for home appliances or factories. Therefore, for safer usage transformers are required to convert these high voltages to lower levels at the receiving end. In addition, generators are used to generate electric power at voltage levels of ~ 10-40 kV for more useful and practical advantages such as less cost and higher efficiency. Therefore, transformers are also required at the sending end of the line to raise the generator voltage to the required transmission levels. Figure 1.3 shows a simplified schematic drawing of a power transmission and distribution system in which actual voltages. Modern power systems usually have multiple voltage drops from each transmission line to final distribution, and a transformer is required with each voltage drop.

As mentioned before, in practice, long-distance power transmission is carried out with voltages up to 100-500 kV and more recently 1000 kV. Before the invention of transformers, in the early days of the electrical industry, power was distributed through direct current (DC) at low voltages. Voltage drops in power lines limited electricity use only to urban areas where consumers were served using small-length distribution circuits. All electrical equipment had to be designed for the same voltage.

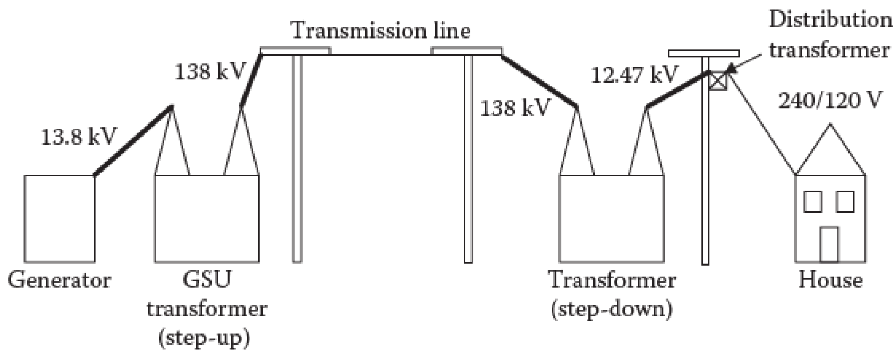


Figure 1.3. Schematic drawing of a power system. GSU stands for generator step-up transformer (Robert M. Del Vecchio, 2010).

The development of the first transformer around 1885 significantly changed the transmission and distribution systems. Power generated by alternating currents at low voltages can be increased to higher voltages (with lower currents) for transmission purposes, reducing voltage drops and transmission losses. The use of transformers made it possible to economically transmit electricity from generating stations to final consumer areas which are hundreds of kilometers away. The reducer or step-down transformers then lowered the voltage at the receiving stations to distribute power at various standardized voltage levels for use by final consumers. Transformers have made AC systems flexible because various parts and equipment of the power system can be operated at economical voltage levels with appropriate voltage ratios. The single line diagram of a typical power system is shown in Figure 1.4. Voltage levels are different in different countries. Transformers can generally be classified into several types, some based on location and wide function, others based on their applications:

1.1. Applications and Types of Transformers

1.1.1. Generator Transformers

Generator transformers are generally used in a generator station to increase voltage level (usually at a voltage in the range of 11 to 25 kV) to a higher voltage levels (200, 220, 345, 400, 416 or higher kV) for transmission of electricity over long distances. The generator transformers are an essential and necessary parts of any power system. They usually designed have uniform loads with higher losses as the cost of power supply is the cheaper than the transformer at the generating station. Lower noise levels are generally not specified, because the generators are noisier than the transformers.

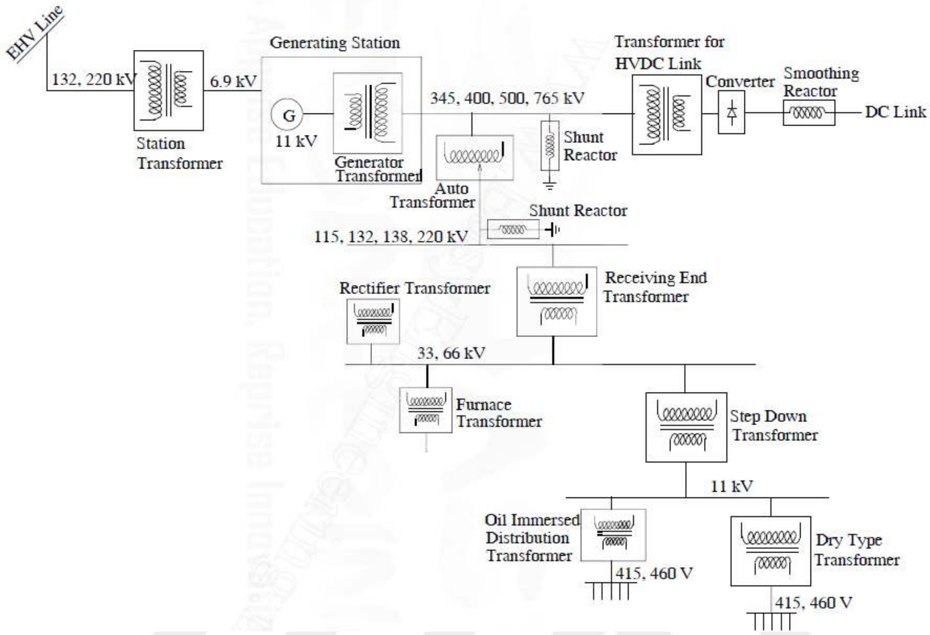


Figure 1.4. The single line diagram of a typical power system (S.V. Kulkarni, 2013).

1.1.2. Unit Auxiliary Transformers

If the voltage of the secondary winding is lower than the primary voltage, by other means voltage signal at the output is lower than the input voltage, these transformers are called step-down transformers. These step-down transformers are the most widely used transformer type. Their primary windings are directly connected to the generator output. The secondary voltage is 0,4 kV to power various auxiliary equipment at the power generation station in Turkey. Figure 1.5 shows a typical step-down transformer which is primary winding is higher than secondary winding so primary voltage is higher than secondary voltage at the same power and frequency.

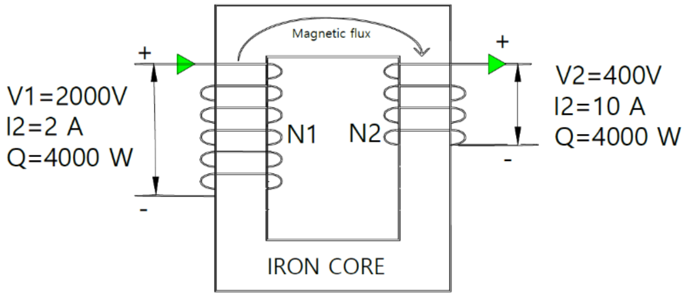


Figure 1.5. A typical step-down transformer.

1.1.3. Station Transformers

The purpose of these transformers is to power auxiliary equipment during the installation and maintenance process of generating stations and later during each start-up process. These transformers are small in value and their primary winding is connected to a high voltage transmission line. This may result in a smaller conductor size for the HV winding and requires special preventions to increase the short circuit strength. A split secondary winding arrangement is often used to achieve economical circuit breaker ratings.

1.1.4. Interconnected Transformers or Auto-Transformers

Transformers in which some or all of the primary winding is used as a secondary winding are called auto transformers. Normal transformers have two windings, primary and secondary, whereas in this type of transformers there is only one winding. This winding serves as both the primary winding and the secondary winding.

Since the voltage conversion is made over a single winding in transformers, a second winding is not required. Since the number of windings is reduced, the leakage reactance is also reduced.

Auto transformers can be voltage up and down. In this type of transformers, many connections are made to the outside to obtain different voltages. They are also used to obtain three-phase high voltages. Since a single winding is used to raise and lower the voltage, it takes up less space at small powers. Output voltage can be adjusted as desired. They heat less than normal transformers. Its efficiency is high and copper and iron losses are low.

On the other hand, it is difficult to connect auto transformers in parallel. In addition, while the leakage current is prevented by placing an insulating material between the primary and the secondary in a normal transformer, it is necessary to make different insulations to prevent leakage in the auto transformers.

These are also used to connect some 3-phase systems together running different system voltages (e.g., 400 kV and 220 kV, 345 kV and 138 kV). There is no electrical isolation between its primary and secondary windings; some volt-amps are converted as conductors and the rest are converted inductively. The design of an autotransformer becomes more cost-effective as the ratio of secondary winding voltage to primary winding voltage approaches unity. For example, 380KV Keban Energy Transmission Lines are connected to the 154 KV system via auto transformer.

1.1.5. Receiving Station Transformers

Receiving station transformers are used to reduce transmission or sub-transmission voltage to the primary usage level (e.g., 154 kV / 33 kV transformers). They are step-down transformers which are used directly to feed industrial plants. Distribution substations step down the voltage coming in from the transmission lines in order to begin the process of sending power to industrial plants. The loads on them vary over a wider range, and it is expensive for the generator to provide the power lost in them in the form of no-load and load loss. The farther the transformers are from the Power Generating Station, the higher the cost of providing losses.

1.1.6. Distribution Transformers (Oil immersed or Hermetically Sealed)

The main task of transformers is to make the electrical energy suitable for consumption or transportation by changing the current and voltage level according to the need. Distribution transformers, on the other hand, are devices that reduce the electrical energy transported to the consumption area to the current and voltage values suitable for the use of the consumer and offer them to the use of the end consumer. Distribution transformers reduce the voltage according to the needs of the end consumer (11 kV, 6.6 kV, 3.3 kV, 440 V, 220 V).

Distribution transformers are generally used in factories, hospitals, homes, etc. used in places. While places with high electricity consumption such as factories and hospitals have distribution transformers dedicated to their use, a distribution transformer can meet the electricity consumption of more than one house or business in places with relatively low electricity consumption such as home. In distribution transformers, if $S \leq 400$ kVA, the transformer is on the pole; $S > 400$ kVA is inside the transformer kiosk. Distribution transformers are generally step-down transformers.

Hermetic transformers are designed to be completely closed to the atmosphere. The internal pressure of the transformer is adjusted during oil filling using special equipment. When the transformer is loaded, it tolerates the volume expansion in the insulating liquid (oil), which is heated due to thermal effects, through the finned tank, which has an elastic structure (expands-shrinks) and also performs cooling function. Since ermetic transformers are completely oil-filled (no air) in the transformer, oil pressure is carried out in special vacuum chambers. Since it is closed to the atmosphere, the insulation oil does not contact with oxygen and insulation deterioration caused by oxidation is eliminated. Transformer life in terms of insulation; and therefore, the life of the transformer is extended.

It does not require any periodic maintenance except cleaning under normal conditions and use. Since there is no expansion tank, its height decreases dimensionally. This provides an advantage in areas where height is a problem.

Most important disadvantage is there is little possibility of on-site intervention, maintenance and repair. Whenever the hermetic pressure setting is broken or will be broken, hermetic pressure adjustment is required under vacuum with the necessary equipment. A typical hermetically sealed distribution transformer is shown in Figure 1.5.

Figure 1.6. Hermetically sealed distribution transformer

Transformers with expansion tanks are designed to be open to the atmosphere. It does not require any pressure adjustment. Only insulating oil level adjustment is required. The expansion tank tolerates the expansion of the insulating oil with the release and withdrawal of the air space inside to the atmosphere. The expansion tank is designed according to the maximum expansion of the insulating oil and while filling, the level is adjusted according to this expansion amount. Air exchange against moisture; It takes place through an air dryer that absorbs moisture and is replaced when moist.

A dangerous pressure will never be created inside the transformer. Therefore, there will be no pressure problems in overload. Deformation in metal will be less than there is no expansion. It has a more suitable structure for on-site maintenance and repair.

The most important disadvantage is that they have elements that require periodic control, testing, change and maintenance.

1.1.7. Phase Shift Transformers

Phase shift Transformers: these are used to control the flow of power on transmission lines by changing the phase angle between the input and output voltages of the transformer. With an appropriate step change, the output voltage can be made to direct or delay the input voltage. The total phase shift required directly affects the value and size of the transformer. At present, two different types of core structure are used; these are single-core design and two-core design. The single-core design is used for small phase shifts and lower MVA / voltage ratings, while the two-core design is used for bulk power transfer with higher phase shift transformer ratios. The design consists of two transformers, one associated with line terminals and the other with a stage changer.

1.1.8. Ground or Earthing Transformers

Ground Transformers: these are used to provide a neutral point in an ungrounded part of the grid (for example, delta-connected systems) that facilitates grounding and detection of ground failures. Its windings are often zigzag bound, which helps to eliminate third harmonic voltages in the lines. This type of transformer has the added advantage that they are not affected by the DC magnetization problems normally associated with power electronics converters.

1.1.9. Transformers for Rectifier and Inverter Circuits

They are special designed and manufactured transformers to eliminate harmonic effects. Because of high harmonic losses, the working flux density in the core is kept around 1,6 Tesla.

In order to reduce eddy losses, the winding conductor sizes need to smaller.

Thermal design aspects need to be carefully considered to eliminate hot spots (S.V. Kulkarni, 2013).

1.1.10. Furnace Duty Transformers

These transformers are used to power arc or induction furnaces characterized by low secondary voltage (80 to 1000 V) and high current (10 to 60 kA) depending on their MVA rating. In applications involving very high currents, the U-shaped copper pipes in the form of copper pipes with appropriate inner and outer diameters are designed to be cooled by oil / water circulation from the inside. In most cases, a step-up transformer is used in conjunction with the main transformer to de-rating the tap changer (S.V. Kulkarni, 2013).

The world's largest furnace transformers have been produced which is 300 MVA 34.5/1.683 to 1.119 kV in Gebze Turkey. It has been manufactured by Alstom Grid to Atakaş company. EAF (Electric Arc Furnace) furnace transformers used in the steel industry in the industry operate under very severe operating conditions. The 300 MVA EAF transformer has been designed, manufactured and tested to convert 300 tons of scrap iron into liquid steel at 1300 ° C in each cycle (35 minutes) and at the same time meet various conditions.

1.1.11. Outdoor and Indoor Transformers

Most of the transformers are suitable for outdoor operation and are designed to withstand atmospheric pollutants. The leakage distance of gate insulators is determined by pollution level. The higher the pollution level, the greater the leakage distance required between the live terminal and the soil. On the other hand, transformers for indoor applications are kept in a weatherproof and properly ventilated room. The standards define the minimum level of ventilation required for effective cooling. Sufficient openings should be left between the walls and the transformer to eliminate the possibility of higher noise levels due to reverberations. Figure 1.6 shows a typical outdoor oil immersed distribution transformer.

Figure 1.7. Oil immersed transformer for outdoor usege

1.1.12. Shunt Reactors

These are used to compensate for the capacitive volt-amperes generated during no-load or light-load conditions in high voltage transmission networks, thereby helping to maintain the voltage profile within desirable limits (S.V. Kulkarni, 2013).

Shunt reactors are inductive loads that compensate the capacitive power occurring in overhead lines. They can be connected to the overhead line, directly or with breakers. By generating inductive loads, they consume the capacitive reactive power generated by the line and provide balance. While capacitive loads in the network energize the network, the shunt reactor draws energy from the network; while capacitive loads draw energy, shunt reactors energize the network. In addition, they can be switched on and off with a breaker depending on the power situation in the network. They are also connected to the network in parallel.

Shunt reactors have a single winding. Winding resistances, eddy current and hysteresis losses are tried to be minimized with appropriate design methods. Generally, an iron core with an air gap is used. Iron core formed by combining thin layer, especially coated steel plates. Its windings are made of copper conductors, just like normal distribution transformers. Conductors are paper insulated. Generally, 5-leg core type shunt reactors are used. Thus, each of the 3 phases becomes magnetically independent. These are also called the enclosed type (shell type). A 3-legged core design is also available. In this type, magnetic bonding occurs between phases (core type).

1.2. Types of Transformers According to Core Structure

Although transformers are basically classified by their function in a power transmission and distribution system, they also have auxiliary classifications according to their core structure. This classification includes core-form and shell-form transformers. The main difference between core form and shell form transformers is shown in figure 1.7. In a core-shaped transformer, the coils are wound or stacked around the core, forming cylindrical-shaped coils. In general, high-voltage and low-voltage coils are co-wound with the low-voltage coil within the high-voltage coil. In shell-shaped design, the core is wound or stacked around the coils, usually called flat or oval-shaped and flat coils, high and low voltage windings are usually stacked side by side in multiple layers. in a changing style. Each of these types of structures has its advantages and disadvantages. Perhaps the ultimate distinction between the two is cost. In distribution transformers, shell form design is very popular because the core can be wrapped around the coils economically. For medium to large power transformers, core-shaped design is more common because short circuit forces can be better managed by cylindrical-shaped windings.

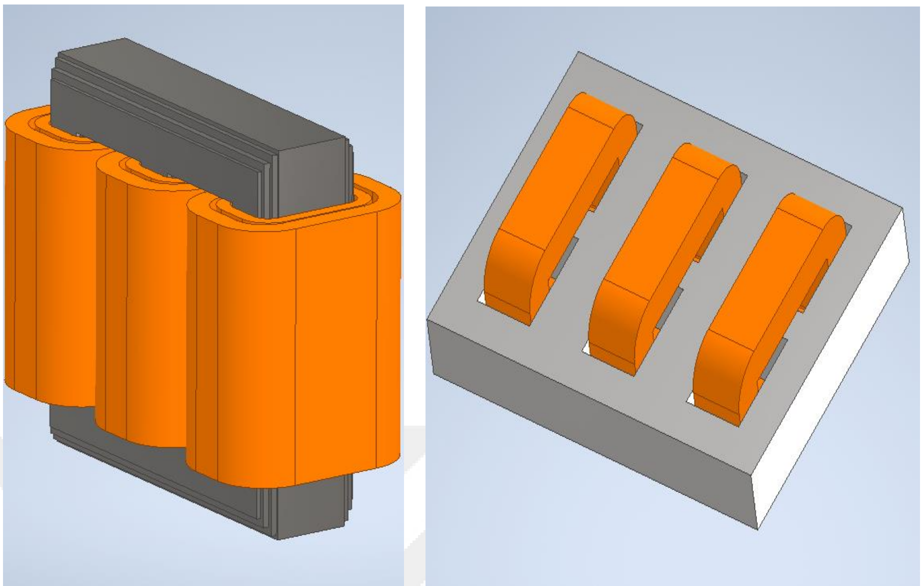


Figure 1.8. Three-phase core-form and shell-form transformers contrasted

1.3. Importance of Parametric Design in Transformer Production Industry

Today, computer technologies are used in every field of production. One of these areas is undoubtedly the design field and parametric design software offers a wide range of support to engineers and designers.

More than thirty years have passed since the design of the paper drawn on the paper with auto cad, but not only the design of the designers has become easier with the software, but also the parametric design software has become the most important tools of the engineers.

In addition to this, increasing production speed, globalizing world, developing technology and increasing foreign trade affect not only the finance departments of the companies but also the design and R&D departments. Firms want to achieve their prestige by having their competitors in their field and getting more customers. For this reason, R&D and design are gaining importance every day and many companies state that R&D units are the most important priorities in official media organs.

At this point, the concepts that we call time, efficiency and accuracy, which are going to compress designers, engineers and painters quite a bit. It is not enough to waste a design in 2 days. It is of great importance for the companies to make both the material list, the technical drawings and the engineering calculations of this design and to make thermal and mechanical analyzes on all of these and to include the visualization process.

It is now possible to make engineering calculations, extract material lists, reveal visual presentations and technical drawings and make some analyzes using parametric design with the aids of 3D design program and Excel visual basic coding in a few hours.

2. LITERATURE SURVEY

2.1 Parametric Design

In the past, the design process consisted entirely of creating a product by the hand of the designer, nowadays this process covers many different stages. After some calculations and drawings, creating a product has been replaced by computer-aided drawing and design software to create products with endless calculation and parameter modification.

Parametric design is one of the algorithmic thinking methods that direct the design depending on a number of variables, parameters and rules.. For example, a form is created by entering the dimensions and variables of the product to be designed in a computer software, when it is desired to make changes in the resulting form, the input parameters are changed, so there is an opportunity to make endless changes and corrections on the design. This way, infinite variations can be produced for a single product.

Thanks to the development of computer-aided design methods, it can be said that parametric design is not only a design method but creates a style of its own. Designs with perfect geometric forms and many layers have taken their place in the design world as a parametric design product. For example, architect Zaha Hadid, known as the designer of geometric patterns and demolished all patterns in design, is one of the pioneers of parametric design used in architecture. In addition, the term parametricism was first used by the architect Patrik Schumacher, who worked for Zaha Hadid.

In the classical design method when it needed to make a change or revise anything in the model, it is necessary to go back to the beginning of the design and remodel again. However, in parametric design, since all numbers, algorithms, methods are interchangeable values, so the desired change can be made at that value immediately. And this change is reflected simultaneously in the final design.

In short, it can be said that parametric design is not actually a design, but a design method that makes design and production more harmonious, more reliable, cheaper and diverse. Parametric design not only provides an optimum and fast geometry, but also enables us to obtain both beneficial and aesthetic options for achieving sustainable designs, especially in engineering and architecture. Therefore, parametric design is seen as the future of design understanding and is highly regarded. Sketchpad is the first parametric design system invented by Ivan Sutherland in 1963 (D.Davis, 2013). This program can be considered as an ancestor of today's modern computer aided design (CAD) programs and is generally considered an important advance in the development of computer graphics. Aish (Robert Aish, 2005) reports that it holds out hope that parametric modeling will reduce the time and effort required for change and reuse.

In parametric design, the geometric shape is modeled with parameters and rules that can be modified by designers. In addition, these parameters are associated with a set of rules. When the value of a parameter is changed (for example, to a length), this change is then applied to other parameters through this dialog and rules. In Computer-Aided Manufacturing (cam), or pro / engineer (Pro / E), CATIA and Autodesk Inventor, such as computer aided engineering (CAD) systems, the relationships between the parameters in 3D part model, assembly models, 2D drawing models, computerized numerical control (CNC) machining and finite element analysis models can also be defined (Zhao and Xue, 2010).

Today, modern 3D CAD speeds up the product development process, enabling efficient and relatively easy reuse and modification of existing models.

The algorithm, which can be defined as the set of steps required for the solution of a problem, and the algorithmic thinking formed accordingly, form the basis of the parametric design. In its most basic form, the parameter can be expressed as a quantity that can be defined and changed for a situation, and the situation containing this quantity as one or more can be perceived parametrically. The number of parameters may vary depending on the situation. The important thing is to establish the relationship between these parameters and to manage these parameters as desired.

Non-standard objects can be produced with this approach. What is meant by the non-standard object is a new paradigm based on the design and production of a series that is produced by mass production technologies, belongs to the same theme and formal language, but differs from each other with small distinctions by changing the parameter values, instead of the standardization paradigm based on the mass production of standard elements in design. diversity proposition.

In the parametric design process, determining and organizing the data that will affect the design as parameters is essential. A design strategy is established in which data is numerically and geometrically defined how it relates to other data, and the limitations are specified. Once such a relational model is established, all possible states can be investigated or derived by changing the parameter values.

Determining the parameters in parametric design guides the design and other possibilities of the established parametric model belonging to the same formal family are obtained by different values entered in the parameters.

The biggest difference and advantage of parametric design from traditional design processes is that the designer can quickly experience the final product in the virtual environment with a new design terminology consisting of parameters, algorithms and coding.

The fact that design geometry becomes easily calculable and can be applied with new tools in design disciplines can be described as not only a technology, but also a way of differentiating traditional geometry creation methods.

Parametric design can be regarded as a design process in which the concept of design is learned using simpler and traditional techniques such as folding extremely ordinary materials such as paper, not only using the computer as a tool.

2.2. Transformer Design

Transformer is AC static electromagnetic machine (as it has no moving part) which steps up or downs the voltage level in power system keeping power at constant levels and frequency remains unchanged.

It is based upon mutual induction between two coils. When current flows, there is magnetic field around the conductor. As magnetic current is due to changing current (AC) the -magnetic field is also alternating. It magnetizes the iron/steel core; voltage is induced in another coil. This is both sides are magnetically linked and no electrical connection between them, so it is also isolated the primary circuits and secondary circuits.

One side of transformer is called as primary side (which is input side) and other is known as secondary side (the output side). Both sides are consisted of just a coil wound on soft iron called as core of transformer. Both coils are magnetically linked, and power is transmitted from primary to secondary side magnetically and has no electrical connection between them. Soft iron (ferromagnetic material) core helps the transmission of magnetic flux with less losses.

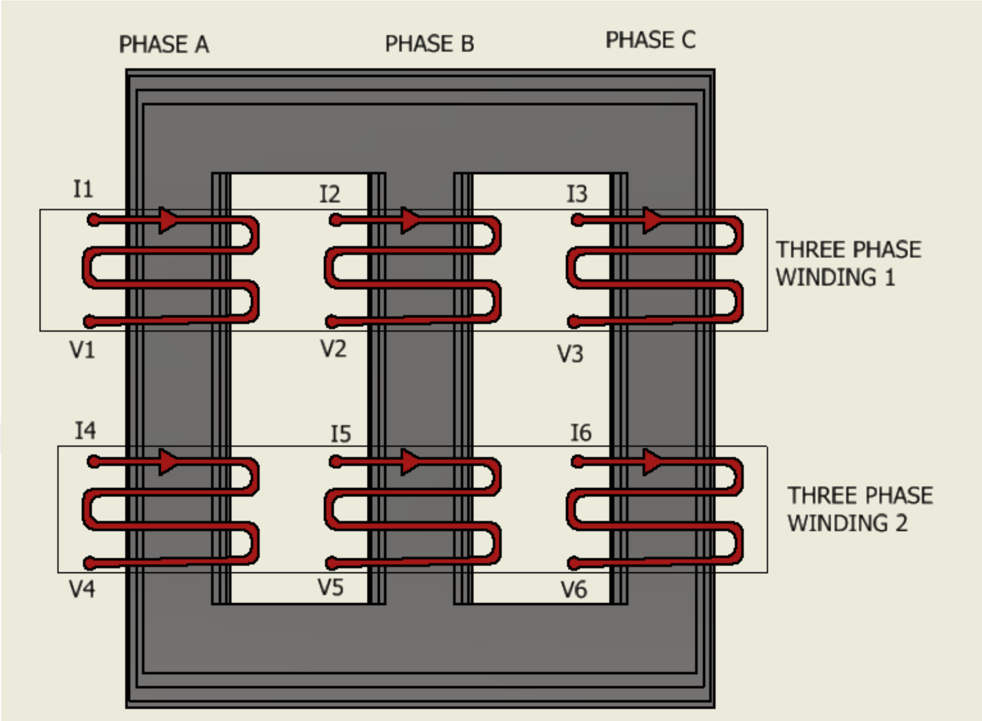


Figure 2.1. The transformer coil structure with three phases

A typical transformer consists of ten main elements. The list of these main system components is listed below.

I. Transformer core: consist of specially laminated Silicon allow metal sheets
II. Winding: cupper wires with isolation lamination
III. Insulation: the insulating material of the transformer
IV. Tank: consist of active part of transformer and cooling oil
V. Bushings and other accessories: LV bushings, HV bushings, thermometer, oil level indicator, hermetically protection relay etc.
VI. Dehydrating breather: used for transformer with oil conservator, contains silica gel, these silica gel keeps moisture inside, thus prevents the deterioration of the air inside the oil conservator.
VII. Oil conservator: containing additional oil to cool transformer

VIII. Buchholz Relay: transformers with oil conservator (oil reservoir) may have a gas detector relay (Buchholz relay) to detect air bubble or buildup of gas inside the transformer

IX. Tap changer: is a mechanism in transformers which adjusts turn ratios to be selected in discrete steps. Tap changers are often placed on the higher voltage winding side (lower current) for easy access and to minimize the current load during operation.

XI. Oil filling and oil drain valve: to fill and to drain oil into the transformer

XII. Lifting lugs: to lift transformer from safety place without damaging fins, active part and tank of transformer

XIII. Earthing terminals: provide grounding of leakage electricity

XIV. Fins: provide cooling of transformer from excessive heat generation

XV. Transformer oil: provide cooling of transformer from excessive heat generation

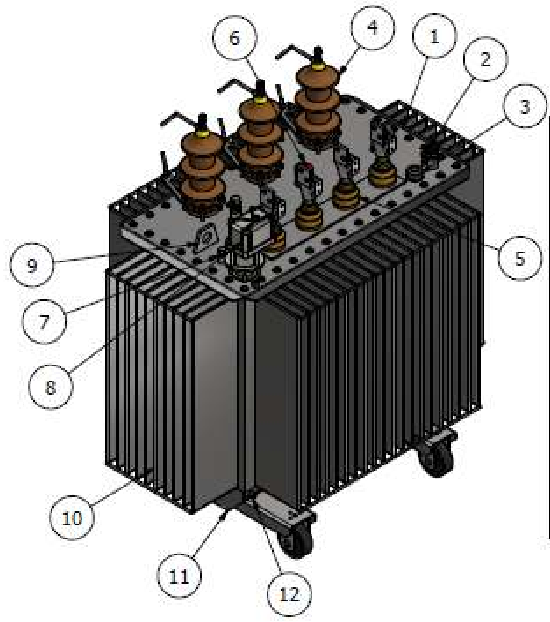


TABLE	
PART NUMBER	PART NAME
1	COVER OF TRANSFORMER
2	OIL FILLING PLUG
3	PRESSURE RELIEF VALVE
4	HV BUSHING
5	LV BUSHING
6	TAP CHANGER
7	THERMOMETER POCKET
8	HERMETIC PROTECTION RELAY
9	LIFTING LUGS
10	FINS
11	TANK OF TRANSFORMER
12	EARTING TERMINALS
13	OIL DRAIN VALVE

Figure 2.2. The picture of assembly of a transformer main body

A typical hermetic transformer (power ≥ 630 kVA) which is shown in Figure 2.2 consists of tank, fins, LV bushings, HV bushings, tap changer, oil filling valve, oil drain valve, pressure relief valve, thermometer, hermetic protection relay, lifting lugs.

Design of transformers basically achieved in three stages**;**

- Electrical design considerations
- Mechanical design considerations
- Thermal considerations

When to start to design a transformer, work stars with a designing an active part which contains bobbins and core. After determining the dimensions of the active part of the transformer, the dimensions of the tank parts are determined according to the electrical jump distances, mechanical strength of material, customer request, working conditions and losses.

2.2.1. Electrical Design

For electrical designing of active part of transformer, we need some design parameters and calculated parameters listed below;

- Power rating of transformer
- Voltage levels (primary and secondary)
- Currents on both sides
- Primary and secondary coils wire diameter/size
- Net iron core area
- Numbers of turns (primary and secondary)

Transformer must be designed to make one of the following quantity as minimum as possible for an optimum design;

- Total volume
- Total weight
- Total cost
- Total loss

All these quantities that are mentioned above vary with r ratio which is shown following equation 2.1.

$$r = \phi\mathrm{m}/AT. \quad (2.1)$$

If we choose high value of 'r' then flux will be high, so large cross section is required which will increase volume, weight and cost of iron and also give higher iron loss. Also, due to decrease in value of 'AT' the volume, weight and cost of copper decreased and also decrease in copper losses. Thus 'r' is a controlling factor for above mention quantities. Choice of flux density is important because the value of flux density in the core determines the core area. High value of flux density gives smaller core area, so saving in iron cost. Also, small core area provides reduced mean turn of winding which gives reduction in copper cost. But higher flux density on increase iron losses resulting high temperature rise. The value of flux density also depends upon service conditions of transformer. A distribution transformer design with low value of flux density to keep down the iron losses and increase in all day efficiency. (Y.C. Bose University of Science and Technology, 2019)

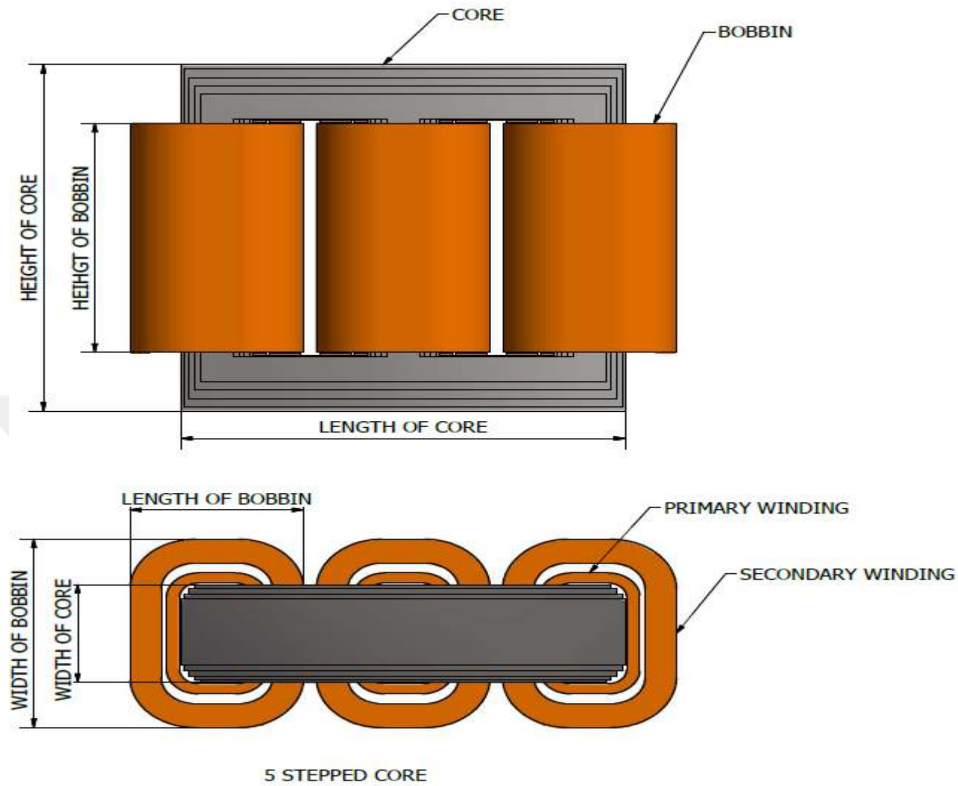


Figure 2.3. The transformer core and windings

Figure 2.3 shows active part of transformer which is consists of bobbins, core, primary and secondary windings.

For the design of a transformer, two important parameters must be considered, which are cost and efficiency. If these parameters can be provided at the best level, the optimal design of the transformer will be realized. In this section, the mathematical model of a 3-phase oil type transformer is given in detail.

The basic formulas, symbols, meanings and units used in transformer calculations are shown below, respectively.

Output equation gives the relationship between electrical rating and physical dimensions of machines.

Let,

V_1 = Primary or input voltage

V_2 = Secondary or output voltage

I_1 = Primary or input current

I_2 = Secondary or output current

N_1 = Primary number of turns

N_2 = Secondary number of turns

a_1 = Sectional area of LV conductors (m^2)

a_2 = Sectional area of HV conductors (m^2)

δ = Permissible current density (A/m^2)

Q = Rating in KVA

f = Frequency

Ø_m = Maximum flux in the core

$\because$ = Because

A_i = Sectional area of core

B_m = Maximum flux density in the core

We place first half of LV on one limb and rest half of LV on other limb to reduce leakage flux. So, arrangement is LV insulation then half LV turns then HV insulation and then half HV turns.

For 1-phase core type transformer rating is given by,

$$a_1 = I_1/\delta \tag{2.2}$$

$$a_2 = I_2/\delta \tag{2.3}$$

$$Q = V_1 * I_1 * 10^{-3}\text{KVA} \tag{2.4}$$

$$Q = (4.44 * f * \O_m * N_1) * I_1 * 10^{-3}\text{KVA} \quad (2,5)$$

$$Q = (4.44 * f * (A_i * B_m) * N_1) * I_1 * 10^{-3}\ \text{KVA} \quad (2.6)$$

$$K_w = \frac{Actual\ Cu\ Section\ Area\ of\ Windings\ in\ Window}{Window\ Area\ (A_w)} \quad (2.7)$$

$$K_w = \frac{(a_1 * N_1) + (a_2 * N_2)}{A_w} \quad (2.8)$$

$$K_w = \frac{\left(\left(\frac{I_1}{\delta}\right) * N_1\right) + ((I_2/\delta) * N_2)}{A_w} \left(\because a_1 = I_1/\delta \ \&\ a_2 = I_2/\delta \right) \quad (2.9)$$

$$K_w = \frac{(I_1 * N_1) + (I_2 * N_2)}{\delta * A_w} \quad (2.10)$$

$$K_w = \frac{2 * (I_1 * N_1)}{\delta * A_w} \quad (2.11)$$

For Ideal Transformer

$$(I_1 * N_1 = I_2 * N_2) \quad (2.12)$$

So,

$$N_1 * I_1 = \frac{\delta * K_w * A_w}{2} \quad (2.13)$$

Put an equation value of $N_1 * I_1$,form equation 2.12 to equation 2.13,

$$Q = 4.44 * f * A_i * B_m * \left(\frac{\delta * K_w * A_w}{2}\right) * 10^{-3}\text{KVA} \quad (2.14)$$

$$Q = 2.22 * f * A_i * B_m * \delta * K_w * A_w * 10^{-3}\text{KVA} \qquad (2.15)$$

For 1- phase shell type transformer

Window space factor can be found,

$$K_w = \frac{(a_1 * N_1) + (a_2 * N_2)}{A_w} \qquad (2.16)$$

$$K_w = \frac{((I_1/\delta) * N_1) + ((I_2/\delta) * N_2)}{A_w} \qquad (2.17)$$

$$K_w = \frac{(I_1 * N_1) + (I_2 * N_2)}{\delta * A_w} \qquad (2.18)$$

$$K_w = \frac{2 * (I_1 * N_1)}{\delta * A_w} \qquad (2.19)$$

For Ideal Transformer

$$(I_1 * N_1 = I_2 * N_2) \qquad (2.20)$$

So,

$$N_1 * I_1 = \frac{\delta * K_w * A_w}{2} \qquad (2.21)$$

Put equation value of $N_1 * I_1$ form equation (2.20) to equation (2.5)

$$Q = 4.44 * f * A_i * B_m * \left(\frac{\delta * K_w * A_w}{2}\right) * 10^{-3}\text{KVA} \qquad (2.22)$$

$$Q = 2.22 * f * A_i * B_m * \delta * K_w * A_w * 10^{-3}\text{KVA} \qquad (2.23)$$

This equation is same as for 1-phase core type transformer.

For 3-phase core type transformer

Rating is given by,

$$Q = 3 * V_1 * I_1 * 10^{-3}\text{KVA} \quad (2.24)$$

$$Q = 3 * (4.44 * f * \varnothing_m * N_1) * I_1 * 10^{-3}\text{KVA} \quad (2.25)$$

$$Q = 3 * (4.44 * f * (A_i * B_m) * N_1) * I_1 * 10^{-3}\text{KVA} \quad (2.26)$$

Window space factor,

$$K_w = \frac{Actual\ Cu\ Section\ Area\ of\ Windings\ in\ Window}{Window\ Area\ (A_w)} \quad (2.27)$$

$$K_w = \frac{2*[(a_1*N_1)+(a_2*N_2)]}{A_w} \quad (2.28)$$

$$K_w = \frac{2*[((I_1/\delta)*N_1)+((I_2/\delta)*N_2)]}{A_w} \quad (2.29)$$

$$K_w = \frac{2*[(I_1*N_1)+(I_2*N_2)]}{\delta*A_w} \quad (2.30)$$

$$K_w = \frac{2*[2*(I_1*N_1)]}{\delta*A_w} \quad (2.31)$$

For Ideal Transformer;

$$I_1 * N_1 = I_2 * N_2 \quad (2.32)$$

So,

$$N_1 * I_1 = \frac{\delta * K_w * A_w}{4} \quad (2.33)$$

Put equation value of $N_1 * I_1$ form equation (7) to equation (6),

$$Q = 3 * 4.44 * f * A_i * B_m * (\frac{\delta * K_w * A_w}{4}) * 10^{-3}\text{KVA} \quad (2.34)$$

$$Q = 3.33 * f * A_i * B_m * \delta * K_w * A_w * 10^{-3}\text{KVA} \quad (2.35)$$

For 3- phase shell type transformer

Window space factor,

$$K_w = \frac{(a_1 * N_1) + (a_2 * N_2)}{A_w} \quad (2.36)$$

$$K_w = \frac{((I_1/\delta) * N_1) + ((I_2/\delta) * N_2)}{A_w} (\because \quad a_1 = I_1/\delta \quad \& \quad a_2 = I_2/\delta) \quad (2.37)$$

$$K_w = \frac{(I_1 * N_1) + (I_2 * N_2)}{\delta * A_w} \quad (2.38)$$

$$K_w = \frac{2 * (I_1 * N_1)}{\delta * A_w} \quad (2.39)$$

For Ideal Transformer

$$I_1 * N_1 = I_2 * N_2 \quad (2.40)$$

So,

$$N_1 * I_1 = \frac{\delta * K_w * A_w}{2} \quad (2.41)$$

Put equation value of $N_1 * I_1$ form equation (2.39) to equation (2.36)

$$Q = 3 * 4.44 * f * A_i * B_m * \left(\frac{\delta * K_w * A_w}{2}\right) * 10^{-3}\text{KVA} \quad (2.42)$$

$$Q = 6.66 * f * A_i * B_m * \delta * K_w * A_w * 10^{-3}\text{KVA} \quad (2.43)$$

Choice of magnetic loading (B_m)

For normal Si-Steel (0.35 mm thickness, 1.5%—3.5% Si)-0.9 to1.1T

For HRGO (Hot Rolled Grain Oriented Si Steel)- 1.2 to 1.4 T

For CRGO (Cold Rolled Grain Oriented Si Steel, 0.14-0.28 mm thickness)-1.4 to 1.7 T

Choice of electric loading (δ)

This depends upon cooling method employed. There are 3 types of cooling: Naturel, forced and water cooling.

(1) Natural Cooling: 1.4-2.3 A/mm2

AN-Air Natural cooling.

ON-Oil Natural cooling.

OFN-Oil Forced circulated with natural air cooling.

(2) Forced Cooling: 2.3-4.0 A/mm2

AB-Air Blast cooling

OB-Oil Blast cooling

OFB-Oil Forced circulated with air blast cooling.

(3) Water Cooling: 4,5 -6.0 A/mm2

OW-Oil immersed with circulated water cooling.

OFW-Oil Forced with circulated water cooling.

EMF per turn

We know,

$$V_1 = 4.44 * f * \text{Ø}_m * N_1 \tag{2.44}$$

So, EMF / TURN

$$E_t = \frac{V_1}{N_1} = 4.44 * f * \text{Ø}_m \tag{2.45}$$

And,

$$Q = V_1 * I_1 * 10^{-3}\text{KVA} \tag{2.46}$$

$$Q = (4.44 * f * \text{Ø}_m * N_1) * I_1 * 10^{-3}\text{KVA} \tag{2.47}$$

$$Q = E_t * N_1 * I_1 * 10^{-3}\text{KVA} \tag{2.48}$$

Magnetic loading=Ø_m (2.49)

Electric loading=$N_1 * I_1$ (2.50)

So,

$$\frac{\text{Ø}_m}{N_1 * I_1} = constant(say\,''r'') \rightarrow N_1 * I_1 = \frac{\text{Ø}_m}{r} \text{ put in equation} \tag{2.51}$$

$$Q = E_t * \frac{\O_m}{r} * 10^{-3}\text{KVA} \quad (2.52)$$

Or,

$$Q = E_t * \frac{E_t}{4.44 * f * r} * 10^{-3}\text{KVA using equation} \quad (2.53)$$

$$E_t^{\,2} = (4.44 * f * r * 10^{-3}) * Q \quad (2.54)$$

Or,

$$E_t = K_t\sqrt{Q}\text{Volts/Turn} \quad (2.55)$$

Where;

$K_t = \sqrt{4.44 * f * r * 10^{-3}}$ is a constant and values are, $K_t = 0.6$ to 0.7 generally for 3-phase core type power transformer.

$K_t = 0.45$ for 3-phase core type distribution transformer

$K_t = 1.3$ for 3-phase shall type transformer

$K_t = 0.75$ to 0.85 for 1-phase core type transformer

$K_t = 1.0$ to 1.2 for 1-phase shall type transformer

Estimation of core x-sectional area A_i

We know,

$$E_t = K_t\sqrt{Q} \quad (2.56)$$

$$E_t = 4.44 * f * \O_m \quad (2.57)$$

Or,

$$E_t = 4.44 * f * A_i * B_m \quad (2.58)$$

So,

$$A_i = \frac{E_t}{4.44 * f * B_m} \quad (2.59)$$

Now the core may be following types,

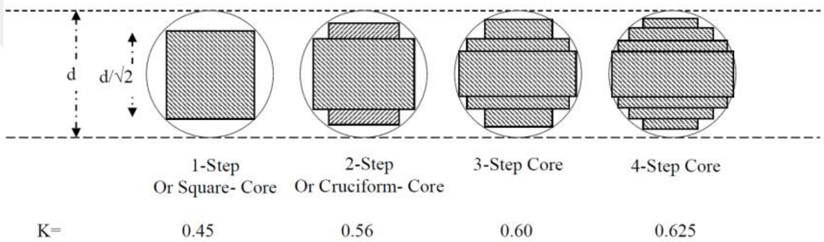


Figure 2.4. K factor depending on step number of core.

For Square core,

$$\text{Gross Area} = \frac{d}{\sqrt{2}} * \frac{d}{\sqrt{2}} = 0.5 * d^2 \quad (2.60)$$

Let stacking factor, $K_i = 0.9$, then Actual Iron Area can be found;

$$A_i = 0.9 * 0.5d^2 \quad (2.61)$$

$$A_i = 0.45 * d^2 \quad (2.62)$$

Constant 0.45 value is for square core and take ‘’K’’ as a general case.

$$A_i = K * d^2 \quad (2.63)$$

So,

$$A_i = K * d^2 \tag{2.64}$$

Or,

$$d = \sqrt{\frac{A_i}{K}} \tag{2.65}$$

Graphical method to calculate dimensions of the core

Consider 2 step core, which is shown in Figure 2.5.

$$\theta = \frac{90^{\circ}}{n+1} \tag{2.66}$$

n= No of steps, i.e. n =2

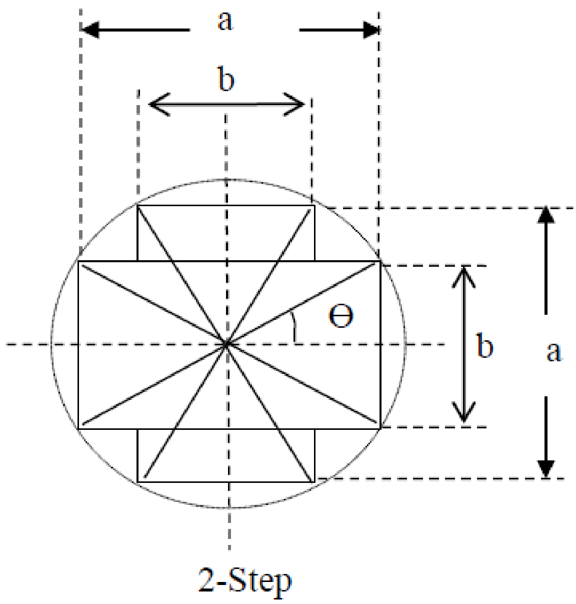


Figure 2.5. 2stepepd core

$$\theta = \frac{90^{\circ}}{2+1} = 30^{\circ} \quad (2.67)$$

So,

$$a = d * \cos\theta \quad (2.68)$$

$$b = d * \sin\theta \quad (2.69)$$

Table 2.1 shows percentage fill depending on number of steps.

$$Percantage\ fill = \frac{Gross\ Area\ of\ Stepped\ core}{Area\ of\ circumcircle} = \frac{(K*d^2)/K_i}{\frac{\pi*d^2}{4}} \quad (2.70)$$

$$\text{For 4 step core of transformer} = \frac{(0.625*d^2)/0.9}{\frac{\pi*d^2}{4}} 0.885\ \ or\ 88.5\% \quad (2.71)$$

Table 2.1. % Fill depending on number of steps.

Number of steps	**%Fiil**
1	**63,70%**
2	**79,20%**
3	**84,90%**
4	**88,50%**
5	**90,80%**
6	**92,30%**
7	**93,40%**
9	**94,80%**
11	**95,80%**

Estimation of main dimensions

$$Q = 3.33 * f * A_i * B_m * \delta * K_w * A_w * 10^{-3}\text{KVA} \quad (2.72)$$

So, Window area

$$A_w = \frac{Q}{3.33 * f * A_i * B_m * \delta * K_w * 10^{-3}} \; m^2 \quad (2.73)$$

Where,

K_w = Window space facto for up to 10 KVA;

$$K_w = \frac{8}{30 + HigherKV} \quad (2.74)$$

for up to 200 KVA;

$$K_w = \frac{10}{30 + HigherKV} \quad (275)$$

for up to 1000 KVA;

$$K_w = \frac{12}{30 + HigherKV} \quad (2.76)$$

For higher rating, $K_w = 0.15$ to 0.20 , assumed some suitable range for, $D =$ (1.7 to 2) d Width of the window,

$$W_w = D - d \quad (2.77)$$

Height of the window,

$$L = \frac{A_w}{width\ of\ window(W_w)} \tag{2.78}$$

Generally, $\frac{L}{W_w} = 2\ to\ 4$, Yoke area A_y is generally taken 10% to 15% higher then core section area (A_i) to reduce the iron loss in the yoke section. But if we increase the core section area (A_i) more copper will be needed in the windings and so more cost through we are reducing the iron loss in the core. Further length of the winding will increase resulting higher resistance so cause higher core loss.

$$A_y = (1.1 \text{ to } 1.15) * A_i \tag{2.79}$$

Depth of yoke,

$$D_y = a \tag{2.80}$$

Height of the yoke,

$$h_y = \frac{A_y}{D_y} \tag{2.81}$$

Width of the core,

$$W = (2 * D) + d \tag{2.82}$$

Height of the core,

$$h = L + (2 * h_y) \tag{2.83}$$

Flux density in yoke,

$$B_y = \frac{A_i}{A_y} * B_m \tag{2.84}$$

Estimation of core loss and core loss component of no-load current I_c,

$$\text{Volume of iron in core} = 3 * L * A_i m^2 \tag{2.85}$$

$$\text{Weight of iron in core} = density * volume \tag{2.86}$$

$$\text{Weight of iron in core} = \rho_i * 3 * L * A_i \text{Kg} \tag{2.87}$$

$$\rho_i = density\ of\ iron\ (\frac{kg}{m^3}) \tag{2.88}$$

For normal iron/steel ,

$$\rho_i = 7600\ (\frac{kg}{m^3}) \tag{2.89}$$

For M-4 steel,

$$\rho_i = 6500\ (\frac{kg}{m^3}) \tag{2.90}$$

From the graph we can find out specific iron loss, $p_i(\frac{Watt}{Kg})$ corresponding to flux density B_m in core.

So,

$$\text{Iron loss in core} = p_i * \rho_i * 3 * L * A_i \text{Watt} \tag{2.91}$$

Similarly,

Iron loss in yoke $= p_y * \rho_i * 2 * W * A_y$ Watt (2.92)

Where,

$$p_y = specific\ iron\ loss\ corresponding\ to\ flux\ density\ B_y\ in\ yoke$$

Total Iron loss,

$$p_i = Iron\ loss\ in\ core + Iron\ loss\ in\ yoke \quad (2.93)$$

Core loss component of no-load current,

$$I_c = \frac{Core\ loss\ per\ phase}{Primary\ Voltage} \quad (2.94)$$

$$I_c = \frac{P_i}{3V_1} \quad (2.95)$$

Estimation of magnetizing current of no-load current I_m

$$(B_m \rightarrow \frac{at_{core}}{m} \qquad B_c \rightarrow \frac{at_{yoke}}{m})$$

So,

$$MMF\ required\ for\ the\ core = 3 * L * at_{core} \quad (2.96)$$

$$MMF\ required\ for\ the\ yoke = 2 * W * at_{yoke} \quad (2.97)$$

We account 5% at for joints etc.

So,

$$total\ MMF\ required = 1.05[MMF\ for\ core + MMF\ for\ yoke] \quad (2.98)$$

Peak value of the magnetizing current,

$$I_{m,peak} \rightarrow \frac{Total\ MMF\ required}{3N_1} \quad (2.99)$$

RMS value of the magnetizing current,

$$I_{m,RMS} \rightarrow \frac{I_{m,peak}}{\sqrt{2}} \quad (2.100)$$

$$I_{m,RMS} \rightarrow \frac{Total\ MMF\ required}{3\sqrt{2}N_1} \quad (2.101)$$

Estimation of no load current

No load current I_0,

$$I_0 = \sqrt{{I_c}^2 + {I_m}^2} \quad (2.102)$$

No load power factor,

$$\text{Cos}\,\emptyset_0 = \frac{I_c}{I_0} \quad (2.103)$$

The no-load current should not exceed 5% of the full load current.

Estimation of number of turns on LV and HW winding

Primary no of turns,

$$N_1 = \frac{V_1}{E_1} \tag{2.104}$$

Secondary no of turns,

$$N_2 = \frac{V_2}{E_2} \tag{2.105}$$

Estimation of sectional area of primary and secondary windings
Primary Current,

$$I_1 = \frac{Q\times10^{-3}}{3V_1} \tag{2.106}$$

Secondary Current,

$$I_2 = \frac{Q\times10^{-3}}{3V_2} \tag{2.107}$$

or,

$$I_2 = \frac{N_1}{N_2} I_1 \tag{2.108}$$

Sectional area of primary windings,

$$a_1 = \frac{I_1}{\delta} \tag{2.109}$$

Sectional area of secondary windings,

$$a_2 = \frac{I_2}{\delta} \tag{2.110}$$

Where δ is current the density.

Determination of R_1 & R_2 and CU losses

Let,

L_{mt} = Length of mean turn

Resistance of primary winding,

$$R_{1,dc,75}=0.021 \times 10^{-6}\frac{L_{mt}N_1(m)}{a_1(m^2)} \quad (2.111)$$

$$R_{1,ac,75}=(1.15\text{to}1.20)R_{1,dc,75} \quad (2.112)$$

Resistance of secodary winding,

$$R_{2,dc,75}=0.021 \times 10^{-6}\frac{L_{mt}N_2(m)}{a_2(m^2)} \quad (2.113)$$

$$R_{2,ac,75}=(1.15 \text{ to } 1.20)\ R_{2,dc,75} \quad (2.114)$$

Copper loss in primary winding=$3I_1^2R_1$Watt (2.115)

Copper loss in secondary winding =$3I_1^2R_2$Watt (2.116)

Total copper loss = $3I_1^2R_1 + 3I_1^2R_2$=$3I_1^2(R_1 + R_2)$= $3I_1^2R_P$ (2.117)

$$R_{01}=R_P=R_1 + R_2 \quad (2.118)$$

Total resistance referred to primary side. On no load, there is magnetic field around connecting leads etc. which causes additional stray losses in the transformer tanks and other metallic parts. There losses may be taken as 7% to 10% total cu losses.

Determination of efficiency

Efficiency,

$$\mu = \frac{\text{Output Power}}{\text{Input Power}} \tag{2.119}$$

$$\mu = \frac{\text{Output Power}}{\text{Input Power+Losses}} \tag{2.120}$$

$$\mu = \frac{\text{Output Power}}{\text{Input Power+Iron Loss+Cu Loss}} \times 100\% \tag{2.121}$$

Estimation of leakage reactance

Assumptions,

1. Consider permeability of iron as infinity that is MMF is needed only for leakage flux path in the window.
2. The leakage flux lines are parallel to the axis of the core.

MMF at distance x,

$$M_X = \frac{N_1 I_1}{b_1} x \tag{2.122}$$

Permeance of this elementary cylinder,

$$\mu_0 \frac{A}{L} = \mu_0 \frac{L_{mt} dx}{L_c}, \left(\therefore S = \frac{1}{\mu_0} \frac{L}{A} \quad \& \; Permeance = \frac{1}{S}\right) \tag{2.123}$$

L_c = Length of winding;

Leakage flux lines associated with elementary cylinder,

$$d\emptyset_x = M_x \times Permeance \tag{2.124}$$

$$\frac{N_1 I_1}{b_1} x \times \mu_0 \frac{L_{mt} d_x}{L_C} \tag{2.125}$$

Flux linkage due to this leakage flux,

$$d\Psi_x = \frac{N_1 I_1}{b_1} x \times \mathrm{d}\emptyset_x \tag{2.126}$$

$$d\Psi_x = \frac{N_1 I_1}{b_1} x \times \left(\frac{N_1 I_1}{b_1} x \times \mu_0 \frac{L_{mt} dx}{L_c}\right) \tag{2.127}$$

$$d\Psi_x = \mu_0 N_1^2 \frac{L_{mt}}{L_C} I_1 \left(\frac{x}{b_1}\right)^2 d_x \tag{2.128}$$

Flux linkages (or associated) with primary winding,

$$\Psi_1{}' = \mu_0 N_1^2 \frac{L_{mt}}{L_C} I_1 \int_0^{b_1} \left(\frac{x}{b_1}\right)^2 d_x = \mu_0 N_1^2 \frac{L_{mt}}{L_C} I_1 \left(\frac{b_1}{3}\right) \tag{2.129}$$

Flux linkages (or associated) with the space ‘a’ between primary and secondary windings,

$$\Psi_0 = \mu_0 N_1^2 \frac{L_{mt}}{L_C} I_1 a \tag{2.130}$$

We consider half of this flux linkage with primary and rest half with the secondary winding. So total flux linkages with primary winding,

$$\Psi_1 = \Psi_1' + \frac{\Psi_0}{2} \tag{2.131}$$

$$\Psi_1 = \mu_0 N_1^2 \frac{L_{mt}}{L_C} I_1 \left(\frac{b_1}{3} + \frac{a}{2}\right) \tag{2.132}$$

Similarly, total flux linkages with secondary winding,

$$\Psi_2 = \Psi_2' + \frac{\Psi_0}{2} \tag{2.133}$$

$$\Psi_2 = \mu_0 N_2^2 \frac{L_{mt}}{L_C} I_1 \left(\frac{b_2}{3} + \frac{a}{2}\right) \tag{2.134}$$

Primary & Secondary leakage inductance,

$$L_1 = \frac{\Psi_1}{I_1} = \mu_0 N_1^2 \frac{L_{mt}}{L_C} \left(\frac{b_1}{3} + \frac{a}{2}\right) \tag{2.135}$$

$$L_2 = \frac{\Psi_2}{I_2} = \mu_0 N_2^2 \frac{L_{mt}}{L_C} \left(\frac{b_2}{3} + \frac{a}{2}\right) \tag{2.136}$$

Primary & Secondary leakage reactance,

$$X_1 = 2\prod f L_1 = 2\prod f \mu_0 N_1^2 \frac{L_{mt}}{L_C} \left(\frac{b_1}{3} + \frac{a}{2}\right) \tag{2.137}$$

$$X_2 = 2\prod f L_2 = 2\prod f \mu_0 N_2^2 \frac{L_{mt}}{L_C} \left(\frac{b_2}{3} + \frac{a}{2}\right) \tag{2.138}$$

Total Leakage reactance referred to primary side,

$$X_{01} = X_p = X_1 + X_2' = 2\prod f \mu_0 N_1^2 \frac{L_{mt}}{L_C} \left(\frac{b_1 + b_2}{3} + a\right) \tag{2.139}$$

Total Leakage reactance referred to secondary side,

$$X_{02} = X_s = X_{1+}' X_2 = 2\prod f \mu_0 N_2^2 \frac{L_{mt}}{L_C} \left(\frac{b_1 + b_2}{3} + a\right) \tag{2.140}$$

It must be 5% to 8% or maximum 10%

To control X_P, window height is changed. If increasing the window height (L), L_C will increase and following will decrease b_1 , b_2 and L_{mt} and so we can reduce the value of X_P.

Calculation of voltage regulation of transformer

$$V.R = \frac{I_2 R_{02} \cos \emptyset_2 \pm I_2 X_{02} \sin \emptyset_2}{E_2} \times 100 \quad (2.141)$$

$$V.R = \frac{R_{02} \cos \emptyset_2}{E_2/I_2} \times 100 \pm \frac{X_{02} \sin \emptyset_2}{E_2/I_2} \times 100 \quad (2.142)$$

$$V.R = \%R_{02} \cos \emptyset_2 \pm \%X_{02} \sin \emptyset_2 \quad (2.143)$$

2.2.2. Mechanical Design

Mechanical design of tank with tubes is important because of the losses in the transformer core and coil. These losses cause in increasing the temperature of the core and coil. In small capacity transformers the surrounding air will cool the transformer effectively and keeps the temperature rise well in the range of permissible limits. As the capacity of the transformer increases, the losses and the temperature rise increases. In order to keep the temperature rising between in limits, air may have to be blown over the transformer. This is not advisable as the atmospheric air containing moisture, oil particles etc., may affect the insulation. To overcome the problem of atmospheric hazards, the transformer is placed in a steel tank filled with oil. The oil conducts the heat from core and coil to the tank walls. From the tank walls the heat goes dissipated to surrounding atmosphere due to radiation and convection.

Insulation and cooling of transformer are very important due to its position in the power system, the transformer, and consequently its insulation system, is subjected to electric and thermal stresses which may cause damage or complete breakdown of the insulation system. Insulation breakdown is one of the most common causes of transformer failure. Therefore, it is very important to properly dimension the insulation system during the transformers' design phase. During the dimensioning process it is important to take into account that the electric field should not exceed the specified critical value and design of tank must tolerate the high temperature which is caused by magnetic field. This requires use of complex analytical or numerical methods for electric field computation and design of cooling system during the design phase.

The coolant used in transformers is air and oil to reduce excessive heat. Methods of Cooling of Transformers (Table 2.2): the choice of cooling method depends upon the size, type of application and the type of conditions of installation sites. The symbols designated these methods depend upon medium of cooling used and type of circulation employed.

Medium: Air-A, Gas-G, Oil-O, Water-W, Solid insulation-S

Circulation: Natural-N, Forced-F

Cooling Types: Air Natural (AN), Air Blast (AB), Oil Natural (ON), Oil Natural Air Forced (ONAF), Oil Natural Air Natural (ONAN), Oil Natural Water Forced (ONWF), Forced Circulation of Oil (OF).

Table 2.2. Cooling types of transformer

1.LETTER			2.LETTER			3.LETTER			4.LETTER		
It relates to the cooling medium contact with the windings						It relates to the cooling medium contact with the external cooling system					
Types of cooling medium		Circulation type		Types of cooling medium		Circulation type		Types of cooling medium		Circulation type	
O	N	A	N	O	N	A	F	O	F	W	F
Oil	Naturel	Air	Naturel	Oil	Naturel	Air	Forced	Oil	Forced	Water	Forced

Transformer tank design

Width of the transformer (Tank),

$$W_t = 2D + D_e + 2b \tag{2.144}$$

Where,

$D_e = External\ diameter\ of\ HV\ winding$

$b = Clearance\ width\ wise\ between\ HV\ and\ tank$

Depth of transformer (Tank),

$$l_t = D_e + 2a \tag{2.145}$$

Where,

$a = Clearance\ depth\ wise\ between\ HV\ and\ tank$

Height of transformer (Tank),

$H_t = H + h$ (2.146)

Where,

$h = h_1 + h_2 = Clearance\ height\ wise\ of\ top\ and\ bottom$ (2.147)

Calculation of temperature rise

Surface area of 4 vertical side of the tank (Heat is considered to be dissipated from 4 vertical sides of the tank),

$S_t = 2(W_t + l_t)H_t\ m^2$ (Excluding area of top and bottom of tank)(2.148)

Let $\theta = Temp\ rise\ of\ oil$ ($35℃\ to\ 50℃$) ;

$Total\ full\ load\ losses\ (Iron\ loss\ +\ Cu\ loss) = 12{,}5 * S_t * \theta$ (2.149)

So temp rise in ℃ **,**

$\theta = \frac{Total\ full\ load\ losses}{12{,}5 * S_t}$ (2.150)

If the temp rise calculated and exceeds the limiting value, the suitable no of cooling tubes or radiators must be provided.

Calculation of no of cooling tubes

Let,

$Surface\ area\ of\ all\ cooling\ tubes\ = x * S_t$ (2.151)

Specific Heat dissipation, $6\frac{\text{Watt}}{m^2}$°C by Radiation and $6{,}5\frac{\text{Watt}}{m^2}$°C by Convection. Then, losses to be dissipated by the transformer walls and cooling tubes (total losses);

$$Total\ losses = (12{,}5 * S_t + 8{,}5 * x * S_t) * \theta \qquad (2.152)$$

$$6W\ \text{Radiation} + 6{,}5\text{W} = 12{,}5\ \text{Convection} \qquad (2.153)$$

$$6{,}5 * 1{,}5W \approx 8{,}5\ (\approx 35\%\ more)\ Convection\ only \qquad (2.154)$$

So, from above equation we can find out total surface are of cooling tubes

total surface are of cooling tubes=$x * S_t$ (2.155)

Normally in transformer, we use 6 mm diameter tubes and keep them minimum 45 mm apart,

$$A_t = Surface\ area\ of\ one\ cooling = \pi * d_{tube} * l_{tube,mean} \qquad (2.156)$$

Hence,

$$No\ of\ cooling\ tubes = \frac{x * S_t}{A_t} \qquad (2.157)$$

The most influential parameters on the thermal performance of the transformer are fin height, length and spacing. Also, increasing the fin height and length reduces the hotspot temperature, while decreasing the fin spacing behaves favorably on the hotspot temperature providing more heat transfer area. It has also been calculated that the hot spot temperature is affected more by the fin height than the fin length and spacing. This greatly affects the transformer lifetime and its safer performance, so that the transformer provides better performance and the lifetime of the transformer is greatly increased.

Weight of transformer

Let,

$$W_i = \text{Weight of Iron in core and yoke(core volume} * \text{density} + \text{yoke volume} * \text{density)Kg} \quad (2.158)$$

$$W_c = Weight\ of\ copper\ in\ winding(volume * density)\text{Kg}\ (density\ of\ cu = 8900\frac{kg}{m^3}) \quad (2.159)$$

$$Weight\ of\ oil = Volume\ of\ oil * 880\text{Kg} \quad (2.160)$$

Add 20% of (W_i + W_i) for fittings, tank etc., total weight is equal to weight of above all parts.

2.2.3. Assembly Process

Assembly process of transformer basically consist of six steps. Firstly, the core of the transformer is cut in core cutting machines and arranged according to the assembly project. Figure 2.6 shows Core of a transformer on a 3D design program and in a real production process.

Figure 2.6. Core of a transformer on a 3D design program and in a real production

Secondly, transformer's coils are wound according to the bobbin project.

Third step is assembly of core and coils of transformer.

Fourth step is assembly of these core and coils with cover of the transformer. This part generally called as an active part of transformer.

In the fifth step, this active part is assembled with a tank of a transformer. Figure 2.7 shows assembly of a coils and core of a transformer.

Figure 2.7. Assembly of a coils and core of a transformer.

3. MATERIAL METHOD

3.1. Transformer Drawing with Aid of 3D Design Software

Today, computer technologies are used in all areas of production. One of these areas is undoubtedly the field of design, and parametric design software offers extensive support to engineers and painters. It has been more than thirty years since the AutoCAD drawing on paper was transferred to the computer, but during this time, not only did the work of designers become easier with software, design software became the most important tools of engineers. It is now possible to create Bill of Materials, create visual presentations and make engineering calculations with design software. In addition to all these, increasing production speed, globalizing world, developing technology, increasing foreign trade affect not only the financial departments of the companies but also the design and R&D departments. Firms want to overcome their competitors in their field and gain prestige as well as gaining superiority and more customers. For this reason, R&D and design gains importance day by day and many companies state their most important priorities in their official media as R&D units and experience in this field.

At this point, the concepts we call time, efficiency and accuracy emerge, which will make designers, engineers and painters quite squeeze. Removing a design in 1 day is not enough waste. Making both the material list, technical drawings and engineering calculations of this design and adding the visualization process, just like adding a cake on a cake, turns out to be a delightful situation for companies.

One of these reasons why Autodesk Inventor is preferred to make parametric design is its useful and easy drawing interface. The I-logic feature of Autodesk Inventor allows easy parameterization of both drawing and mounting parts. Also, I-logic makes easy to convert them to technical drawings in Autodesk Inventor. However, the parameterization process mentioned above is not the process of manually reordering in this study, but it is a process of returning to the desired variation more easily and easily with coding.

In order to parameterize a mechanical model, it should first be clarified about determining the characteristic parameters of the model and how they should be parameterized. Characteristic parameters can be multiple or valid for a specific range. For this reason, the point to be considered is that they are used and examined in a way that does not disturb the flexibility of the model.

Firstly, we will draw the transformer generally to give numerical dimensions on Inventor, then we will assign parameters to each dimension by using Excel. All parameters and rules must be formed before drawing just once in Excel. Then, these parametric rules and features are introduced into Inventor by using i-logic environment and its tool. That’s why the design is linked to the parameters that we define in Excel and the design updates itself when each parameter is changed automatically.

With this study, we will try to explain how fast designs can be made and how we can quickly create different variations of a design. Therefore, we will take advantage of a software and use its features. These features are:

- Characteristic Parameters
- I-logic environment and tools
- Codification
- Form

When you start designing in Autodesk Inventor, the software automatically starts assigning measurements as parameters, resulting in these measurements being named and listed in the parameter window. Dimensioning continues as d0, d1, d2 etc. if the user does not name himself.

Parameters

Parameter Name	Consumed b	Unit/Type	Equation	Nominal Valu	Tol.	Model Value	Key	Exp	Comment
Sheet Metal Parame...									
Thickness	d123, d90...	mm	KLMP_T	6,000000		6,000000			
BendRadius	d9, d7, Ja...	mm	Thickness	6,000000		6,000000			
BendReliefWidth	d4	mm	Thickness	6,000000		6,000000			
BendReliefDepth	d5	mm	Thickness * 0,5 ul	3,000000		3,000000			
CornerReliefSize	d11	mm	Thickness * 4 ul	24,000000		24,000000			
MinimumRemnant	d6	mm	Thickness * 2,0 ul	12,000000		12,000000			
TransitionRadius		mm	BendRadius	6,000000		6,000000			
JacobiRadiusSize	d13	mm	BendRadius	6,000000		6,000000			
GapSize	d12	mm	Thickness	6,000000		6,000000			

Figure 3.1. Parameters tool of the software

For example, as can be seen in the figure above, the parameters were automatically named, and in addition, another parameter was used by the user by changing its name. The first column specifies the parameter name, and the second column specifies where this parameter is used. The third column indicates which unit this parameter uses. The fourth column specifies the value of the parameter. The fifth column indicates the nominal value of the parameter, and the sixth column indicates tolerance. The Key column indicates whether this parameter has priority. The comment column allows the parameter to be interpreted by the user.

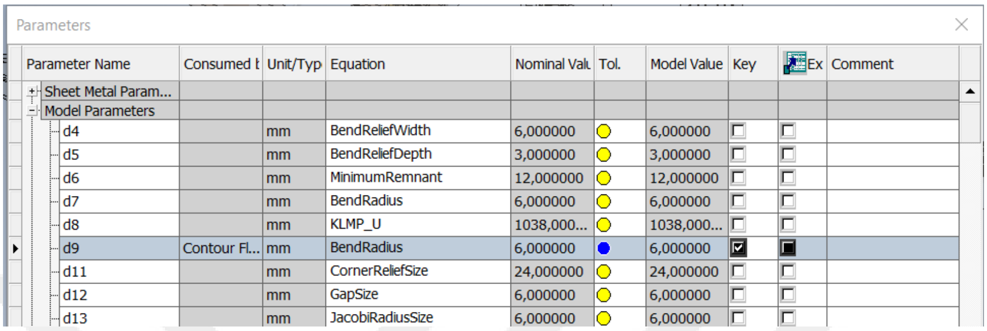
Parameters are also divided into two as Model Parameter and User Parameter. As we mentioned above, the model parameter is the parameters that appear automatically and are named d0, d1 if they are not named. User Parameters are parameters created by the user.

Parameters

Parameter Name	Consumed b	Unit/Type	Equation	Nominal Valu	Tol.	Model Value	Key	Exp	Comment
Model Parameters									
User Parameters									
E:\GAMZE\GAMZE ...									

Figure 3.2. Model and user parameters

For example, the parameter created in this model was determined with three options as can be seen below. Besides, it will be seen that the parameter is defined as key, on the other hand, as a characteristic parameter. Defining this key as a key is very useful when there are many parameters in the parameter window.



Parameters

Parameter Name	Consumed b	Unit/Typ	Equation	Nominal Valu	Tol.	Model Value	Key	Ex	Comment
Sheet Metal Param...									
Model Parameters									
d4		mm	BendReliefWidth	6,000000		6,000000	☐	☐	
d5		mm	BendReliefDepth	3,000000		3,000000	☐	☐	
d6		mm	MinimumRemnant	12,000000		12,000000	☐	☐	
d7		mm	BendRadius	6,000000		6,000000	☐	☐	
d8		mm	KLMP_U	1038,000...		1038,000...	☐	☐	
d9	Contour Fl...	mm	BendRadius	6,000000		6,000000	☑	■	
d11		mm	CornerReliefSize	24,000000		24,000000	☐	☐	
d12		mm	GapSize	6,000000		6,000000	☐	☐	
d13		mm	JacobiRadiusSize	6,000000		6,000000	☐	☐	

Figure 3.3. Model parameters

This design program transfers the coding to its users, which they can normally develop using software language, through an easy interface. In this interface, panels are positioned for easy access to commands and parameters, and the user can transfer the details they want to the code screen thanks to these panels. To make the model parametric, both model parameters and Inventor's functions can be easily transferred to the coding area. In addition, the loops and mathematical operators frequently used during coding and the details that a code developer will often need are on the panel.

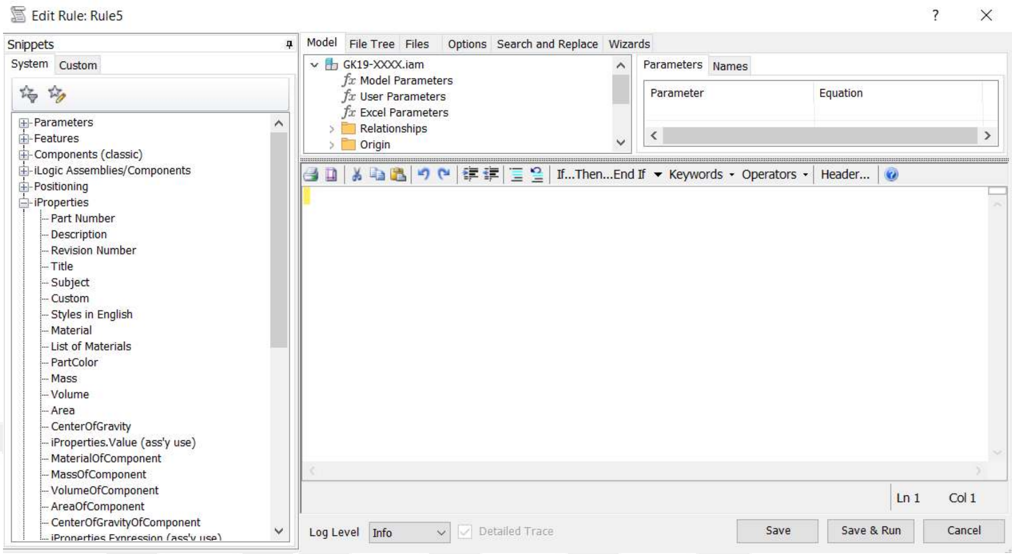


Figure 3.4. I-logic interface of the software

The three windows you see in figure 3.4 above are positioned for different purposes. The window on the left is the snippets section with ready code blocks. The above window facilitates the selection of the elements and related parameters in the model tree that is located and the desired model to be used. The window below is the coding section and the auxiliary tools (cut, paste, comment). For example, in cases such as whether a component is active or inactive, the code to be written can be transferred to the coding screen by clicking on the relevant title, as can be seen from the figure 3.5 numbered below.

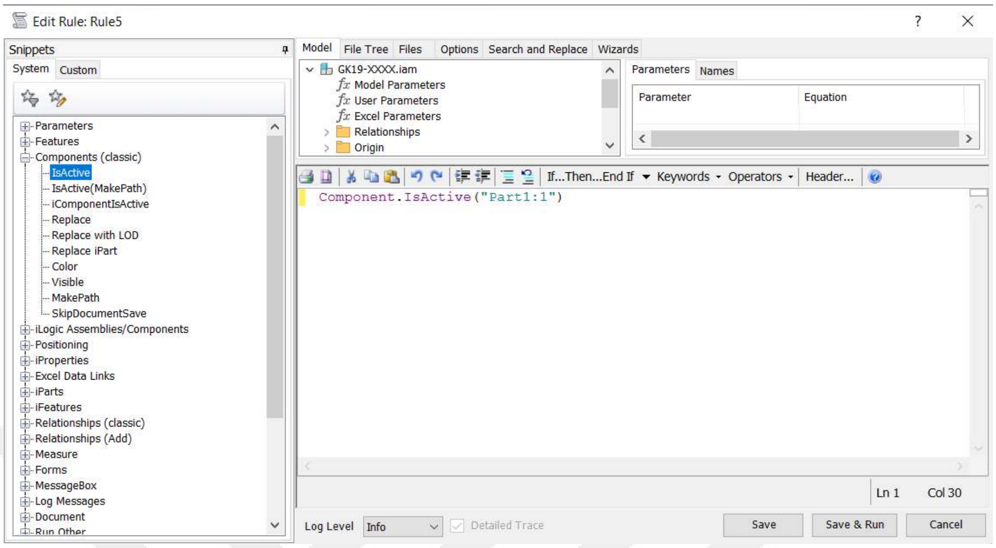


Figure 3.5. I-logic component interface

After understanding the definition of I-logic and what the tools are, we can start coding for the sample model. First, it is necessary to know the purpose of coding in our code block and which parameters will be used. Writing this will enable to us remember what was done and why in long coding.

Adding loops are tool loops that allow us to ensure that certain changes that will occur in the model when encoding occur. These loops, which contain expressions such as if, case, and so on, check the model to see if the requirement for change is met. Here we can talk about various cycles. These loops are:

- If-Then-Else
- If…Then
- End If
- Case

It is considered whether a condition is met together with the IF-then-else cycle. If it is provided, the rule is operated, if it is not provided, the rule is operated in a fractured manner. To further clarify the "if" situation, we can share the following as a sample code block.

```
If power < “250” Then
Thickness of cover = 5.0
Else
Thickness of cover = 6.0
End If
```

In the if-then loop, action is taken if the "if" condition is met. If the condition is not met, no action is taken. We can share the following code block for this loop.

```
If power > “1250” Then
Thickness of cover = 6.0
```

The case structure offers the user a different flexibility than If loops. The user allows the user to define more than one condition and make a separate application for each condition. As an example, the code block is as follows.

```
If material = “Carbon Steel” Then
density = 0.785
ElseIf material = “Copper” Then
density = 0.894
ElseIf material = “Aluminum” Then
density = 0.27
End If
```

3.2. Interface of the Parametric Program

P Parametric design consists of many parts and information. however, the most important part for users is the user interface and the basic project inputs to be entered. These inputs are listed below and interface of the program can be seen in table 3.1.

Table 3.1. Program Interface

1000	Power (25-4000 kVA)
1095	MAX.LENGTH
600	MAX.WIDTH
1150	MAX.HEIGTH
1665	MAX.LWEIGHT
xxxx	PROJECT NO
xxxx	PROJECT NAME
A	QUALITY
33	H VOLTAGE
0,4	L VOLTAGE
H	HERMETIC/OIL TANK
Dyn-11	WIND CONNECTION
2100	PFE
13500	PKD
6	%UK
60	T RISE
65	LV T RISE
1000	ALTITUDE
17.01.2021	DATE

Power,

- HV voltage
- LV voltage
- Maximum length, width, height and weight
- Project no and project name
- Quality
- Hermetic or oil tank
- Winding connection
- Losses
- % UK

- T rise
- LV T rise
- Altitude

Power, HV and LV voltages are necessary for initial calculation. Otherwise, it could not be known customer system and its requirements.

Sometimes there are size limitations for the places where the transformers are placed. Transformers can be placed inside a certain room or mansion. In this case, it will be necessary to design according to this size limitation. Otherwise, the designed transformer will not have any usability.

Project no and project name are not necessary for any designing step. They are only information for naming and grouping projects.

The quality of a transformer depends on many parameters. As the quality increases, the price of the transformer will increase. The quality of the metal sheets used in the transformer, the type and quality of the cooling fluid used, the fact that the conductor used in the transformer windings is AL or CU, the brand and type of accessories used are factors that affect both the size and weight of the transformer and its quality.

Losses and % UK of a transformer are specific and obvious according to each country or the customer's own conditions. Even if the customer does not provide this information, the relevant values can be found by looking at the specification of the relevant country. Distribution transformers for Turkey have two specifications, hermetic and oil expansion tank. While the electrical design of the transformer is made, loss values are selected according to this specification. Table 3.1 shows hermetic and expansion tank type eco-design losses. Losses in Table 3.1 are used for high voltage 24 kV (including) low voltage 1.1 kV and below voltages. In order to find eco-design losses of voltages above 24 kV, the Po column in the table is multiplied by 1.15 and the Pk column by 1.1.

As with all electrical machines, transformers have losses. These losses are two types: iron losses and copper losses.

No Load Losses (Iron Loss)

It is the loss that occurs in empty operation in the transformer. Energy loss caused by temperature in the magnetic circuit of the transformer occurs as iron losses. Iron losses are also called core or core losses.

Load Losses (Copper losses)

By connecting the load to the secondary end, more losses occur, since current will occur in both the primary and secondary windings. Because these losses are caused by the resistance of the windings, they are called Copper losses. If the customer doses not specify any input for losses, loss value is determined according to the IEC standard specified in Table 3.2. for high voltage side is equal and lower than 24 kV. If high voltage side higher than 24 kV, Table 3.3 is used.

Table 3.2. IEC load losses with hermetic type and expansion tank

	Tier 1		**Tier 2**	
Rated power	**Max. load losses Pk (W)**	**Max. no-load losses Pk (W)**	**Max. load losses Pk (W)**	**Max. no-load losses Pk (W)**
<25	Ck (900)	A_0 (70)	A_k (600)	A_0 -%10 (63)
50	Ck 110)	A_0 (90)	A_k (750)	A_0 -%10 (81)
100	Ck (1750)	A_0 (145)	A_k (1250)	A_0 -%10 (130)
160	Ck (2350)	A_0 (210)	A_k (1750)	A_0 -%10 (189)
250	Ck (3250)	A_0 (300)	A_k (2350)	A_0 -%10 (270)
315	Ck (3900)	A_0 (360)	A_k (2800)	A_0 -%10 (324)
400	Ck (4600)	A_0 (430)	A_k (3250)	A_0 -%10 (387)
500	Ck (5500)	A_0 (510)	A_k (3900)	A_0 -%10 (459)
630	Ck (6500)	A_0 (600)	A_k (4600)	A_0 -%10 (540)
800	Ck (8400)	A_0 (650)	A_k (6000)	A_0 -%10 (585)
1000	Ck (10500)	A_0 (770)	A_k (7600)	A_0 -%10 (693)
1250	Ck (11000)	A_0 (950)	A_k (9500)	A_0 -%10 (855)
1600	Ck (14000)	A_0(1200)	A_k (12000)	A_0 -%10 (1080)
2000	Ck (18000)	A_0(1450)	A_k (15000)	A_0 -%10 (1305)
2500	Ck (22000)	A_0(1750)	A_k (18500)	A_0 -%10 (1575)
3150	Ck (2500)	A_0 2200)	A_k (23000)	A_0 -%10 (1980)

Table 3.3. Losses in IEC load with hermetic type and expansion tank

No load P (W) and sound level (Lw) for ≤24 Kv											
Rated power	E0		D0		C0		B0		A0		Short circuit impedance
kVA	P0	LwA	P1	LwA	P0	LwA	P0	LwA	P0	LwA	%
	W	dB(A)	W	dB(A)	W	dB(A)	W	dB(A)	W	dB(A)	
50	190	55	145	50	125	47	110	42	90	39	4
100	320	59	260	54	210	49	180	44	145	41	
160	460	62	375	57	300	52	260	47	210	44	
250	650	65	530	60	425	55	360	50	300	47	
315	770	67	630	61	520	57	440	52	360	49	
400	930	68	750	63	610	58	520	53	430	50	
500	1100	69	880	64	720	59	610	54	510	51	
630	1300	70	1030	65	860	60	730	55	600	52	
630	1200	70	940	65	800	60	680	55	560	52	6
800	1400	71	1150	66	930	61	800	56	650	53	
1000	1700	73	1400	68	1100	63	940	58	770	55	
1250	2100	74	1750	69	1350	64	1150	59	950	56	
1600	2600	76	2200	71	1700	66	1450	61	1200	58	
2000	3100	78	2700	73	2100	68	1800	63	1450	60	
2500	3500	81	3200	76	2500	71	2150	66	1750	63	

Table 3.4. Losses in IEC load with hermetic type and expansion tank

Load losses Pk36 (W) at 75 °C for Um=36 kV				
Rated power	**Ck36**	**Bk36**	**Ak36**	**Short-circuit impedance**
kVA	**W**	**W**	**W**	**%**
50	1450	1250	1050	4 or 4,5
100	2350	1950	1650	
160	3350	2550	2150	
250	4250	3500	3000	
400	6200	4900	4150	
630	8800	6500	5500	
800	10500	8400	7000	6
1000	13000	10500	8900	
1250	16000	13500	11500	
1600	19200	17000	1500	
2000	24000	21000	18000	
2500	29400	26500	22500	

3.3. Excel File and Working Principle

In order to parameterize a mechanical model, it is necessary to clarify the characteristic parameters of the model and how these parameters should be parameterized. The characteristic parameters are more than one and some of them apply to a specific range. Therefore, the point to be considered is that they should be used and examined in a way that does not impair the flexibility of the model. So, we have to define parameters correct, add design rules and make standards. After drawing the model generally, all dimensions must be converted into mathematical formulas by using Excel macros and VBA coding for automatically update for each design case. After entering initial requirement data, firstly dimensions of electrical parts are calculated depending upon some rules and formulas. Figure 3.5 shows some bushing rules which are coding in Excel. Then dimensions of mechanical parts are calculated depending on electrical jump distances, mechanical strength of material that we choose based on required quality, additional customer request, working conditions of transformer in Excel.

Initial required data:

- Working conditions (place, temperature, altitude, using aim)
- Required power
- Required quality (low, medium, high)

BUSHING								ANTIMAGNETIC						
BUSHING	HOLE DIA.	AXIS D.	CODE	CON.H.	HEIGHT	AMP	USED TYPE	HOLE D.	WIDTH	HOLE D.2	LENG.	THICKNESS	D22	D35
250A X1	28	150	1		125	250	LV	190	110	56	685	6	0	0
250A X1 3KV	39	150	18		180	250	LV	190	110	56	685	6	0	0
630A X1	45	150	2		165	630	LV	190	110	56	685	6	0	0
630A X1 3KV	45	150	19		210	630	LV	190	110	56	685	6	0	0
1000A X1	56	190	3		250	1000	LV	190	110	56	685	6	0	0
1000A X1U	56	190	9		340	1000	LV	190	110	56	685	6	0	0
1250A X1	56	190	4		250	1250	LV	190	110	56	685	6	0	0
2000A X1	68	230	5		320	2000	LV	230	122	68	845	6	0	0
2000A X1U	88	230	10		370	2000	LV	230	122	68	845	6	0	0
3150A X1	88	270	6		330	3150	LV	270	144	88	1010	6	0	0

Figure 3.6. Some of the bushing design rules and related coding in Excel

Figure 3.7 shows required design data before drawing transformer. Firstly, we will define working conditions, power, input and output voltages. Then we will make electrical design based on desired quality and losses. After electrical design is finished, mechanical design is made according to electrical safety distances.

630	POWER (25 - 3200)
1110	LK
570	BK
1080	HK

19-EXAMPLE	PROJECT NO
TURKEY	PROJECT NAME
15	H VOLTAGE2
20	H VOLTAGE1 (kV)
0,4	L VOLTAGE (kV)
H	**H**ermetic/**D**(Oil conservator)
BAND	BAND / KP / U
410	OIL (Kg)
Dyn-11	CONNECTION

CLEAN

EDIT

RESET

FORM

CORE			
INNER WİNDOW LENGTH			580
INNER WİNDOW WIDTH			195
	F	**C HV**	**C LV**
1	160	89,08	
2	150	13,34	
3	130	16,10	
4	100	14,72	
5	80	7,36	
6			
7			
8			
9			
10			

Figure 3.7. Some detailed resulting design data

3.4. Design Parameters and Rules

In this work more than 300 hundred design parameters and rules were used. These parameters are defined based on the specifications such as its value depending on power, voltages, losses and quality. Table 3.6 shows some design parameters depending on transformer rated power. For example, for 630 kVA transformer tank thickness is 4 mm, tank frame is 6x60x60 mm L bracket, tightening stud is M10 stud, active part lifting part thickness is 12 mm, cover lifting thickness is 12 mm, cover thickness is 6 mm, cover and tank bolt is M10, lifting lug is type 2, fins thickness is 1.2 mm, active part clamp thickness is 6 mm, wheel axis is 670 mm.

POWER	TANK THICKNESS	FRAME	TIGHTENING STUD	ACTIVE PART LIFTING	COVER LIFTING	COVER THICKNESS	COVER BOLT	LIFTING LUGS	FINS	CLAMPS	WHEEL AXIS
25	3	50	10	10	5	5	10	2	1,2	4	420
50	3	50	10	10	5	5	10	2	1,2	4	520
63	3	50	10	10	5	5	10	2	1,2	4	520
100	3	50	10	10	5	5	10	2	1,2	4	520
160	3	50	10	10	5	5	10	2	1,2	5	520
200	3	50	10	10	5	5	10	2	1,2	5	520
250	3	50	10	10	5	5	10	2	1,2	5	520
300	3	50	12	10	5	5	10	2	1,2	5	670
315	3	50	12	10	5	5	10	2	1,2	5	670
400	4	50	12	12	5	5	10	2	1,2	5	670
500	4	60	12	12	5	5	10	2	1,2	5	670
630	4	60	12	12	6	6	10	5	1,2	6	670

Figure 3.8. Design parameters of software

3.5. Transferring Information to Drawing and Creating Solid Model

Before opening design on Inventor, all parameters and required design data must be entered to the Excel design page. After, required parameters and rules are determined in Excel, Inventor take this data from Excel and starts parametric design. Design and updating process takes a few minutes, also, technical drawings and part list are finished in a few minutes which is very quickly. Also, we can change parameters easily to create different variations of design. Figure 3.9 and Figure 3.8 show Inventor design window with its coding window.

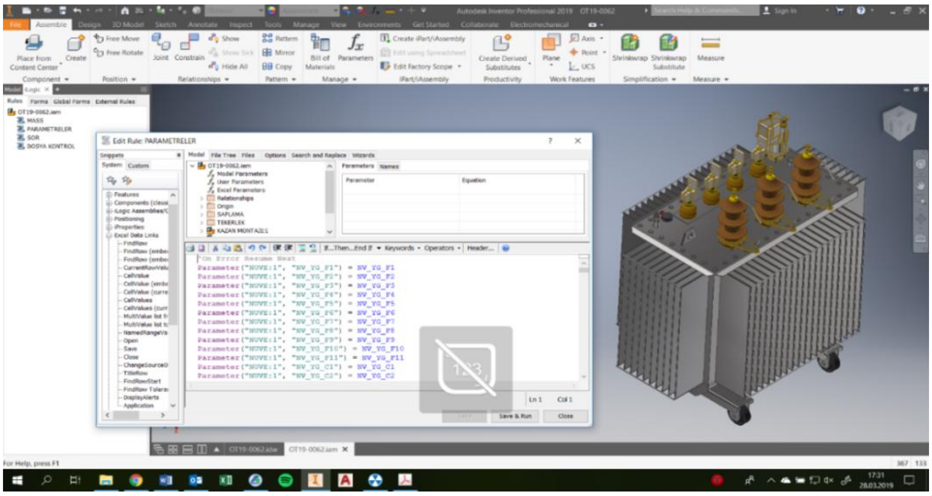


Figure 3.9. Inventor coding window-1

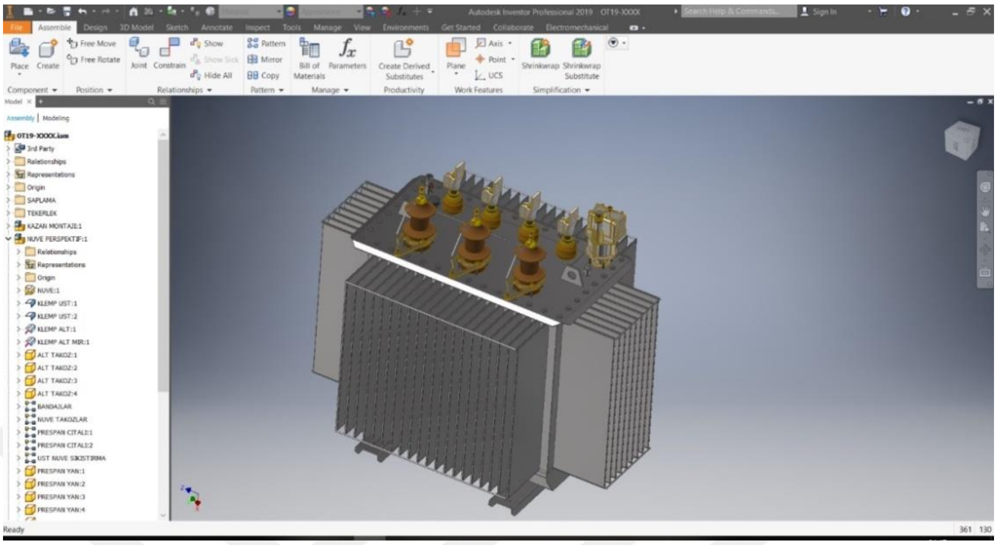


Figure 3.10. Inventor coding window-2

Also, part list and material list which are contains number of each parts, weight, thickness and material types are automatically created with using Excel. Inventor's I-logic feature provides to get mass, thickness, material type, number of use and length information of each component from 3-D drawing. Then we will add a VBA code to transfer these detailed components data into Excel part list page. Finally, we will get detailed part list which is included all parts with their name, type, mass, length and number of use. Figure 3.11 shows an example of a part list.

19-EXAMPLE TURKEY 630KVA 15-20-0,4KV HERMETİK										G.KILAGÖZ
ASSEMBLY GROUP	SUB-ASSEMBLY	PART NAME	MATERL.	THICKNESS mm	NUMBER	KG	TOT. KG	LENG. mm	TOT. LENG.	EXPLANATION
ACTIVE	COVER	COVER SHEET METAL	ST37	6	1	0,00	0,000	0	0	
ACTIVE	COVER	LIFTING LUGS	ST37	10	2	0,00	0,000	0	0	
ACTIVE	COVER	ACTIVE PART LIFTING	ST37	6	4	0,00	0,000	0	0	
ACTIVE	COVER	UNDER COVER SUPPORT	ST37	6	2	0,00	0,000	0	0	
ACTIVE	COVER	COVER SUPPORT SHEET METAL	ST37	6	1	0,00	0,000	0	0	
ACTIVE	COVER	ANTIMAGNETIC SHEET METAL	CHROME	6	1	0,00	0,000	0	0	
ACTIVE	COVER	OIL FILLING VALVE	PROCURANCE	0	1	0,30	0,300	0	0	3/4"
ACTIVE	COVER	T10 PRESSURE RELIEF VALVE	PROCURANCE	0	1	0,20	0,200	0	0	1"
ACTIVE	COVER	1-2 THERMOMETER POCKET	PROCURANCE	0	1	0,00	0,000	0	0	1/2"
ACTIVE	COVER	1"TERMOMETER	PROCURANCE	0	0	0,700	0,000	0	0	1"
ACTIVE	COVER	1"TERMOMETER WITH CONTACT	PROCURANCE	0	0	0,00	0,000	0	0	
ACTIVE	COVER	1"TERMOMETER NO CONTACT	PROCURANCE	0	0	0,50	0,000	0	0	

Figure 3.11. Part List, number of parts and weights of part

4. RESULTS

Previous chapters have shown that this parametric design program is a well-established design tool that provides a solution to the problem of designing projects that used to be time consuming

This study provides how to make engineering calculations, extract material lists, reveal visual presentations and technical drawings and make some analysis using parametric design with Autodesk Inventor and Excel visual basic coding in a basic manner. After defining design parameters correctly, add design rules and make standards as a once time, parametric 3-D drawing is obtained in each case even though, required design data is changed entirely. That's why this work provides efficiency, designing speed, accuracy and quality for designing and manufacturing.

The design programme provides very close results according to customer requests and specifications. When all required data is given the programme, design is completed after a few minutes.

For example; there is a customer request a 400 kVA 33-0,4 kV distribution transformer which has Tesla value is 1,7, no load loss is 690 watts, load loss is 4150 watts. After design is completed, program gives result shown below table 4.1.

Table 4. 1.Design result of 400 kVA distribution transformer

Power	400	kVA
Magnetic flux	1,7	Tesla
No load loss	685	Watt
Load loss	5017	Watt
Core section	203,493924	cm^2
Phase current HV	4,04	Amper
Phase current LV	577,350269189626	Amper
Number of Turns LV/HV	29 / 4521	Turn
Window height	630	mm
Current density LV/HV	1,087 /1,3542	A/mm^2
Volt/Turn	7,96	

All design result also made analysis with a FEA analysis program to make sure design has optimum and efficient results. This 400 kVA transformer is analyzed in a FEA program to see magnetic flux, load loss, current and voltage values. In Figure 4.1 shows magnetic flux result of this 400 kVA distribution transformer. Analysis shows maximum magnetic flux value reaches 1,762 Tesla. Figure 4.2 shows no loss of this transformer. No load loss has average value of 790 watts. Figure 4.3 shows voltage result of 400 kVA transformer.

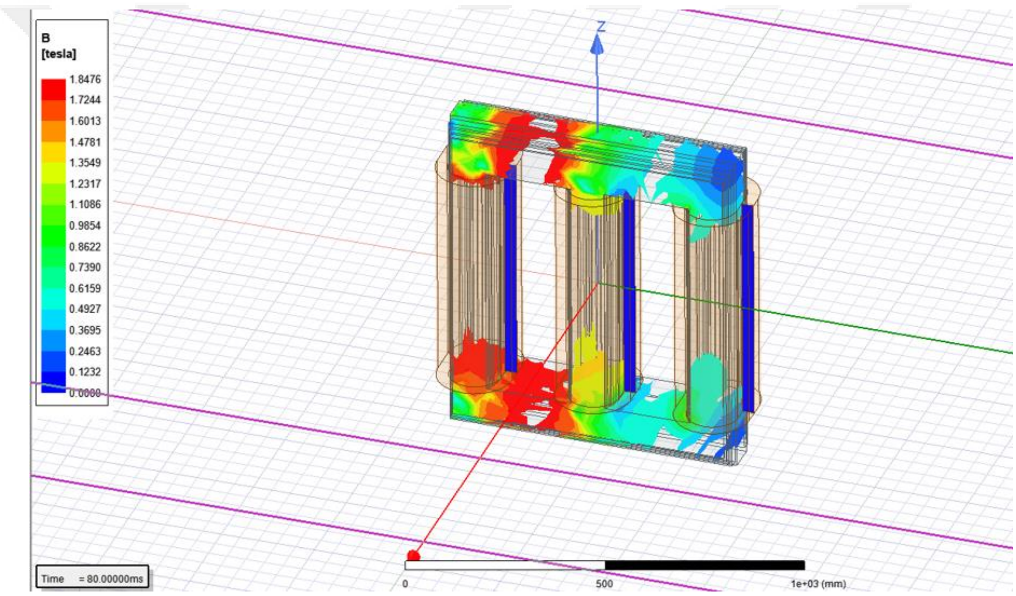


Figure 4. 1. Magnetic flux value of 400 kVA transformer

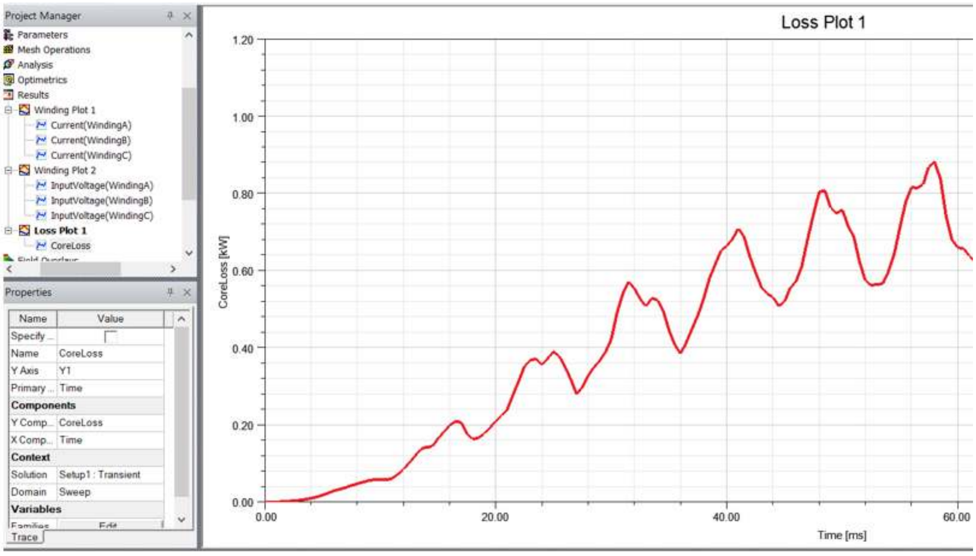


Figure 4. 2. No load loss analysis of 400 KVA transformer

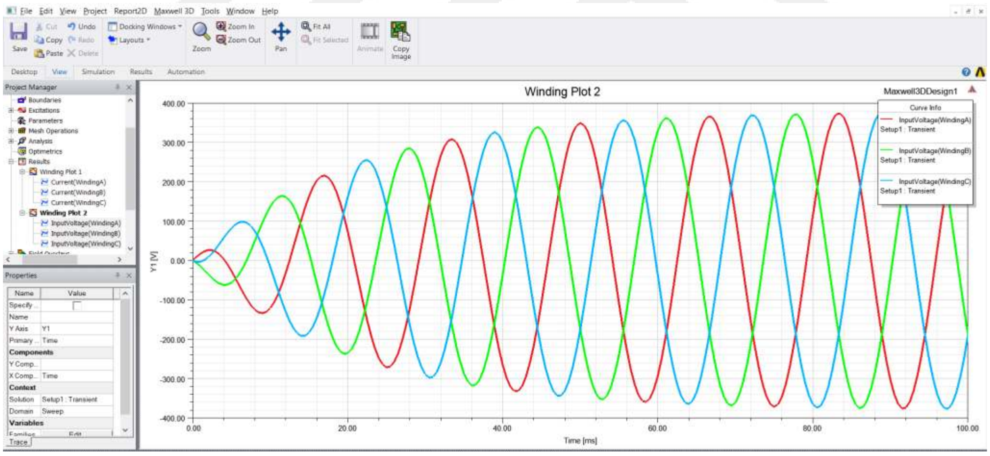


Figure 4. 3. Voltage result of 400 kVA transformer

Another design example; there is a customer request a 1600 kVA 33-0,4 kV distribution transformer which has Tesla value is 1,78, no load loss is 2200 watts, load loss is 14500 watts. After design is completed, program gives result shown below table 4.2.

Table 4. 2 Design result of 1600 kVA distribution transformer

Power	1600	kVA
Magnetic flux	1,779	Tesla
No load loss	2183	Watt
Load loss	14480	cm^2
Core section	1417,5	cm^2
Phase current HV	2309,4	A
Phase current LV	16,2	A
Number of Turns LV/HV	14/2182	Turn
Window height	815	mm
Current density LV/HV	1,192/1,540	A/mm^2
Volt/Turn	16,5	

This 1600 kVA transformer is also analysed in a FEA programme to see magnetic flux, load loss, current and voltage values. In Figure 4.4 shows magnetic flux result of this 1600 kVA distribution transformer. Analysis shows maximum magnetic flux value reaches 1,788 Tesla. Figure 4.5 shows no loss of this transformer. No load loss has average value of 2200 watts. Figure 4.6 shows voltage result of a 1600 kVA transformer.

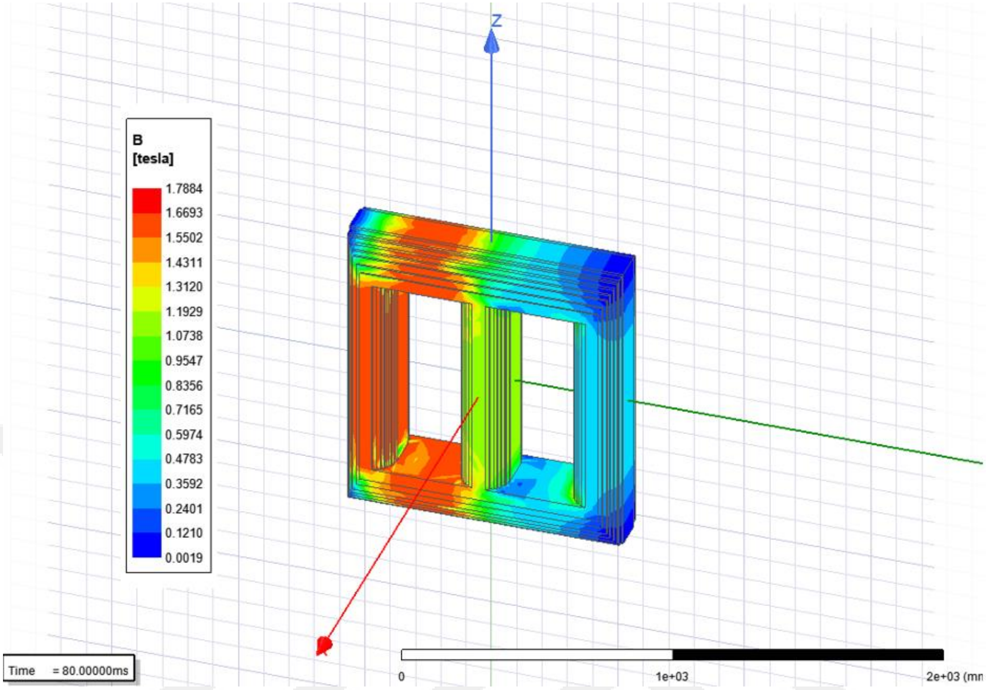


Figure 4. 4. Magnetic flux value of 1600 kVA transformer

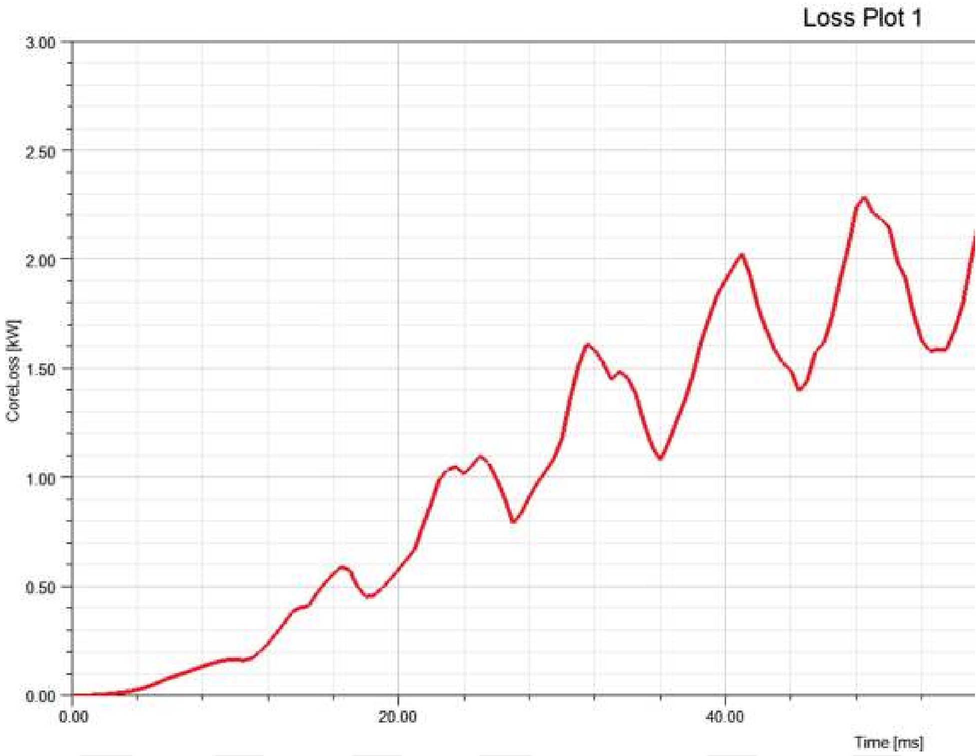


Figure 4. 5. No load loss analysis of 400 KVA transformer

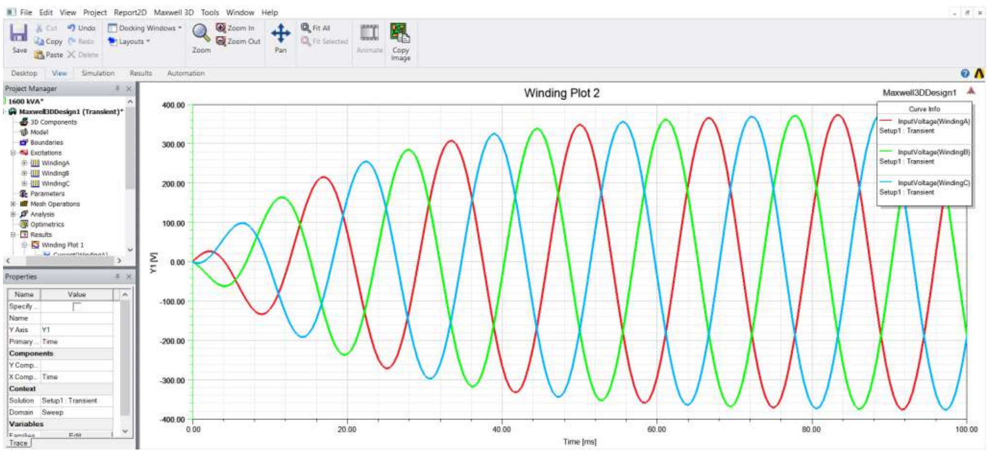


Figure 4. 6. Voltage result of 00 kVA transformer

The parametric design described in this study not only has an easy and understandable interface, but also speeds up the design process and facilitates the design process. Designers can easily and quickly adapt to the program and complete the desired designs in a very short time. The program easily adapts and changes to various alternatives and revisions for the same project. Thus, designers can devote time to design instead of dealing with details and tiring repetitions. All these conveniences increase efficiency and design speed and reduce the error rate. In other words, this design program ensures that more work is done correctly in less time.

Finally, it is only the engineer who can be the most creative and innovative, but it is believed that these CAD-supported parametric design programs will enable engineers and designers to achieve their goals faster and with a higher degree of reliability.

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CURRICULUM VITAE

After completing her undergraduate education in Mechanical Engineering at Çukurova University, Gamze Kılagöz started her graduate education at the same university and in the same department. She has gained experience in various design and analysis programs, especially working in the field of transformer design. She joined Beta Transformer in 2018 and works as a specialist design engineer.