

## Design and Simulation of 11/0.4 kV Distribution Transformer Using ANSYS

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### ABSTRACT

This work presents a Finite Element Method (FEM) modeling of a 3-phase, 11/0.4 kV, 50 Hz, oil immersed, core (stack) type distribution transformer. In this work The ANSYS package is used to build the finite element model of the transformer, using actual transformer parameters. To investigate transformer performance several analyses are accomplished on this model such as; static analysis, transient analysis, harmonic analysis. Two types of analysis are considered; the linear analysis (using constant permeability) and the nonlinear analysis using the B-H curve of iron. The results are presented in 2D vector and contour colored plots of the FE model, the voltage and current curves, the magnetic flux lines, flux density, field intensity, current density, and magnetic forces.

**Keywords:** Distribution Transformer, FEM model, ANSYS.

### تصميم وعمل نموذج حاسوبي لمحوّلة توزيع 11/0.4 كيلو فولت باستخدام برنامج ANSYS

#### الخلاصة

هذا العمل يقدم نمذجة بطريقة العناصر المحددة FEM لمحوّلة توزيع ثلاثية الطور، 11/0.4 كيلو فولت، 50 هرتز، مغطّسة بالزيت من نوع اللب. في هذا العمل استخدمت حقيبة البرمجيات ANSYS لبناء نموذج العناصر المحددة للمحوّلة، باستخدام متغيرات لمحوّلة فعلية. للتحقق من أداء المحوّلة تم إجراء عدة تحليلات على هذا الموديل مثل تحليل الحالة المستقرة، الحالة العابرة، و الحالة التوافقية. تم اعتماد نوعين من التحليل وهما التحليل الخطي (باستخدام سماحية ثابتة) و التحليل اللاخطي باستخدام منحنى B-H للحديد. النتائج تم عرضها في رسوم ثنائية الأبعاد ملونة لنموذج العناصر المحددة، منحنيات الجهد والتيار، خطوط الفيض المغناطيسي، كثافة الفيض، شدة المجال المغناطيسي، كثافة التيار، و القوى المغناطيسية.

### INTRODUCTION

**A**NSYS is powerful software based on the finite element method for electromagnetism analysis [1]. In this work ANSYS is used to create a Finite Element (FE) model based on actual transformer parameters taken

from AlWazeria factory in Baghdad. The model comprises all the nodes, elements, material properties, real constants, boundary conditions, and other features that are used to represent the physical transformer.

The FE model is to estimate the performance of a three-phase 11/0.4 kV Delta/star distribution transformer, oil immersed, stack (core) type, 400 kVA, 50 Hz. This FE model is coupled to an external circuit to represent an actual 3-phase transformer under no-load and full load and short circuit conditions.

The solution is based on three types of analyses; the static analysis, the transient analysis, and the harmonic analysis. The analyses are of two type linear using constant permeability and nonlinear using the B-H curve for iron.

ANSYS Parametric Design Language (APDL) is used to automate building models in terms of parameters (variables) [1]. That includes creating the geometrical model, the formation of the FE model and the coupling with the external circuit. The direct coupling of the FE model with the electrical circuit includes coupling of the three phases with the input (delta connected) and output (star connected) circuits.

### ANSYS PROGRAM

The proposed program is written using ANSYS (version 11) Parametric Design Language (APDL), to attain two main objectives:

1. Creating the FE model of the distribution transformer.
2. Performing the required analyses on the FEM model.

Figure (1) shows a Flowchart of the proposed program for distribution transformer modeling and analysis.

### BUILDING THE TRANSFORMER MODEL

The practical parameters given in Table (1) [2] are used as input data for the modeling program. The program defines element types, system of units, element real constants, as given in Table (2), and material properties for insulators, oil, copper coils, and for iron core.

### BUILDING THE GEOMETRICAL MODEL

The proposed program is instructed to build the geometrical model of the transformer, as follows:

**Iron core:** With solid modeling the geometric shape of the iron core is created, as shown in Figure (2), according to practical cutting program of core sheets used by AlWazeria factory, as shown in Figure (3), and the input data from Table (1) [2]. The ANSYS program assigns material properties to the iron core of the transformer with a certain color to discriminate it from other materials such as coils and oil.

**High and Low voltage coils:** With solid modeling, the geometric shape of the high and low voltage coils is created using the input data. The ANSYS program assigns material properties to the high and low voltage coils with a certain color to be discriminated from other materials.

**Insulation areas (oil and other insulating materials):** the geometric shape of the insulation areas around core and coils is created using the input data. The ANSYS program defines the insulation areas material properties with a certain color.

The final geometrical model consisting of the four materials (iron, HV copper coils, LV copper coils, and the insulating materials) is shown in Figure (4).

### MESHING THE GEOMETRICAL MODEL

The next step is generating the finite element model. The ANSYS program is instructed to mesh the geometry automatically with nodes and elements using the triangular and quadrilateral shaped meshing.

Mesh control factors such as the element shape and the element size, to be used in meshing the solid model, will affect the accuracy and economy of the analysis [1].

**Core meshing:** The core of the transformer is meshed by triangular type mesh.

**Meshing of HV and LV Coils:** The coils of the transformer are meshed using quadrilateral shaped mesh.

**Meshing of the insulation areas between coils:** The insulation areas between coils of the transformer are meshed using triangular shaped mesh.

**Meshing of the insulation areas:** All the insulation areas of the transformer are meshed using triangular shaped mesh.

### THE TRANSFORMER FEM MODEL

The final transformer FE model meshed using triangular and quadrilateral shaped mesh is shown in Figure (5).

### APPLYING LOADS AND BOUNDARY CONDITIONS

After building the finite element model, loads have to be inserted and boundary conditions have to be specified and external circuits have to be connected to the FE model to simulate the distribution transformer.

#### a) Parallel flux boundary conditions:

Since the transformer tank is grounded, The boundary conditions for this FEM is chosen to be a zero flux at the earthed tank of the transformer, this means a parallel flux density  $D = 0$  at all external nodes.

#### b) Electrical circuit coupling:

The insertion of excitation loads to the FE model is achieved through direct coupling to external circuits.

Circuit element CIRCU124 can work together with magnetic element PLANE53 to simulate circuit fed magnetic analysis [1]. To do so, the following tasks are performed:

A PLANE53 stranded coils in the finite element model is created with the appropriate degree of freedom option KEYOPT (1) = 3, and the coil real constants are defined.

All the nodes of the PLANE53 coil elements are selected and coupled in the CURR degree of freedom and in the EMF degree of freedom.

**HV circuit coupling:** For connecting the transformer high voltage coils to the 3-ph electricity source 11KVA, a circuit of independent voltage source and a stranded coil circuit element are built for each phase.

**LV circuit coupling:** For connecting the transformer low voltage coils to the external load circuit, a stranded coil circuit element and external resistor circuit element are built for each phase to represent the load circuit.

Figure (6) shows the transformer FE model connected to the 11kV supply source and to the 0.4 kV load circuit, with nodes of HV and LV coils are coupled.

### PRELIMINARY INDIVIDUAL PHASE ANALYSIS

The analysis with constant permeability  $\mu_r = 1000$  is carried on one phase at a time to assure the validity of the FEM model, and the results are:

- When coil R is excited alone the flux is created in the limb of phase R and distributed through the other limbs as shown in Figure (7) (a), and the flux density distribution is shown in Figure (7) (b).
- Similarly when coil S is excited alone the flux in the middle limb for phase S is double the flux in the other two limbs, Figure (8) (a, b).
- When coil T is excited the flux in the third limb for phase T is also double the flux in the other two limbs, Figure (9) (a, b).

This shows clearly that the FE model is well built and the iron core carries almost all the linkage magnetic flux due to its high permeability while coils and insulations have no flux passing through them, only few percentage due to leakage flux.

### THREE PHASE ANALYSIS

The 11 kV supply network is represented by its Thevenin equivalent circuit for each phase.

The voltage for Thevenin voltage source is  $11 \text{ kV}/\sqrt{3} = 6350.85 \text{ V}$  and the peak to peak value is:  $6350.85 \times \sqrt{2} = 8981.46 \text{ V}$

Thevenin equivalent impedance is taken for a distribution network with short circuit level = 250 MVA,  $R = 0.07 \text{ m}\Omega$ ,  $X_L = 0.7 \text{ m}\Omega$ .

Three star connected Thevenin equivalent circuits represent the three phase supply network. This network is connected by three delta connected stranded coil circuit elements to the three phases of the transformer FEM, as shown in Figure (10) (a).

The low voltage secondary load circuit is represented by three stranded coil circuit elements star connected, with earthed common point to simulate the grounded neutral. The external resistance is connected to each phase (element terminal) to represent a resistive load connected to the output circuit. These loads end with an earthed common point to simulate connection of loads to the earthed neutral, as shown in Figure (10) (b). The resistive load can be replaced by a resistance and an inductor to simulate actual reactive loads, a load with certain power factor. In this work the resistive load is chosen that draws the maximum rated current at unity power factor. Taking the voltage at transformer secondary terminals = 416 V, the maximum load current is calculated as follows:

$$I_m = \text{kVA}/\sqrt{3} \times 416 = 400000/1.732 \times 416 = 555.16 \text{ A}$$

and the resistance per phase that draws this current is:

$$V_{ph}/I_m = 240/555.16 = 0.4323 \Omega$$

The final model with the coupled three phase circuit is shown in Figure (11).

### TYPES OF ANALYSIS

The distribution transformer is an alternating current device and the suitable analyses are the harmonic analysis and the transient analysis.

## HARMONIC ANALYSIS

For the three phase harmonic analysis the results are complex consisting of real and imaginary components and therefore the real and imaginary results are plotted separately.

**A) Linear analysis:** The first analysis is the linear harmonic analysis with constant iron core permeability  $\mu_r=1000$ . The results are presented as follows:

Figure (12) shows the flux lines distribution in the iron core, Figure (13) shows the flux density distribution contour plot, Figure (14) shows the flux density distribution vector plot, Figure (15) shows the magnetic field intensity distribution vector plot, and Figure (16) shows the Joule heat generation contour plot.

Part (a) of each the above figures presents the real component while part (b) presents the imaginary component.

**B) Non linear analysis:** The second analysis is the non-linear harmonic analysis using the B-H curve given in Figure (17) for M5 steel sheets. This leads to a non linear analysis due to the flux density saturation expected in the iron core. The analysis results are presented as follows:

Figure (18) shows the flux lines distribution in the iron core, Figure (19) shows the flux density distribution contour plot, Figure (20) shows the flux density distribution vector plot, Figure (21) shows the magnetic field intensity distribution vector plot. Part (a) in each of the above figures presents the real component, while part (b) presents the imaginary component.

## TRANSIENT ANALYSIS

In this analysis the same FE model and the same 3 phase coupled circuits given in Figure (11) is used to simulate the distribution transformer under transient condition.

The boundary conditions for this FEM is chosen to be a zero flux at the earthed tank of the transformer, this means a parallel flux density  $D = 0$  at all external nodes.

The applied excitation load are the sinusoidal voltage for the 11kV supply network with maximum phase voltage peak to peak value  $(11000/\sqrt{3})\times\sqrt{2} = 8981.46$  V. The other imposed voltage, are zero voltage at certain points so that the independent voltage source can operate adequately.

The excitation loads are applied for the three phases in 50 steps for a time of one cycle = 0.02 sec, this gives a step of time =  $0.02/50 = 0.0004$  sec.

**Transient analysis results:** The first analysis is linear considering iron core with constant permeability  $\mu_r = 1000$ .

The second analysis is non-linear considering iron core made of M5 steel sheets with the B-H curve as shown in Figure (17). The results are presented as follows:

Phase voltages in the primary and secondary windings for the three phases are shown in Figure (22), Phase currents in the primary and secondary windings for the three phases are shown in Figure (23),

Flux lines distribution in the iron core is shown in Figure (24), Flux density distribution contour plot is shown in Figure (25), Flux density distribution vector plot is shown in Figure (26), Magnetic field intensity distribution vector plot is shown in Figure (27).

In each of the above Figures (a) present a plot for the linear analysis results and (b) present a plot of the non-linear analysis results.

## DISCUSSION OF RESULTS

The results show the validity of this program. This can be highlighted through the following remarks:

1. The uniform flux density distribution in the iron core, represent a healthy magnetic circuit, as shown in Figures (12) to (14). Figure (14) shows that the linking flux is completely concentrated in the iron core, while the blue dots surrounding the iron core represent the stray field (leakage flux) and they are of negligible magnitude as it should be.
2. Figure (15) shows the magnetic field intensity H between primary and secondary windings.
3. The current densities induced in the secondary windings is in opposite direction to the primary winding supply current and has approximately the same current density as it should be.
4. Figure (16) (a) shows the heat generated in the windings.
5. Figures (18) (21) show the non-linear analysis using B-H curve for the iron core. In these figures, the difference is in the flux density distribution where noted the saturated regions in the iron core.
6. In the transient analysis the excitation voltage are applied to primary winding in 50 steps in sinusoidal wave form for one cycle = 0.02 sec. (frequency = 50 Hz) this enables getting the time response of voltage and current wave forms, Figure (22) shows the primary high phase voltage  $11000/\sqrt{3}$  (volt) and the secondary low voltage. Figure (38) shows the secondary high current, and the primary low current.
7. Figures (24-28) show the results obtained from transient analysis, in these figures noted some increase in the stray field outside the iron core, also some difference in flux density and magnetic field intensity distribution. The other result is the magnetic force generated between the primary and secondary windings, as shown in Figure (28). This analysis is very important in calculating forces exerted between windings due to transient conditions such as short circuit conditions.

## CONCLUSIONS

The proposed program is written using ANSYS APDL language as a general program to automate building the FE model of a distribution transformer depending on its actual parameters. This program was verified by building the FE model of a practical 400 kVA distribution transformer of Alwazeria factory in Baghdad.

Different analyses are carried on this FE model and the results obtained show the validity of this program.

**Table (1) Practical parameters of the 400kVA, 11/0.416 kV distribution transformer [2].**

Description of parameter	Practical parameter	Unit
e.m.f. per turn	9.607	Volt/turn
area of iron core	0.0255	m <sup>2</sup>
diameter of iron core	0.1962	m
No. of secondary turns per phase	25	non
No. of primary turns per phase	1145	non
area of core window	0.0527	m <sup>2</sup>
distance between core-centers	0.295	m
Width of window	0.155	m
height of window	0.34	m
width of iron core	0.73	m
Height of iron core	0.62	
total iron losses	0.85	KW
Magnetizing current	0.38	Amp
Secondary phase current	555.14	Amp
Cross-section of secondary conductor	232	mm <sup>2</sup>
Resistance of Secondary winding	0.0013	Ω
Primary Current	12.12	Amp
Cross-section of Primary conductor	4.93	mm <sup>2</sup>
Resistance of Primary winding	4.111	Ω
Total copper losses	4.25	kW
Total losses iron+copper	5.1	kW
Efficiency at unity power factor	98.74	%
Weight of iron	465	kg
Weight of copper	272	kg
Total weight of iron+copper	737	kg

**Table (2): Real constant set for the different element types.**

Real Constant	Set No.	CARE	TURN	LENG	DIRZ	FILL
R (iron, oil, insulators)	1					
R (cu coil LV)	2	0.0116	25	0.256	-1	0.29
R (cu coil LV)	3	0.0116	25	0.256	1	0.29
R (cu coil HV)	4	0.009715	1145	0.352	-1	0.29
R (cu coil HV)	5	0.009715	1145	0.352	1	0.29

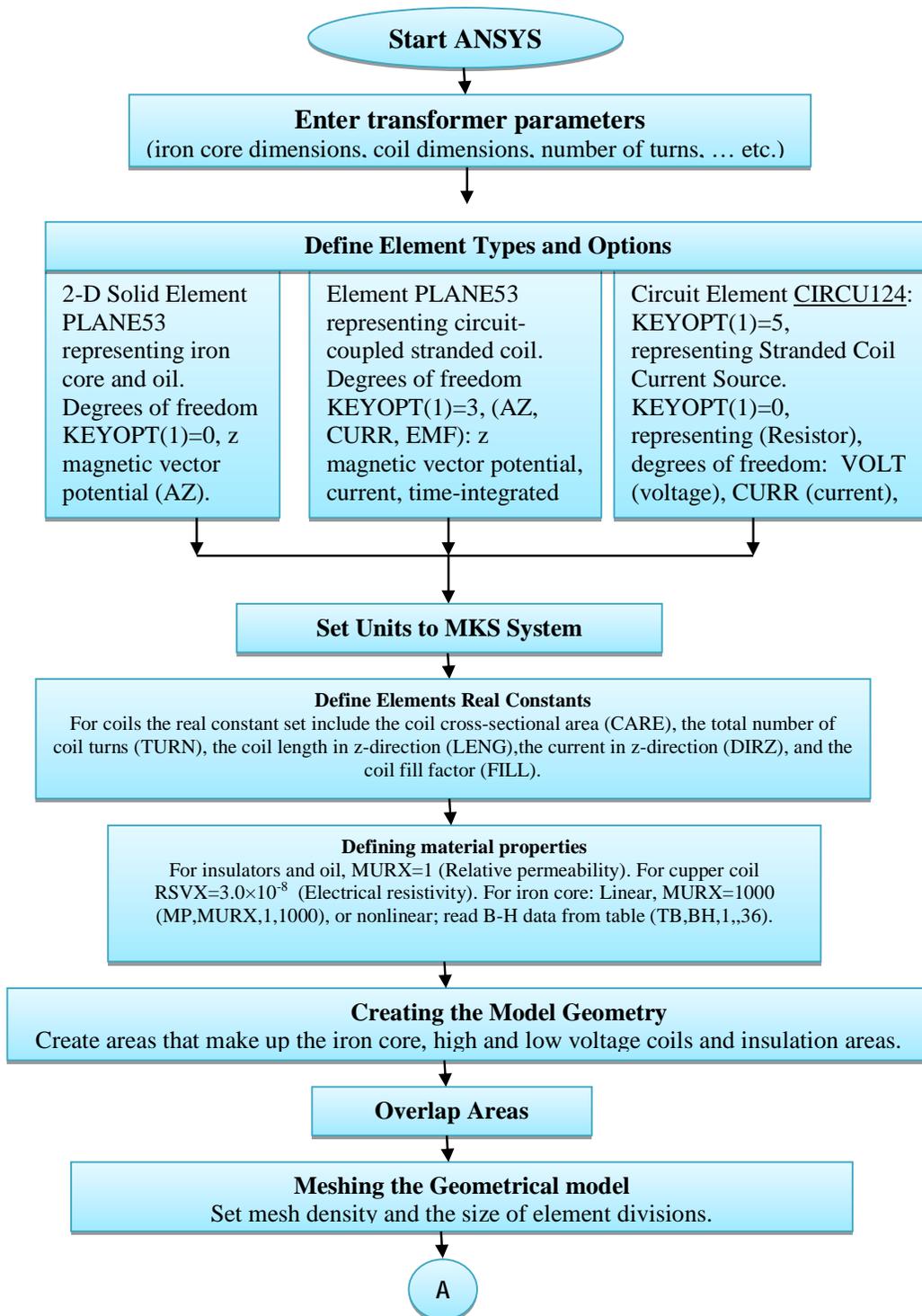


Figure (1) Flowchart of the proposed program written in ANSYS using APDL language, for a distribution transformer modeling and analysis.

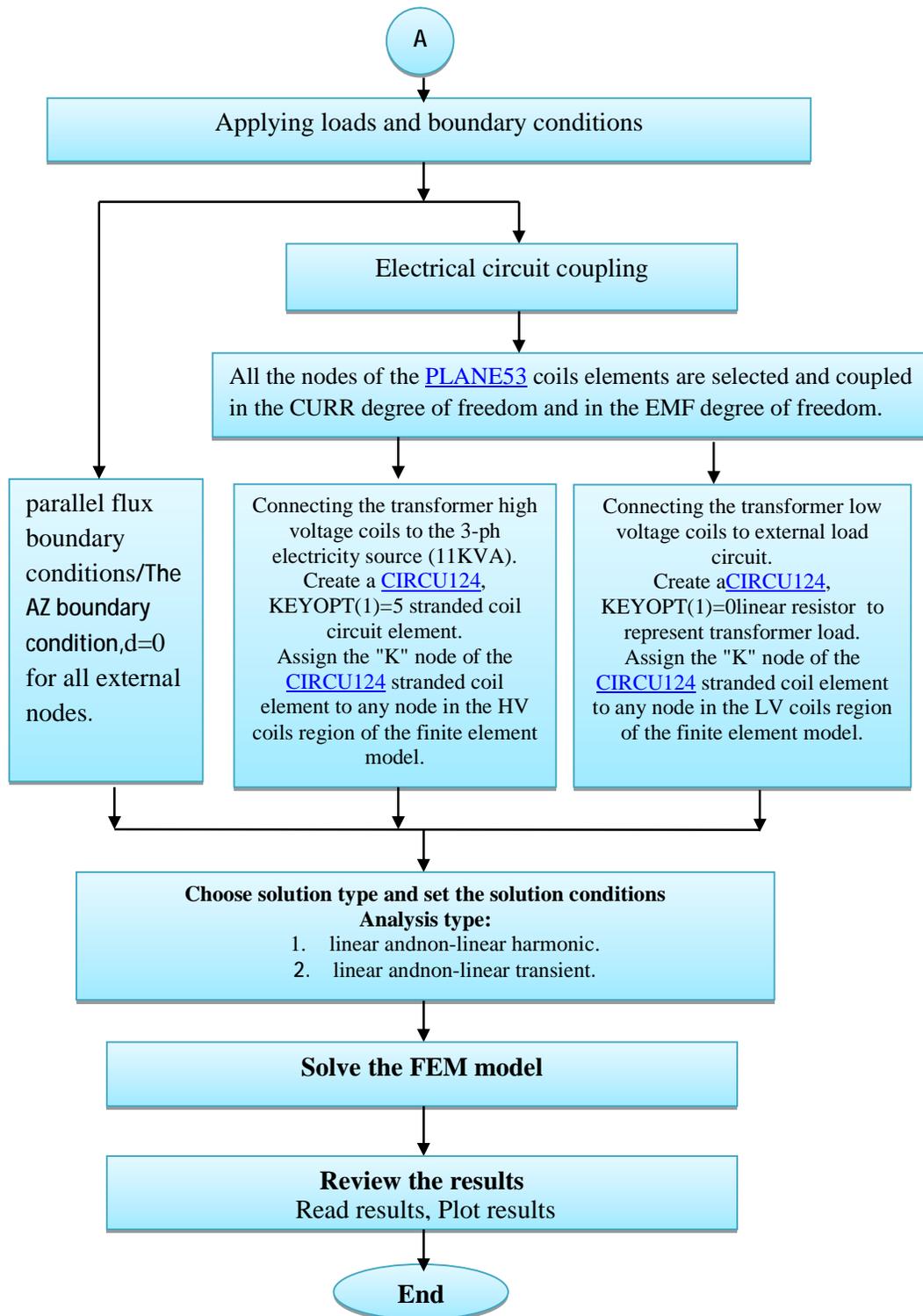


Figure (1) : (Continued)

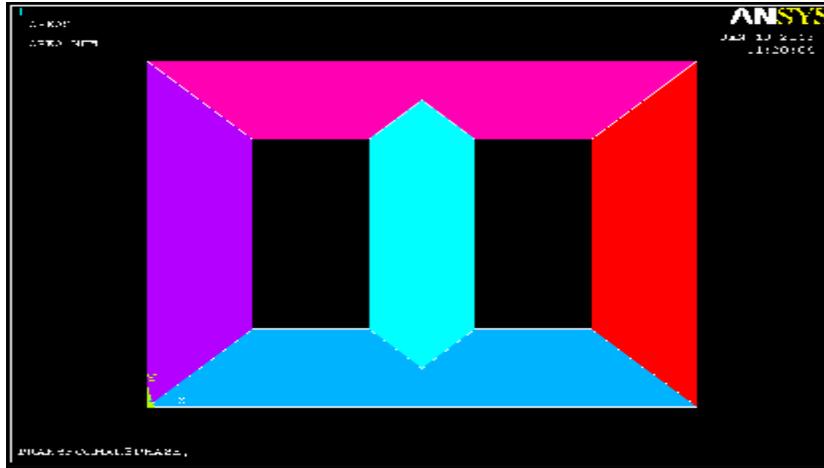


Figure (2) Iron core 2D geometric shape built according to practical sheet cutting.

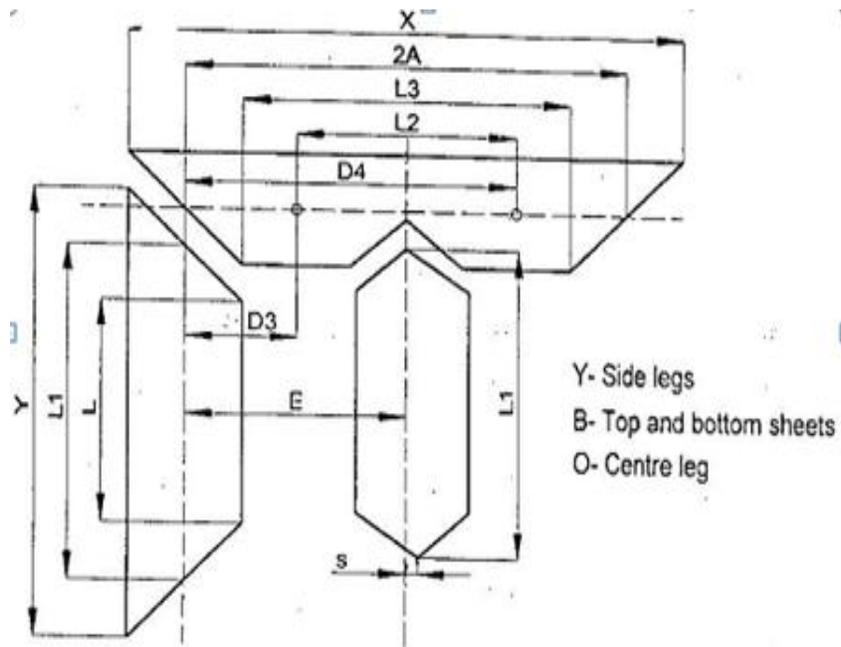


Figure (3) Cutting program of core sheets [2].

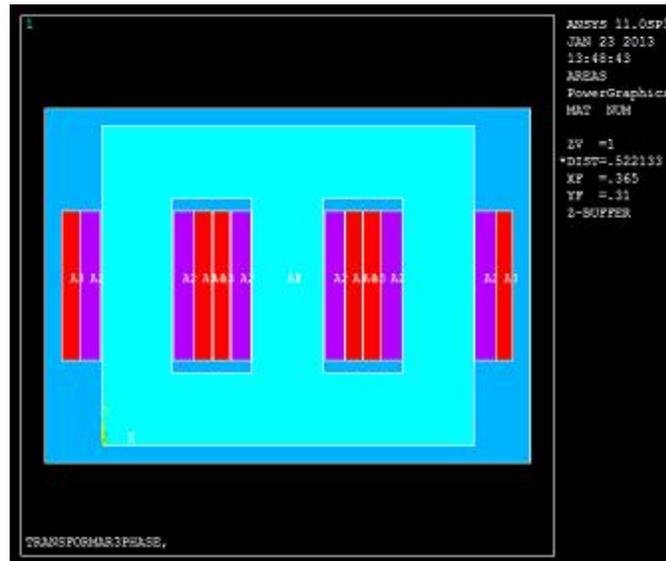


Figure (4) Transformer final geometric model with material properties assigned.

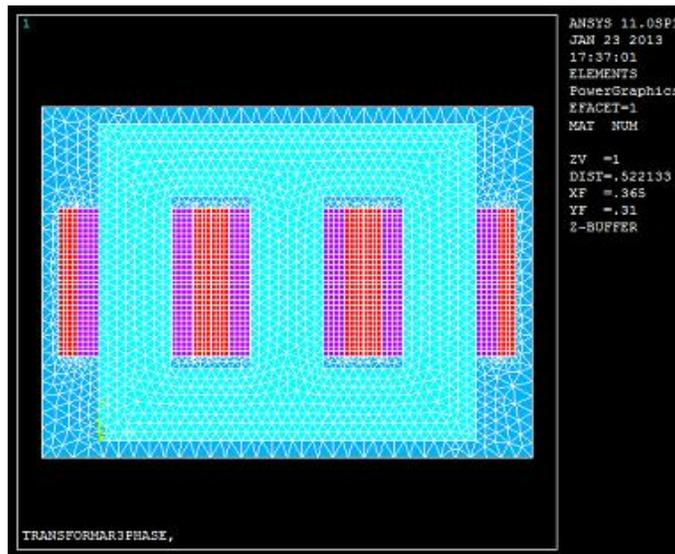


Figure (5): The final transformer FE model meshed using triangular and quadrilateral shaped meshing.

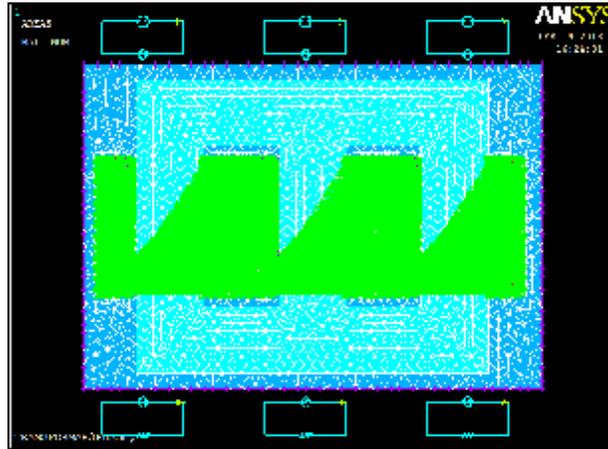
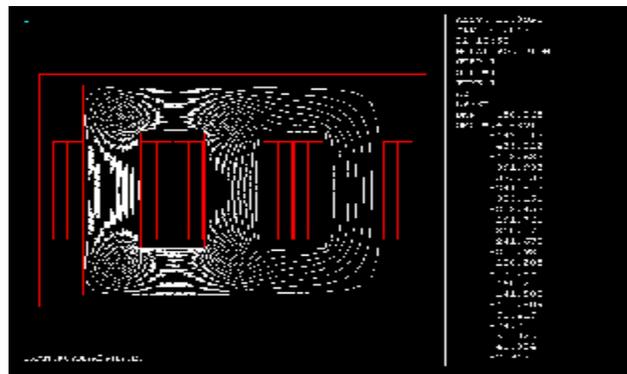
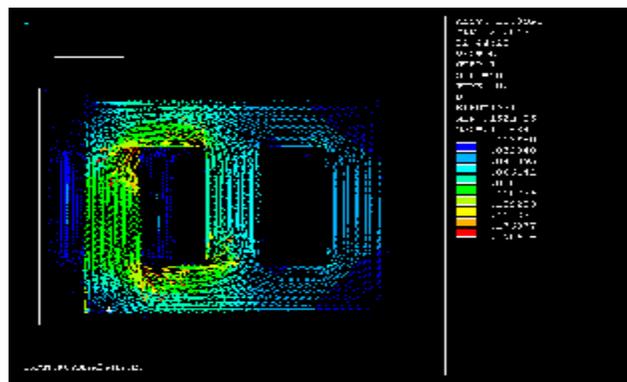


Figure (6) The complete transformer FE model connected to the 11kV supply source and to the 0.4 kV load circuit. with nodes of HV and LV coils are coupled.



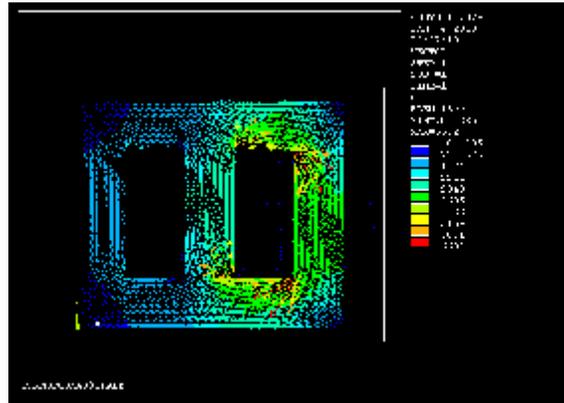
(a) Flux lines distribution.



(b) Flux density distribution vector plot.

Figure (7) (a) flux lines distribution and (b) flux density distribution vector plot, due to excitation in phase R alone.





(b) Flux density distribution vector plot.

**Figure (9) (a) flux lines distribution and (b) flux density distribution vector plot, due to excitation in phase T alone.**



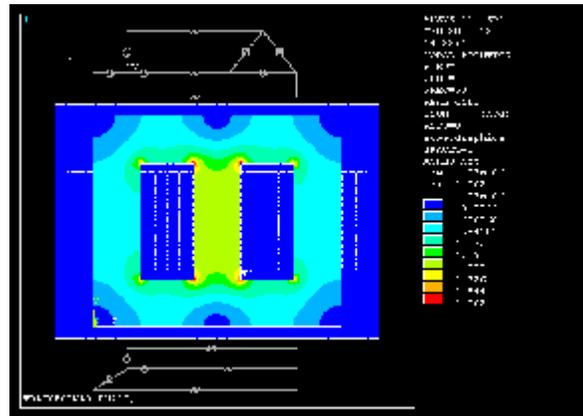
(a) Thevenin equivalent circuit for the three phase supply network connected to the delta connected stranded coil circuit elements to feed the three phases of the transformer FE model.



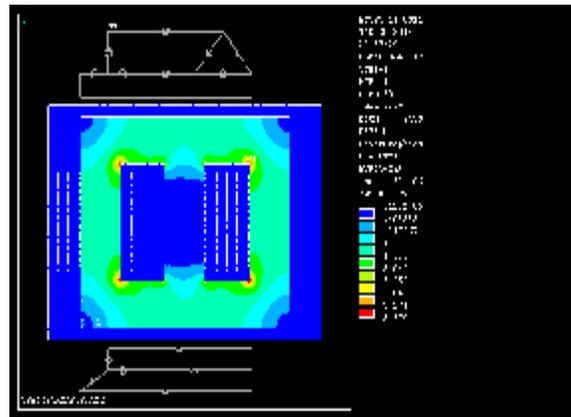
(b) Secondary load circuit represented by three stranded coil circuit elements, star connected with earthed common point, and a 3 phase resistive load.

**Figure (10) Three phase coupled circuit. (a) Supply circuit. (b) Load circuit.**



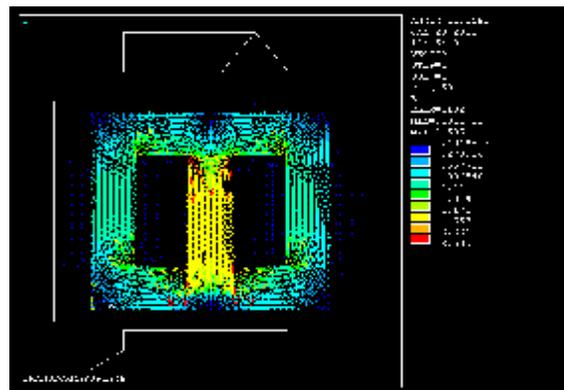


(a) real component.

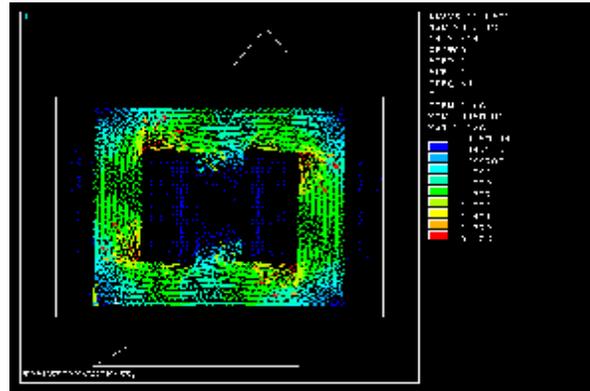


(b) imaginary component.

**Figure (13) Flux density distribution contour plot for the 3 phase linear harmonic analysis.**

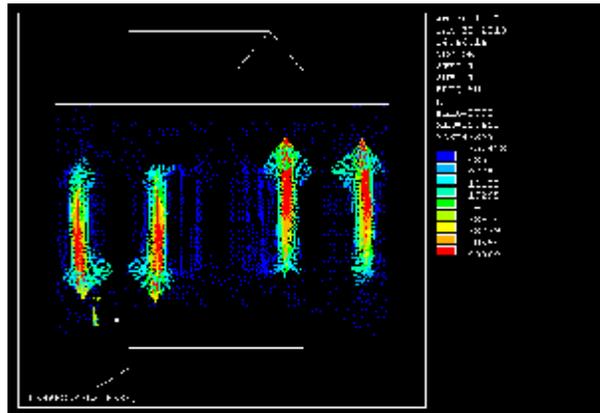


(a) real component.

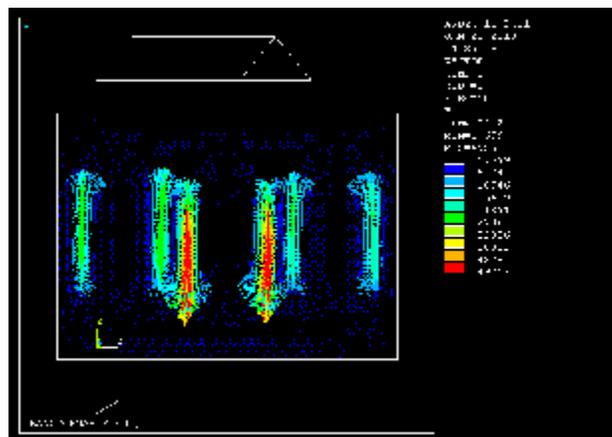


(b) imaginary component.

**Figure (14) Flux density distribution vector plot for the 3 phase linear harmonic analysis.**



(a) real component.



(b) imaginary component.

**Figure (15) Magnetic field intensity distribution vector plot for the 3 phase linear harmonic analysis.**

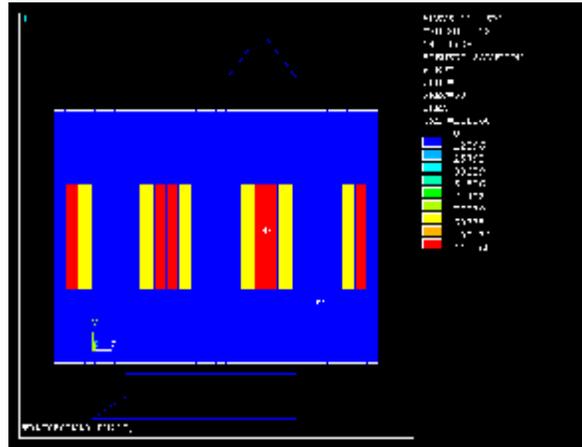


Figure (16): Joule heat generation contour plot for the 3 phase linear harmonic analysis.

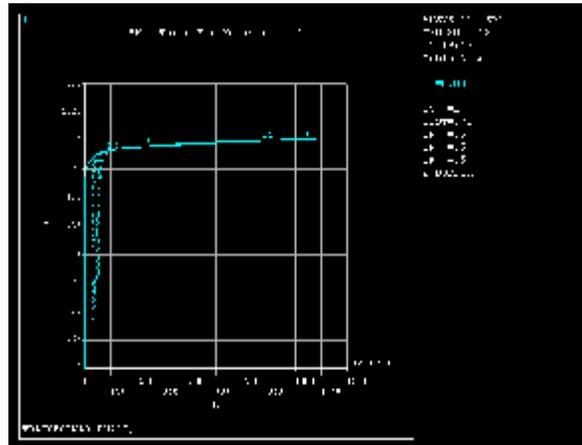
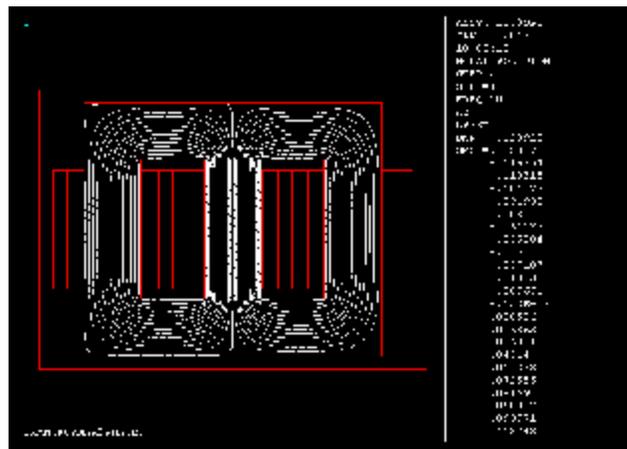
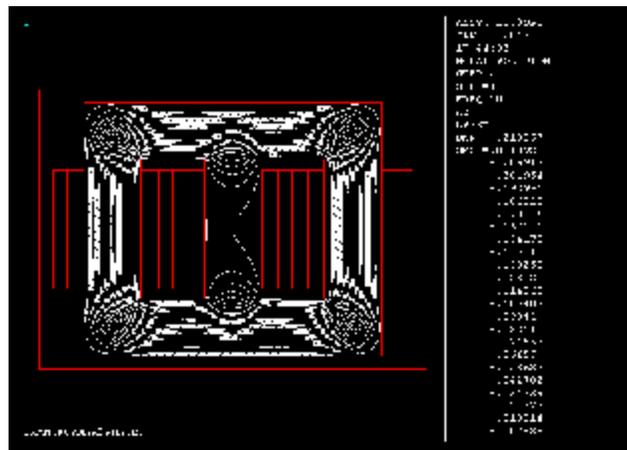


Figure (17) A plot using ANSYS for the data of the M5 steel B-H curve.

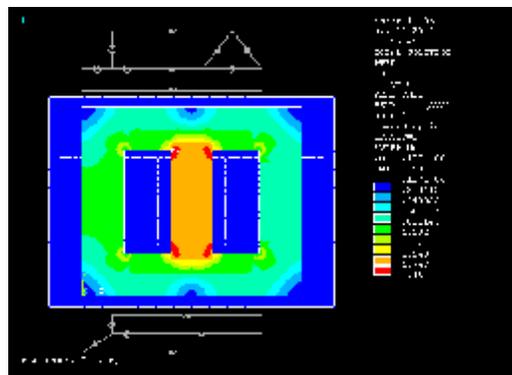


(a) real component.

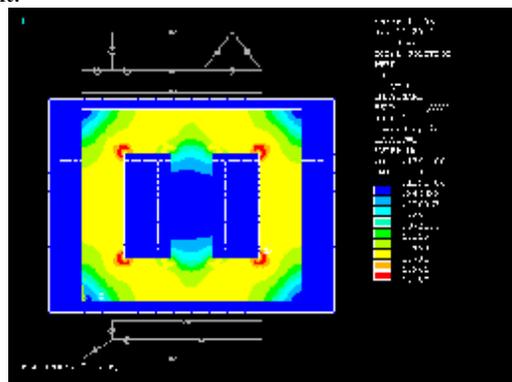


(b) imaginary component.

**Figure (18): Flux lines distribution in the iron core for the 3 phase non-linear harmonic analysis.**

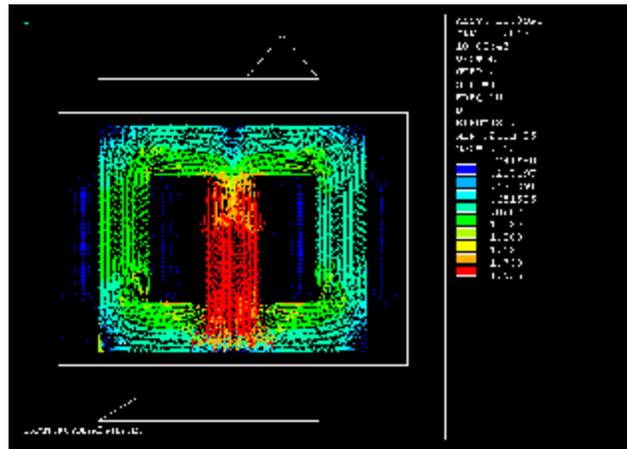


(a) real component.

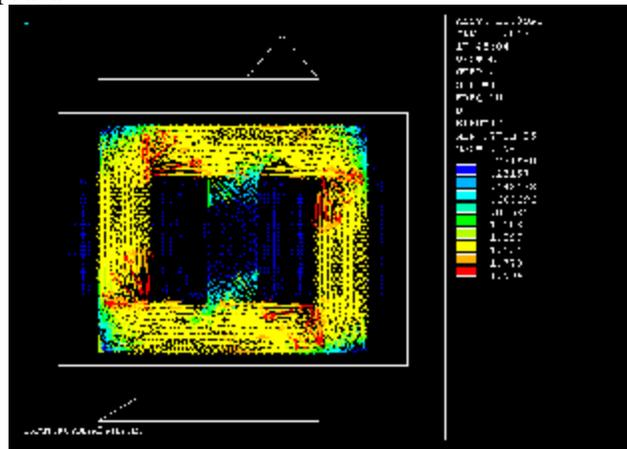


(b) imaginary component.

**Figure (19) Flux density distribution contour plot for the 3 phase non-linear harmonic analysis.**

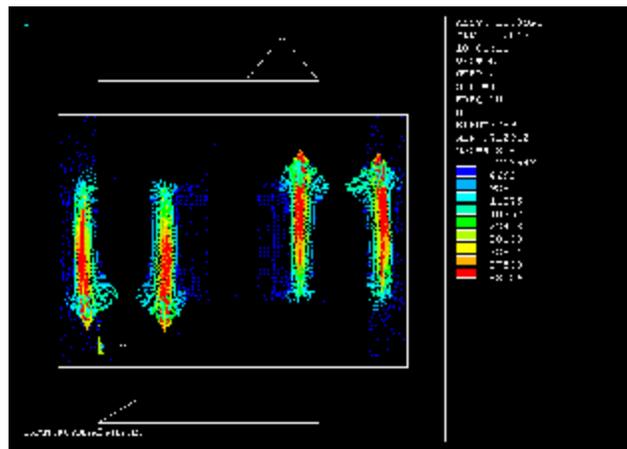


(a) real component.

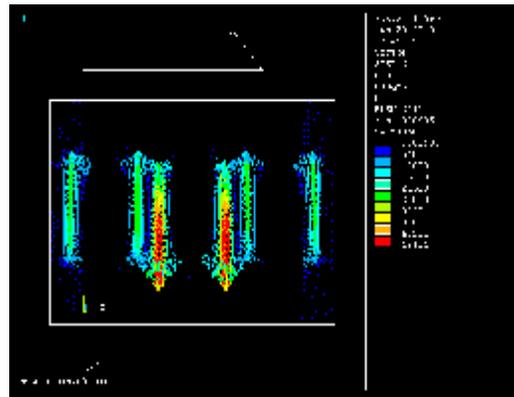


(b) imaginary component.

**Figure (20) Flux density distribution vector plot for 3-ph non-linear harmonic analysis.**



(a) real component.



(b) imaginary component.

Figure (21) Magnetic field intensity distribution vector plot for the 3 phase non-linear harmonic analysis. (a) real component. (b) imaginary component.

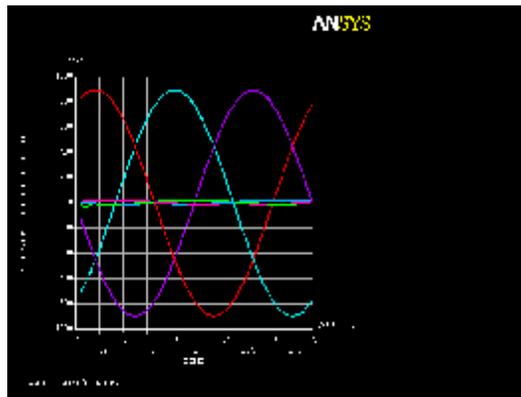


Figure (22) Phase voltages in the primary and secondary windings for the three phases.

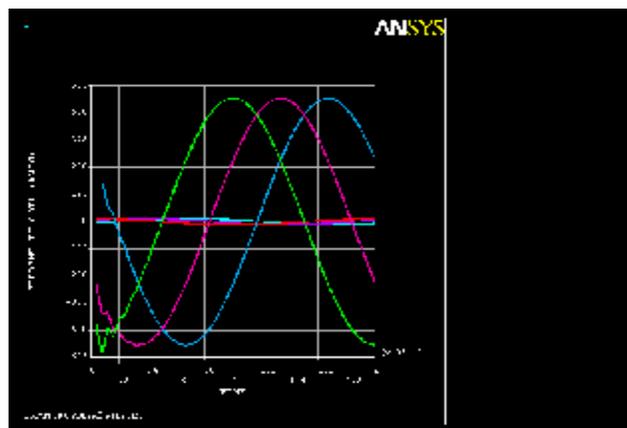
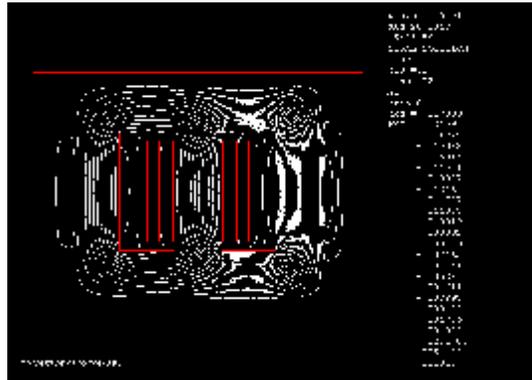
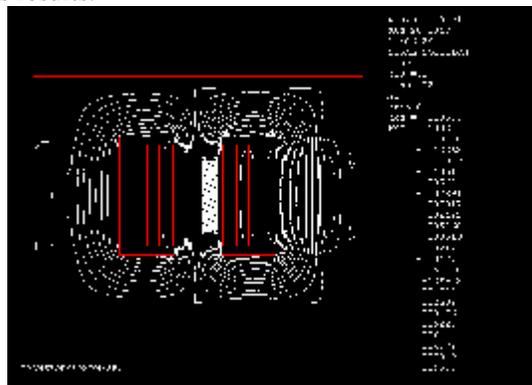


Figure (23) Phase currents in the primary and secondary windings for the three phases.

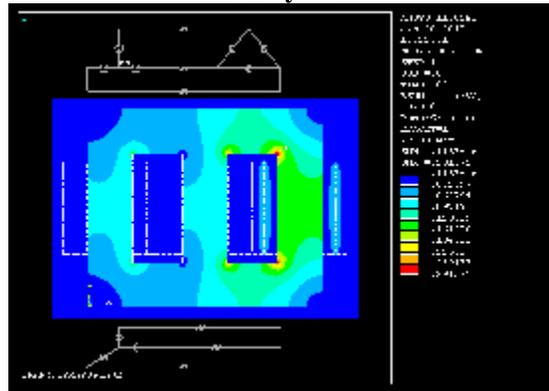


(a) linear analysis results.

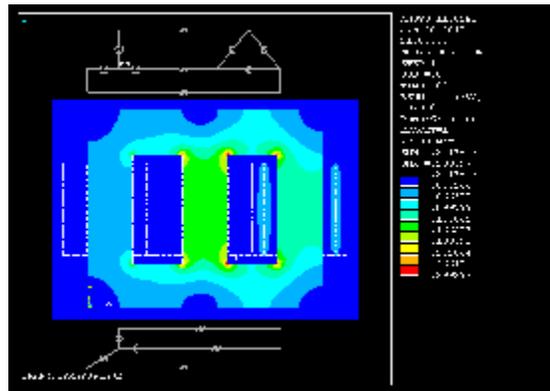


(b) non-linear analysis results.

**Figure (24) Flux lines distribution in the iron core for the 3-ph transient analysis.**

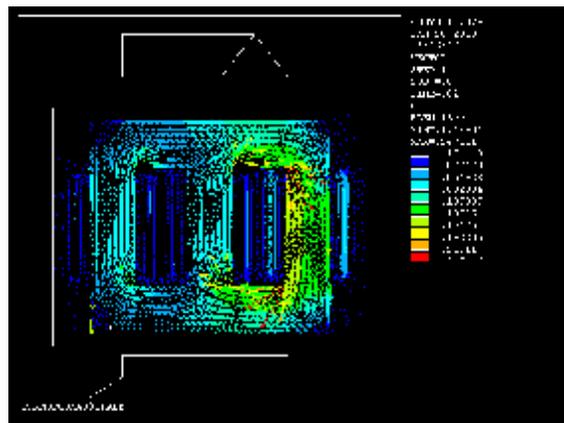


(a) linear analysis results.

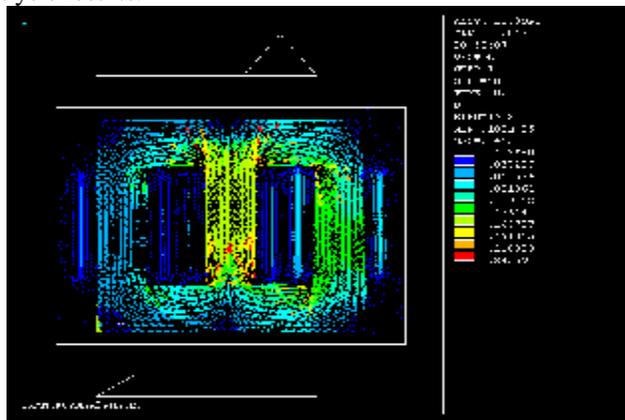


(b) non-linear analysis results.

Figure (25) Flux density distribution contour plot for the 3-ph transient analysis.

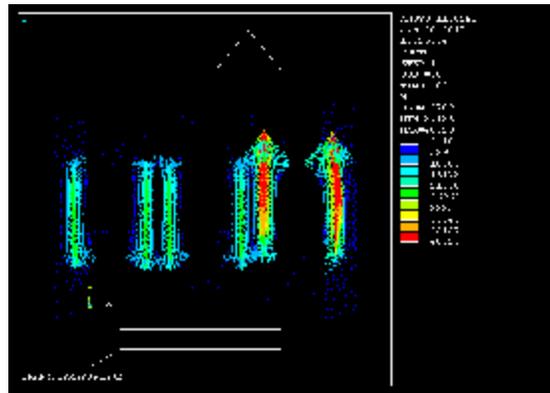


(a) linear analysis results.

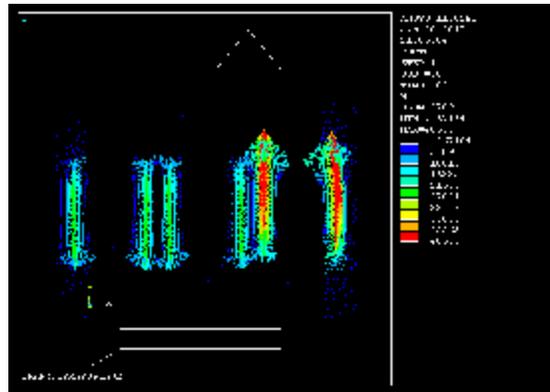


(b) non-linear analysis results.

Figure (26) Flux density distribution vector plot for the 3 phase transient analysis.

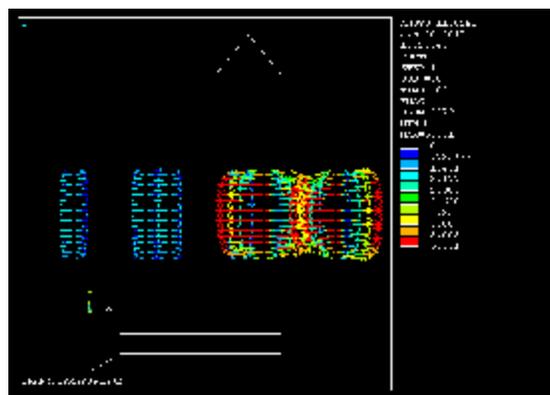


(a) linear analysis results.

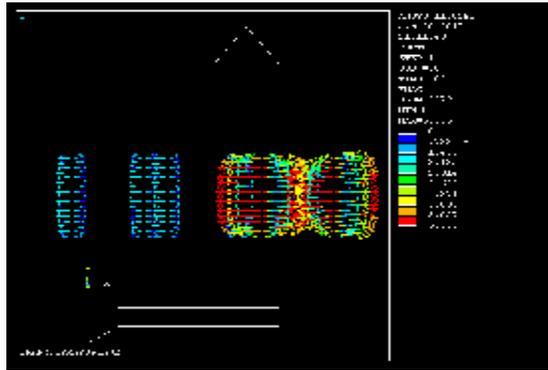


(b) non-linear analysis results.

**Figure (27) Magnetic field intensity distribution vector plot for the 3 phase transient analysis.**



(a) linear analysis results.



(b) Non-linear analysis results.

**Figure (28) Magnetic force distribution vector plot for the 3 phase transient analysis.**

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