ELECTRICAL WELDING TRANSFORMER DESIGN

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ABSTRACT
This paper presents a survey to the design procedures of dry cooling moving limb arc welding transformer types. Two different methods are used for this purpose. The first method is based on analytical approach, while the second method is based on numerical approach, finite element method (FEM). A two dimensional finite element method is used to compute the flux distribution in each transformer parts. The transformer parameters, losses and losses distributions, electromagnetic force on the windings and force distribution, temperature rise and performance characteristics during the design process are calculated, also. The nonlinearly and saturation of iron core are taken into account by using the actual B-H curve of the iron core. This procedures is established and used to build and analyze different types and ratings of transformers. Theoretical, analytical and FEM, and experimental characteristics are carried out on 400A welding transformer and a comparison is given between them. It has been shown that the FEM method gives better results than analytical method, where a good agreement is obtained between the predicted characteristics that calculated using FEM and experimental ones.

Keyword: Welding transformer design, FEM for transformer analysis, force computation in transformer, loss computation in transformer, temperature rise calculation, automatic triangle FE grid generation.

1. INTRODUCTION
The moving limb arc-welding transformer is popular for welding process, due to simple construction, lower cost and its welding characteristics. Figure (1) shows two sections, elevation and plan, of shell type arc welding moving limb transformer. The design of welding transformer likes the design of power transformer but has some different ranges for chosen the design factors. The most important factors are [1-3,5]:

1. The air gap length in the magnetic circuit, lg.
2. The ratio of window height/ window width, Kwh.
3. The ratio of core depth/ core width, Kdw.
4. Steel lamination type, B-H curve.
5. Winding material type, ρ.
6. Winding current density, J.
7. Core flux density, Bm.
8. Window space factor, Kw.
9. Duty cycle, DS.
10. The moving limb dimensions and shape.
11. The maximum temperature rise, Tm.

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All of these factors are studied to choose the suitable values for optimum transformer design. About ten years researching for design, analysis, molding and developing welding transformers gave a lot of information, data, analysis, equivalent circuits and complete procedures for AC and DC welding transformers design [1-8].

2. *PROCEDURES OF WELDING TRANSFORMER DESIGN*

The procedures of power transformer design[12-13] were developed to give complete procedures of welding transformer design [1-8]. Two procedures were obtained which are analytical[1-3] and numerical (i.e FEM) [4-8] approches. They are sharing the main steps of the transformer design but each approch had different method for calculating the equivelant circuit parameters. Before starting the design steps, some important terms and design factors should be difined as given bellow:

2.1 Constant and Variable Parameters

1. Supply frequency, F.
2. Winding current density, J.
3. Maximum flux density, Bm.
4. Window space factor. Kw.
5. Voltage per turn, Et.
6. Core depth/ core width, Kdw.
7. Winding resistivety, ρ.
8. Lamination steel B-H curve.
9. Window height/ window depth, kwh.

2.2 Welding Transformer Specification

1. Maximum welding current.
2. Primary and secondary voltages.
3. Rated power.
4. Duty cycle.

2.3 Design Steps

The main steps of welding transformer design may be classified as:

2.3.1 Core Design

- Calculate the voltage per turn, Et, using input power and duty cycle.
- Calculate the iron core area from Et equation.
- Calculate the window dimensions from the transformer output equation.
- Calculate the transformer depth from core area and Kdw.
- Calculate the overall dimensions of the transformer core, Ht & Wt.

2.3.2 Winding Design

- Calculate the numbers of primary and secondary windings, N1 & N2, using the primary and secondary voltages and Et.
- Calculate the conductor areas of both windings using the rated currents, Ip, Is and J.
- Calculate the number of turns per layer of each winding.
- Calculate the number of layers of each winding.

2.3.3 Moving Limb Design

- Depth of moving limb equals (100 % -110 %) of transformer depth.
- Height of moving limb equals (15% - 25 %) of window height.
- Width of moving limb equals the window width out of it 2 lg.
- Moving limb controlling system (mechanical system).

2.3.4 Container Design

Container design depends on the final dimensions of the core after wounding and the available space required and the accessories.

2.3.5 Additions for DC Welding Transformer

- High current inductor design as smoothing element [2,15].
- Full wave bridge rectifier [2].
- Some simple electronic circuit.

3. WELDING TRANSFORMER ANALYSIS USING ANALYTICAL METHOD

An analytical method was developed[1,3] and used to calculate the transformer parameters. These equations take into account the insertion depth of moving limb through the winding transformer leakage reactances [1,3], as given below:-

$$Xlp=2\pi f\mu o\, Np^2 [(Lmt\, b1/ 3\, Wc)+ d\, am/Lg + d\, (ac-am) / Wc + ac\, (Lmt- 2\, d) / 2\, Wc] \quad (1)$$

$$Xlsd=2\pi f\mu o\, Np^2 [(Lmt\, b2/ 3\, Wc)+ d\, am/Lg + d\, (ac-am) / Wc + ac\, (Lmt- 2\, d) / 2\, Wc] \quad (2)$$

$$Xm = V1/ (Io \sin \phi o)^2 \quad (3)$$

$$Rm = Pir/ (Io \cos \phi o)^2 \quad (4)$$

$$Rp = Kr\, \rho\, Lmt1\, Np / a1 \quad (5)$$

$$Rs = Kr\, \rho\, Lmt2\, Ns/ a2 \quad (6)$$

$$Lmt = (Lmt1 + Lmt2) /2 \quad (7)$$

$$Wc = (Wc1 + Wc2) /2 \quad (8)$$

$$Pir = Gi\, pis \quad (9)$$

where;

f : supply frequency.

μo : free space permeabilty.

Np ,Ns : primary and secodary number of turns respectively.

Lmt1, Lmt2 : the lengthes of main turns of primary and secondary windings recpectively.

b1 ,b2 : hight of primary and secondary windings respectively.

d : transformer depth.

am : moving limb hight.

Lg : air gap length between the moving limb and the transformer limbs, as shown in Fig. (1).

ac : the hight between the two transformer windings.

Wc1, Wc2 : width of primary and secondary windings recpectively.

a1, a2 : cross sectional area of primary and secondary windings recpectivly.

Kr : resistance correction factor (1.1 - 1.15).

Io , ϕo : no-load current and its angle .

Gi : iron wight of transformer core.

Pir, pis : total iron losses and specific iron loss of transformer sheet recpectively.

Xlp, Xlsd : primary and secondary leakage reactances recpectively refared to primary side.

Rp, Rs : resistance of primary and secondary winding recpectively.

Rm, Xm : equivlant resistance of iron losses and mutal reactance of transformer core recpectively.

The operating characteristics of a welding transformer during the design process was calculated using the above parameters and a development transformer equivelant circuit [1,3]. The calculated characteristics of the welding transformer (E-405)[1,3] at load, using that method, are shown in Figs. (14-17).

For more accurate calculation of flux distribution and prediction of transformer characteristics, the difficulty of magnetic flux distribution due to the moving limb is solved using a nonlinear two dimensional magneto-static finite element method, N2DFEM [5-6]. New equations for welding transformer equivelant circuit parameters (i.e Xlp, Xls, Xm & Rm) were formulated based on the FE flux calculation [4,6]. Aftar that the operating characteristics were calculated [4,6]. The full design procediuer of welding transformer using the FEM is sammarized in the following sections based on the published workes[1-8,12,15] which are given in the References.

Finite Element method becomes usefull toole for flux calculation in electrical apparatus [3-10]. Once, the flux distribution is obtained all the related machine parameters (such as inductance, force, stored energy, etc.) can be calculated. With FEM, the global area should be divided into suitable number of finite elements. In welding transformer analysis [4-8], two dimensional, nonlinear, magneto-static triangular element was used. New algorithm to build the triangular finite element grid automatically is discovered [6,8].The new method is simple, reliable and needs minimum information.

4.1 Finite Element Grid

There are two general cells to build the whole mesh as shown in Figs. (2&3). The equations of the general cell Fig. (2-a) are formulated and given with full details in Reference [8]. While the equations of Fig. (2-b) is discovered during the Ph.D. research [6] and they are given here. These algorithms were successfuly applied to welding transformer analysis[4-8]. They can be used for any application has a rectangular global area. The main objectives of these algorithms are samiler. These general cells are mainly used for:-

- Calculating the total number of nodes, NN, and elements, NE, in the global area as;

$NN = NX\ NY$ (10)

$NE = 2\ (NX - 1)\ (NY - 1)$ (11)

where ; NX : the number of nodes on the x- axiss
NY : the number of nodes on the y- axiss

- Numbering each node in the global area as;

for upper triangle, N1: K=R, L= R+NX+1 & M=R+NX (12)

for lower triangle, N2: K=R, L= R+1 & M=R+NX+1 (13)

where; K,L &M the vertices of each triangle in the FE grid.

- Numbering each element in the global area as;

for upper element,N1 = 2 (R - current row number)+1 (14)

for lower element,N2 = 2 (R - current row number)+2 (15)

- Calculating the area of each element, Ae, as;

$Ae = Dx\ Dy / 2.$ (16)

- Determining the x-y co-ordinate of each node in the FE grid using the main equations of the vertices of the general cell as;

node	R	R+1	R+NX+1	R+NX
X-Y coor.	(x,y)	(x+Dx)	(x+Dx ,y+Dy)	(x, y+Dy)

- Building the finite element connection matrix as;

for N1:

ICON (1,N1) = K = R, ICON (2,N1) = L =R+NX+1, ICON (3,N1) = M =R+NX (17)

for N2 :

ICON (1,N2) = K =R, ICON (2,N2) = L = R+1, ICON (3,N2) =M = R+NX+1 (18)

- Calculating the element center co-ordinates.

4.2 Flux Density Computation

After covering the global area with finite element grid as shown in Fig. (3), stating the boundary conditions and defining the element types, the solution can then start. By solving the Posion's Equations (23), in the global area using FEM the flux density in each element can be obtained [4-12]. The derivation of the main equations of the FEM are picked up from References [6,11] and rewritten as the following.

4.2.1 Derivation of the main equations of the FEM

To obtain the Posion's Equation which governing the electromagnetic equation in the welding transformer in cartesian co-ordinates in two dimenstions (i.e the winding currents in the z-direction) the following sequence was considered based on Maxwell's field equations [6,11] ;-

$$\text{Div}\ \mathbf{B} = 0 \quad (19)$$

$$\mathbf{B} = \text{Curl}\ \mathbf{A} \quad (20)$$

$$\mathbf{H} = \gamma\ \mathbf{B} \quad (21)$$

$$\text{Curl}\ \mathbf{H} = \mathbf{J} \quad (22)$$

$$\text{Curl}\ (\gamma\ \text{Curl}\ \mathbf{A}) = \mathbf{J} \quad (23)$$

After expansion, this will lead to:

$$\frac{\partial}{\partial x}(\gamma \frac{\partial Az}{\partial x}) + \frac{\partial}{\partial y}(\gamma \frac{\partial Az}{\partial y}) = - Jz \qquad (24)$$

$$B(x, y) = \frac{\partial Az}{\partial y} ax - \frac{\partial Az}{\partial x} ay \qquad (25)$$

Where,
B: magnetic flux density vector, T.
H: magnetic flux intensity vector, A/m.
J: current density vector, A/ m2.
$\gamma = 1 / \mu$: iron reluctivity

In order to achieve a numerical solution to the nonlinear partial differential Eqs. (23 & 24), the Euler equation is applied to solve the following energy function[6,9-10];

$$F(A) = \sum_{e=1}^{ne} Fe(A) = \sum_{e=1}^{ne} \iint_{Re} (\int_{B=0}^{Be} \gamma . B . dB - Je . Ae). dx . dy \qquad (26)$$

With chosen the firest order triangular elements,as shown in Fig. (2), the interpolation polynomial of the vector magnetic potential, **Ae**, in each element has the following form [6,10-11];

$$Ae(x,y) = (\sum_{j=k,l,m} (Pj + qj\, x + rj\, y)\, Aj) / (2\, Se) \qquad (27)$$

The parameters Pj, q j & rj are considered also, functions of the co-ordinates of the elemental vertices(i.e k,l &m)[6,9-10] as followes;

for k	pk =xl ym -xm yl	qk = yl- ym	rk = -(xl-xm)	
for l	pl = xm ym - xk ym	ql = ym- yk	rl = - (xm-xk)	(28)
for m	pm = xk yl - xl yk	qm = yk - yl	rm = - (xk -xl)	

Euler's Equation must be satsfied at the stationary point of the function Fe(A). This stationary point is determined by setting the first derivative of the function Fe(A) equal to zero[6,10-11]. The result of this process over all nodes of the finite element grid gave the following matrix equation;

$$[S]\,[A] = [I] \qquad (29)$$

Vector **[I]** is the nodal currents (the forcing function). It has NN elements, for k th node was defined as;

$$Ik = (\sum_{e=1}^{e=nchk} Se\, Je) / 3 \qquad (30)$$

where, nchk : the number of elements sharing at the k th node.
Matrix **[S]** is the global coefficient matrix and it has NN x NN elements. It is nolinear, sparse, symmetric, banded and singular. The jk th entry of this matrix is defined as followes;

$$Sjk = (\sum_{e=1}^{e=nchjk} \gamma e\, (qj\, qk + rj\, rk) / (4\, Se) \qquad (31)$$

where, nchjk : the number of elements sharing the j th and k th nodes.
Vector **[A]** is the unknown magnetic vector potential and it has NN elements.

After solving Eq. (29), the magnetic vector potential [A] is determined and the magnetic flux density at the center of each element can be calculated by ;

$$Bex = (Ak\, rk + Al\, rl + Am\, rm) / (2\, Se) \qquad (32)$$
$$Bey = (Ak\, qk + Al\, ql + Am\, qm) / (2\, Se) \qquad (33)$$
$$\mathbf{Be} = Bex\, \mathbf{ax} + Bey\, \mathbf{ay} \qquad (34)$$

triangle elements, as shown in Fig. (3), and the element types with the boundary conditions should be correctly known.

4.2.2 Boundary conditions

The boundary conditions mean a group of real conditions and some logic assumptions required to solve the magnetic vector potential [A] in Eq. (29). The real conditions include determining the types of all elements of the FE grid, where these elements can be classified to :-

1- Air element, which has no iron sheet nor exciting electric current (i.e. $J=0$, $\mu r=1$).
2- Iron element, which contains iron sheet only(i.e. $J=0$, $\mu r >> 1$ & $\rho=0$).
3- Exciting element, which contains exciting electric winding (i.e. $J> 0$, $\mu r=1$ & $\rho >0$).

While the logic aasumptions include the values of the magnetic potential of the nodes laying on the border lines. Where for shell type welding transformer these nodes had zero values mainly due to the following assuptions :-

1- The border line within the center limb is the seperation line between two symmetrical magnetic circuits and has not any flux lines (i.e $\Phi=0$ & $A=0$).
2- The other borders have very low value of magnetic flux and can be neglected (i.e $\Phi=0$ & $A=0$).

4.2.3 Application

The above sequance is used to calculating the flux density distribution in different ratings of welding transformers. As a sample of these calculations, Figs. (4-7) show the results of flux density distribution of E-405, moving limb arc welding transformer. Table (1) gives the experimental and numerical calculation of flux density, at the five positions shown in Fig.(3-b), at four different operating conditions. The search coil method is used for experimental verification. The recorded emf of som search coils wounded on different positions on the magnetic circuit are given in Fig. (8) while these position are shown in Figs. (3,10).

4.3 Losses Distribution

The ordinary equation of calculating copper and iron losses in power transformer [13-14] are modified to suit the FEM [6,8] to calculate the loss density distribution and total losses. The derivation of these equations with simple and accurate representation was obtained in[8]. The summary of those derivations are given through the following equations as .

$$Pie = pise \; Gie \qquad (35)$$

$$Pi = \sum_{e=1}^{NOIE} Pie \qquad (36)$$

$$pcse = (\rho cue / \gamma cue) \; Je^2 \qquad (37)$$

$$Pcue = pcse \; Gcue \qquad (38)$$

$$Pcup = a \left(\sum_{e=1}^{NOPE} Pcue \right) \qquad (39)$$

$$Pcus = b \left(\sum_{e=1}^{NOSE} Pcue \right) \qquad (40)$$

$$Ploss = 2 \, Pi + (Pcup + Pcus) \qquad (41)$$

where;

pise : element specific iron losses, w/Kg.
Pie : iron element loss.
Gie : weight of iron element, Kg.
Pi : iron losses of half transformer core.
NOIE : number of iron elements.
ρcue : winding resistivity.
γcue : winding spesific weight, Kg/ m^3.
Je : element current denisty, A/ m^2.

pcse : element specific copper loss, w/Kg.
Gcue : weight of copper element, Kg.
Pcue : winding element loss.
a,b : corection factors of winding losses and thier values depend on the ratio of Lmt/d.
Pcup, Pcus : primary and secondart copper loss respectively.
NOPE, NOSE : primary and secondary number of elements.
Ploss : total transformer loss.

Figures 6-7 show the iron and copper losses distribution at minimum and maximum welding current of E-405.

4.4 Force Computation on Windings

The force computation on windings of welding transformer can be calculated with three developed methods [7,12]. Analytical method, AM, Image representation method [12], IRM and FEM. Lorenz's Force equation is developed to calculate the redial and axial force components in welding transformer [7]. The comparisons between these methods show that good agreement between FEM and experimental result [7,12]. The IRM gives the total force on each winding around the calculated values using FEM. But the force distribution is different over the height of the windings. IRM and FEM can be used to calculate redial and axial force components but AM can not calculate the redial component. Figure (9 a-b) show the forces distribution at full load, with and without moving limb [7], while, Fig. (9-c) shows the comparison between FEM, IRM and measured values of axial force on the secondary winding [12]. Tabel 2 shows the axial and radial forces for E-405 on the secondary winding at 400 A welding current.

Table 2
Total axial and radial forces on secondary windings for E-405 at 400 A welding current

Forc, in N.	Measured value	FEM	IRM	AM
Axial, Fas	407.992	395.265	375.213	387.346
Radial, Frs	----------	21.052	54.741	----------

The detailes of those developed methods are summrized here as the following.

4.4.1 FEM [7]

In Reference[7] the formulation of force on current-carrying conductors was developed to suit the welding transformer and the N2DFEM. Where the axial and radial components of electromagnetic force for both primary and secondary windings, Frp, Fap, Frs & Fas, were written in the following forms;

$$Frp = \sum_{e=1}^{NOPE} -Jp\ Bye\ Se\ Lmte\ Kov \tag{42}$$

$$Fap = \sum_{e=1}^{NOPE} Jp\ Bxe\ Se\ Lmte\ Kov \tag{43}$$

$$Frs = \sum_{e=1}^{NOSE} -Js\ Bye\ Se\ LmteKov \tag{44}$$

$$Fas = \sum_{e=1}^{NOSE} Js\ Bxe\ Se\ Lmte\ Kov \tag{45}$$

Also, the radial and axial force distributions, fr &fa, along a winding having NOD divisions and NOEPD elements per division, as shown in Fig. (10-11), wrer calculated by;

$$fr = \left(\sum_{e=1}^{NOEPD} Fre\right) / Dh \tag{46}$$

$$fa = \left(\sum_{e=1}^{NOEPD} Fae \right) / Dh \qquad (47)$$

where; Bxe, Bye : x and y flux density components of e th element.
Jp, Js : primary and secondary current density.
Lmte : winding main turn of e th element.
Kov : over hang factor.
Fre, Fae : radial and axial force components of e th element.
Dh : division height

4.4.2 AM [7]

The analytical equation for axial force calculation, fa, for the interleaved windings[16] was developed in [6] and used for calculating the axial force in shell type welding transformer as follows;

$$fa = (19.62\pi^2 (ni)^2 Dm\ k) / (10^8\ Wc\ m^2) \qquad (48)$$

where; Dm : the circular main winding diameter equivelant to the rectangular cross section core.

$Dm = 2 \sqrt{\text{area of rectangular core} / \pi} + Wc$

Wc : winding width.
k : corection factor.
ni : ampertum of the winding.
m : number of groups of interleaved windings.

4.4.3 IRM [12]

The image representation method[16] which uesd to calculate the electric force between the transimation lines was developed in [12] to calculate the electromagnetic forces on the windings of the shell type welding transformer. The IRM was developed under the following asumptions:-

1- The first image of primary and secondary windings on the nearist iron core was taken into account.
2- The images of each winding have the same dimenstions, and currents (i.e. value and direction).
3- The iron core was represented by semi-infinite mass of permeability and its surface at the window was considered the surface of the mirrore.
4- The primary and secodary windings were represented by straight lines of finite lengthes laying in the window in thier positions.
5- Each winding can be represented by actual number of turns or one coductor centroied at the winding center or represented by any number of elements, where all cases must have the same equivelant amper-trun, ni.
6- The total force on any winding is the summation of the forces due to the other winding and all winding images using Biot-Savart's Law. Also, the total electromagnetic forces on both windings are equale in magnetude and oppesite in direction.

The above considerations are shown in Figs. (12-13) while Fig. (14) shows the details for calculating the force bteween two finite parallel filaments using Biot-Savart's Law . The main equations for calculating the axial and radial forces on the two filements shown in Fig. (14) were formulated in Ref.[12] as the following;

$$F12 = fa\ \mathbf{ay} + fr\ \mathbf{ax} \qquad (49)$$
$$fa = I1\ I2\ l\ (\sin \alpha 1 - \sin \alpha 2)\ (\cos \beta) / (4 \pi r) \qquad (50)$$
$$fr = I1\ I2\ l\ (\sin \alpha 1 - \sin \alpha 2)\ (\sin \beta) / (4 \pi r) \qquad (51)$$
$$r = ((x1-x2)^2 + (y1-y2)^2)^{(1/2)} \qquad (52)$$

The total force on each winding and the force distribution were calculated in Ref.[12] using procedures like those used with the FEM for winding representation. The foce on i th element of the secondary winding, Fsi, the force distribution, Fsd, and the total force, Fst, were obtained in Ref. [12] as the following;

$$Fsi = \sum_{j=1}^{NOPE} fji + \sum_{j=1}^{NOPER} fji + \sum_{j=1}^{NOPEL} fji + \sum_{j=1}^{NOPED} fji +$$

$$\sum_{j=1}^{NOSER} fji + \sum_{j=1}^{NOSEL} fji + \sum_{j=1}^{NOSEU} fji \quad (53)$$

$$Fsd = \sum_{j=1}^{NOSEPD} Fsi / Dj \quad (54)$$

$$Fst = \sum_{i=1}^{NOSE} Fsi = Fas\ \mathbf{ay} + Frs\ \mathbf{ax} \quad (55)$$

While for concentrated windings the total force on the secondary winding was;

$$Fst = Fas\ \mathbf{ay} + Frs\ \mathbf{ax} = \mathbf{Fp} + \mathbf{Fpl} + \mathbf{Fpr} + \mathbf{Fpd} + \mathbf{Fsl} + \mathbf{Fsr} + \mathbf{Fsu} \quad (56)$$

4.4.4 Force experimental verification[6]

The Volts-per -Turn method was used for force exprimental verification for interleaved windinds' transformers[16]. This method was developed in [7] to calculate the axial force in separetly windings welding transformers. Where the sereach coil method was used to measure the voltage per turn difference with wounding two search coils at the two ends of each winding , as shown in Fig. (10). The output emf of these search coils are shown in Fig. (9). The equation of the peake value of the winding axial force, Fam in Ton, of this method is;

Fam = (rms amper-turn per inch) (rms volt per trun difference) / (800 f) (57)

4.5 Transformer Temperature Rise

Temperature rise is the result of heat generated inside the transformer due to windings and iron losses. This temperature should be remaining under allowable maximum value to avoid the failure of the windings by breakdown its insulation, especially at higher values of duty cycle operation. The generated heat is dissipated from the exterior surface of the transformer by a combination of radiation and convection [1,7,12-13]. In welding transformer the equivalent power of convection component equals about 55% of total power losses [1,7]. This equation was expressed in[1,8] as;

$$Pc = 0.55\ Ploss / Cs = Kc\ Fc\ (Tm - Ti)^{N}\ P^{(1/2)} \quad (58)$$

where; Kc : constant =2.17

Fc : air friction factor = 1 - 1.2

N : real number =0.8 [1].

P : relative barometric pressure, unity at sea level.

Ti : initial surrounding temperature, K°.

Solving that equation gives the maximum temperature rise, Tm. There are two modes of operation are formulated, modified and solved in [7] to give the instantaneous values of the transformer temperature as follows;

- **Continuos operation**

$$Tr = (Tm - Ti) - (Tm - 2\ Ti)\ e^{-(t/TH)} \quad (59)$$

- **Duty cycle operation**

The temperature rising of the transformer for on -period (welding time) at n cycle, Tr(n), was calculated by;

$$Tr(n) = (Tm - Ti)\ (1 - e^{-(t/TH)}) + Tf(n-1)\ e^{-(t/TH)} \quad (60)$$

where; $(n-1)\ tp < t < ton + (n-1)\ tp$

While the falling temperature for off-priod (no load time) during the n cycle, Tf(n), was calculated by;

$$Tf(n) = Tr(n)\ e^{-(t/TC)} \quad (61)$$

where; $ton + (n-1)\ tp < t < (n)\ tp$

Tf(n-1) = Ti at the first cycle : is temperature of the transformer at beginning this cycle and its equals the falling temperature at the end of the previous cycle.

ton : the time of on-period.

TH : heating time constant.
TC : cooling time constant.

Recommendation about ventilating ducts at the winding overhangs was advised [7]. The theoretical calculations and the experimental measurements are carried out on different types and ratings of transformers [1,7]. A sample of these characteristics is shown in Figs. 10-12.

4.6 Transformer Equivalent Circuit and its Parameters

In moving limb welding transformer, the moving iron limb is used for changing the welding current. The limb can be moving into and out of the transformer core causing changing both the leakage and mutual inductance [1-7]. A proposed equivalent circuit of this transformer is given [3-4] as shown in Fig. 13. The equivalent circuit parameters refered to the primary side are:

1. *Rp: primary winding resistance.
2. *Rs: secondary winding resistance.
3. #Xlp: primary leakage reactance.
4. #Xlsd: secondary leakage reactance refered to primary side.
5. # Rmp: iron loss equivalent resistance.
6. #Xmp: Magnetizing reactance.

The "*" parameters are calculated from the winding dimension design [1,4,6]using Eqs. (5 &6).
The "#" parameters are calculated using FEM [4,6] as the following :-

$$Rmp = Eo^2 / (2\ Pi) \quad (62)$$
$$Xmp = 4\ w\ Wm / Im^2 \quad (63)$$
$$Xlp = 2w\ Wpl / Ip^2 \quad (64)$$
$$Xls = 2w\ Wsl\ (Np/Ns)^2 / Is^2 \quad (65)$$

Where the linkage and leakage magnetic energies, Wm, Wpl & Wsl, were calculated using the N2DFEM[6] as follows;

$$Wm = d\left(\sum_{e=1}^{NOIE} \int_{B=0}^{Be} (He\ dBe)\ Se\right) \quad (66)$$

$$Wpl = \gamma o\ d\left(\sum_{e=1}^{NEFP} Be^2\ Se\right) + 0.5\ \gamma o\ Kov\ (Lmt-2d)\left(\sum_{e=1}^{TNEFP} Be^2\ Se\right) + 2\ d\left(\sum_{e=1}^{NEFM} \int_{B=0}^{Be} (He\ dBe)\ Se\right) \quad (67)$$

$$Wsl = \gamma o\ d\left(\sum_{e=1}^{NEFS} Be^2\ Se\right) + 0.5\ \gamma o\ Kov\ (Lmt-2d)\left(\sum_{e=1}^{TNEFS} Be^2\ Se\right) + 2\ d\left(\sum_{e=1}^{NEFM} \int_{B=0}^{Be} (He\ dBe)\ Se\right) \quad (68)$$

where;
Eo : emf of primary winding at no-load
w $= 2\pi f$: angluer frequency, rad/sec.
Im, Ip, Is : magnetizing, primary and secondary currents.
He, Be : element amper-turn and magnetic flux density respectivly.
$\gamma o = 1/\mu o$.
NEFP : number of elements in the window for primary winding.
NEFM : half number of elements occupied by the moving limb.
TNEFP = NOPW + NOPM : total number of elements belong to primary side in the window.
NEFS : number of elements of secodary winding in the window.
NEFM : half number of elements occupied by the moving limb.
TNEFS = NOSW + NOSM : total number of elements belong to secondary side in the window.
Kov = 0.8 - 1.0 : over hang factor, high value for totaly insertion of the moving limb in the window.

5. THE PERFORMANCE CHARACTERSITICS

Hence the equivalent circuit parameters are calculated as discussed above, based on the published information in Refereces [1-15], the performance characteristics can be determined. These characteristics were calculated at different insertion of moving limb with variable resistive load. This load can be changed gradually from no load to short circuit values. Load inductance can be taken into account as a ratio of the load resistance. The most important characteristics are [1-6]:

- The variation of secondary voltage and welding current.
- The variation of input power with welding current.
- The variation of input current with welding current.
- The variation of input power factor with welding current.
- The variation of efficency with welding current.

The operating point defined as the intersection between the theoretical (or measured curves) and operating line. The operating line defines the arcing voltage at different welding current. Figures (19-23) show the performance characteristics of the E-405 transformer with three methods. These figures are taken from Refernce[6]. These methods are analytical [1,3], FEM [4-6] and experimental [1,6]. Discussion about these methods is given in details [1,6]. Also, the suitable values for design factors to give accurate characteristics perdition are recommended [1-4,6].

6. WELDING TRANSFORMER PROGRAM

During the FRCU Projects [1-2], the author Ph.D. thesis [6] and the continuos research about transformer using FEM [1-8] till now, a complete package of Fortran Program is designed, written and tested [4-8]. This program starts with the analytical equations of the transformer design [1-2,13-14] ending at performance characteristics through the FEM analysis [4-8]. Figure (24) shows a program flowchart of the transformer design [6], while, Fig. (25) shows the flowchart of the performance characteristic calculation [6].

7. CONCLUSIONS

This paper presents a survey study about the welding transformer design and analysis. The main procedure of power transformer design was devloped to suit the welding transformer design. Two procedures for wedling transformers analysis to calculate the transformer equivelant circuit parameters and operating chcracteristics are summarized.These procedures are analytical aproch and FEM as a numerical aproch.

In FEM, during the design process, the flux distribution in all elements of the global area for any load condition can be computed. Nonlinear Two .Ddimesional Finite Element Method, N2DFEM, with linear triangle elements was used for flux computation which tooke into account the nonlineraly of B-H curve of iron core. It solved the main problem of flux distribution due to the moving limb insertion. This study has been showing that, this flux distribution is the **Master Kay** of all gates to calculate the transformer parameters, specifications and operating characteristics.

New method for buding the triangular finite element grid automaticaly with two principale cells was discovered. This method is simple, relable and saving time and effort for calculating finite element geometrical calculation, finite element numbering and finite element conections matrix . Also, new equations for computing iron losses, copper loss, loss distribution, welding transformer equivelant circuit parameters (i.e Xlp, Xls, Xmp &Rmp) have already given. So a developed equivelant circuit was perposed to take into account the variation of leakage and linkage flux with moving limb insertion.

Three developed methods for electromagnetic force calculation on shell type welding transformer windings are discused. These methods are analytical methode, AM, electric image representation method, IRM, and finite element method, FEM. This study show that the radial force on the windings of the shell type with separatly windings can be neglected with respect to the axial force. This force is incresed with increasing the welding current and it is reached its maximum value at the short circuit of secondary winding when the moving limb was out the leakage winding reactances which limet the short circuit currents to finite values. .

Finaly developed equations for instantaneous tempreature rise calculation of welding transformer at continuos and duty cycle operations are given. Ventilating ducts and small fan at the winding overhangs were recomended for good cooling condition.

Finite Element Method gives better agreement between the theoretical and experimental results than analytical method. Some differences are occurred may be due to the assumptions of the theoretical variable load and more adjustment can be obtained.

8.ACKNOWLEDGEMENTS

Most of this work is born at starting the FRCU Progect [1] . The author would like to thank the Egyptian Government and FRCU about their interest against these types of progects . Those Progects [1-2] wer financially supports through the FRCU Unit . Many thanks to Prof. Hassan ,S. A., the principal investigator, Prof. El-Maghraby, Cairo University, Prof. Demerdash, N. A., the USA Partner AND Prof. Abdel-Kader, F. E., Co-investigator, for their advise, FEM through our meeting and his notes, experience of testing, practical, modling and analysis. Thanks for all the team members with the same level of appreciation for their well give. Thanks for El-MACO Co. Partners for fast response for building different prototypes during the Projects.

The author would like to do thanks for Prof. M. El-Hawary, Dalhousie University, Canada, for pointing him to do this survey during his visiting to, Dalhousie University, Nova Scotia, Halifax, Canada.

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APPENDIX

General specification of the 400-A moving limb welding transformer under test:

Core type	: shell, as shown in Fig.1
Primary voltage	: 380 V.
Secondary voltage	: 48 V.
Primary number of turns	: 161 turns
Secondary number of turns	: 21 turns
Maximum short-circuit current	: 530 A.
Minimum short-circuit current	: 100 A.
Winding current density	: 5 A/mm2
Winding arrangement	: as shown in Fig. 1.
Operating flux density	: 1.6 T.
Type of iron laminations	: grain oriented electrical steel, grad Orsi-097, with 0.3 mm lamination thickness.
Window height, Hw	: 18.5 cm.
Total primary winding height	: 8.5 cm.
Total secondary winding height	: 7.5 cm.
Moving limb height	: 2.5 cm.
Window width	: 6 CM.
Average winding width	: 5cm.
Moving limb width	: 5.5 cm.
Core width	: 7 cm.

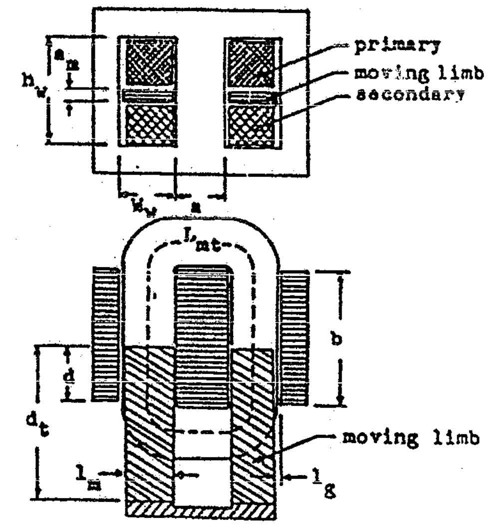

Fig. 1 Construction details of moving limb welding transformer.

a- Lower / Upper

b- Upper / Lower

Fig. 2 The general cells of 2D first order triangular elements

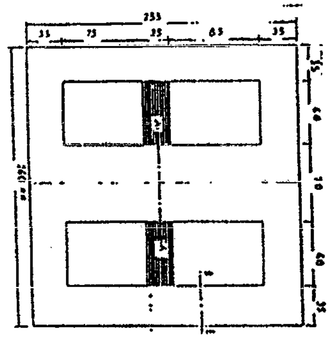

Fig. 3-a The core of the welding transformer under study.

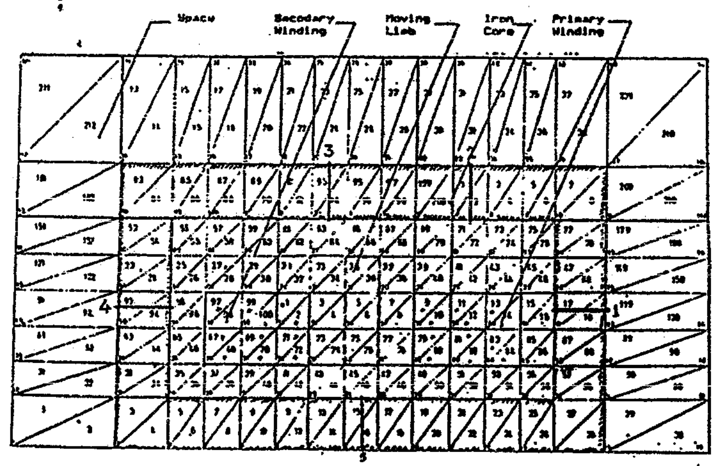

Fig 3-b Finite element mesh for a half section of the transformer core as a global area.

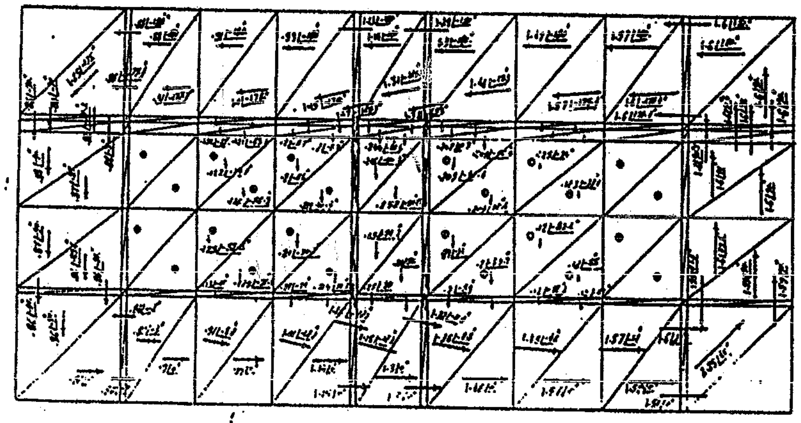

Fig.(4): Flux density distribution of the transformer half-core at load without the moving limb at 380 volt.

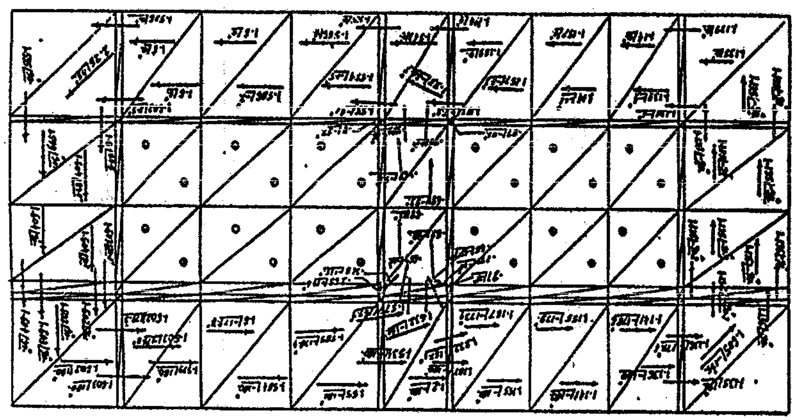

Fig.(5): Flux density distribution of the transformer half-core at load with the moving limb at 380 volt.

Table (1): Experimental and Numerical Calculation of Flux Density at the Five Positions.

PN.	The Case	Flux Density,T.		The Case	Flux Density,T.	
		Measu.	Compu.		Measu.	Compu.
1	No-load	1.556	1.602	No-load	1.588	1.602
2	without	1.571	1.603	with	1.553	1.605
3	moving	1.516	1.591	moving	1.397	1.536
4	limb at	1.553	1.573	limb at	1.418	1.518
5	380-V.	1.571	1.596	380-V.	1.550	1.570
1	Load	1.565	1.603	Load	1.546	1.604
2	without	0.908	1.519	with	1.202	1.592
3	moving	0.356	1.149	moving	0.858	1.209
4	limb at	0.442	0.875	limb at	0.894	1.136
5	380-V.	0.997	1.239	380-V.	1.300	1.439
1	No-load	1.546	1.532	No-Load	1.487	1.534
2	without	1.507	1.535	with	1.482	1.537
3	moving	1.447	1.526	moving	1.370	1.481
4	limb at	1.417	1.514	limb at	1.389	1.469
5	220-V.	1.565	1.531	220-V.	1.152	1.510
1	load	1.409	1.577	load	1.500	1.563
2	without	1.036	1.469	with	1,335	1.542
3	moving	0.662	1.180	moving	0.562	1.162
4	limb at	0.554	0.905	limb at	0.612	1.100
5	220-V	0.907	1.249	220-V.	0.855	1.398

* PN : Position number.
* Measu.: Measured values.
* Compu.: Computed values.
* T. : Tesla.

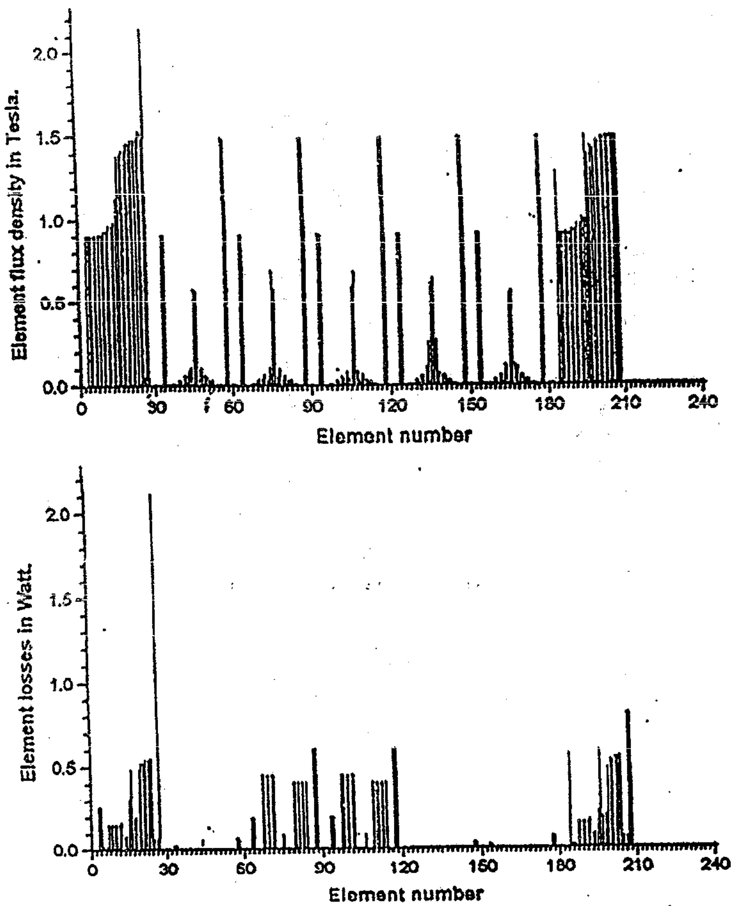

Fig. 7 Elements flux and losses at minimum welding current (Is=92A).

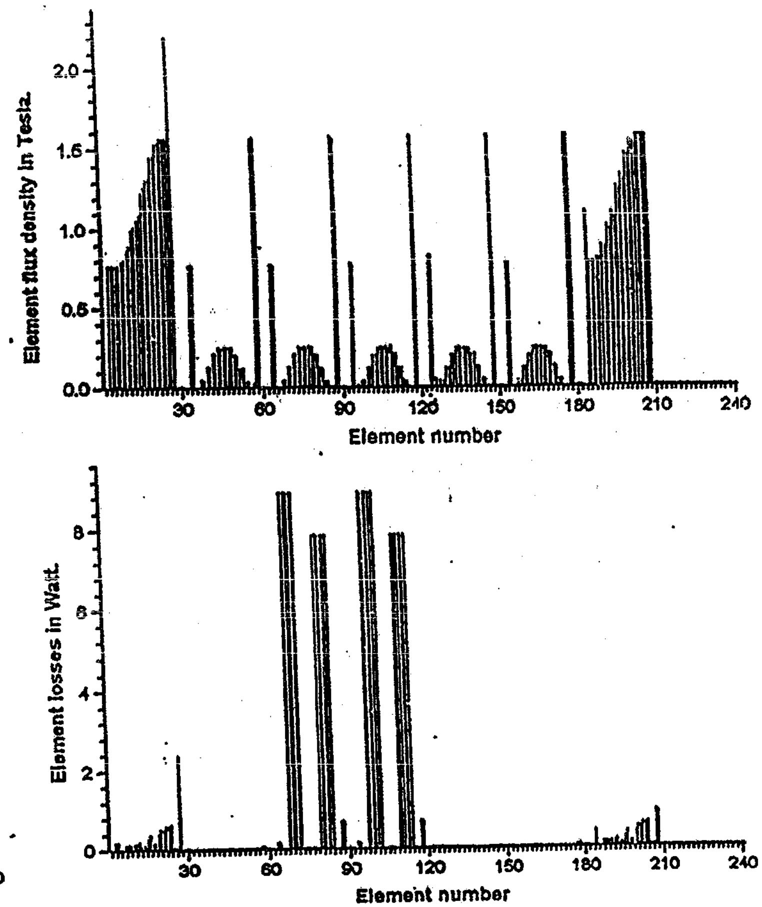

Fig. 6 Elements flux and losses at maximum welding current (Is=400).

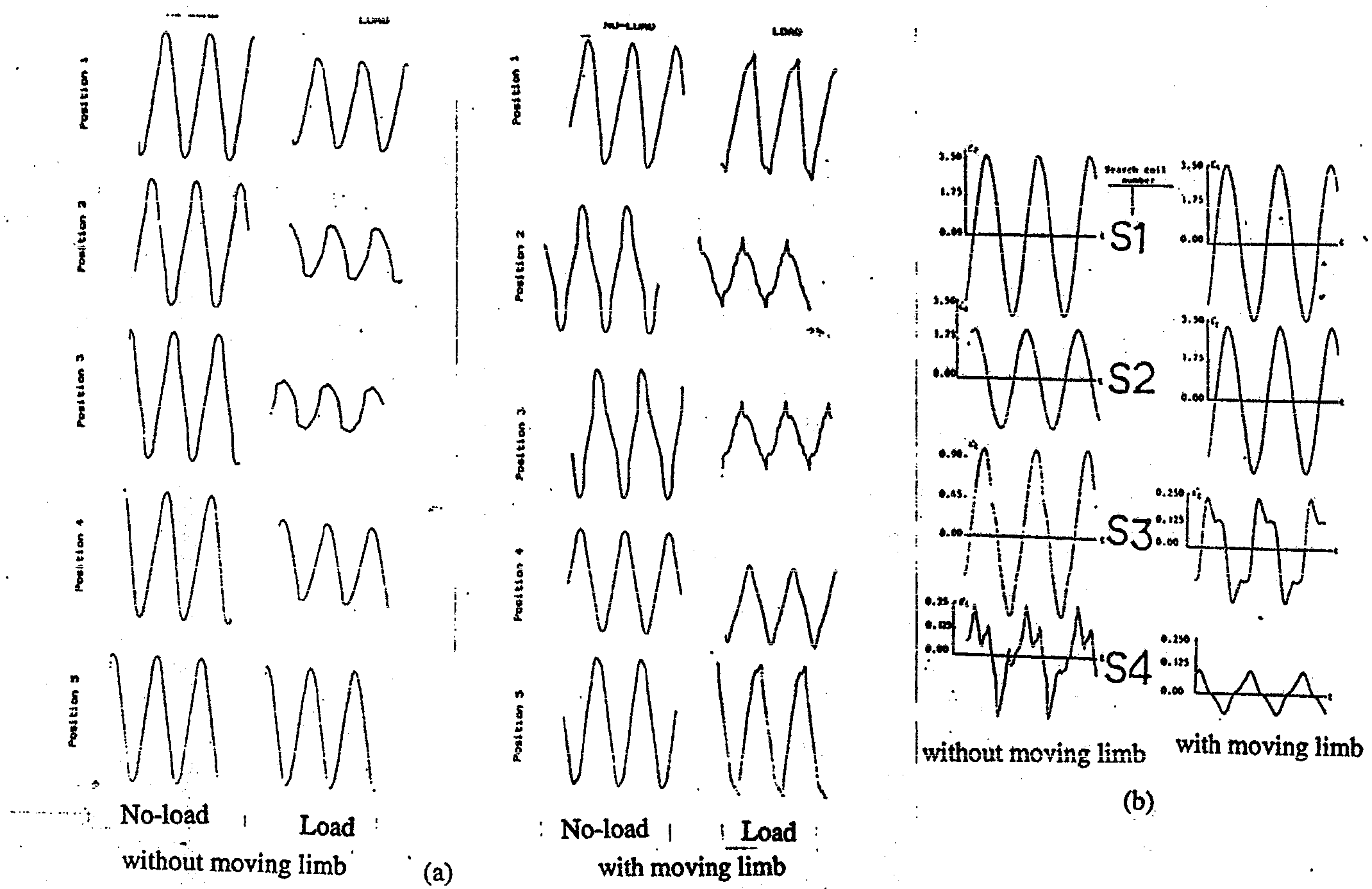

Fig. (8) EMF's the search coils of:
(a) Fig. (3-b) with and without moving limb at minimum and maximum welding current.
(b) Fig. (10) with and without moving limb at load.

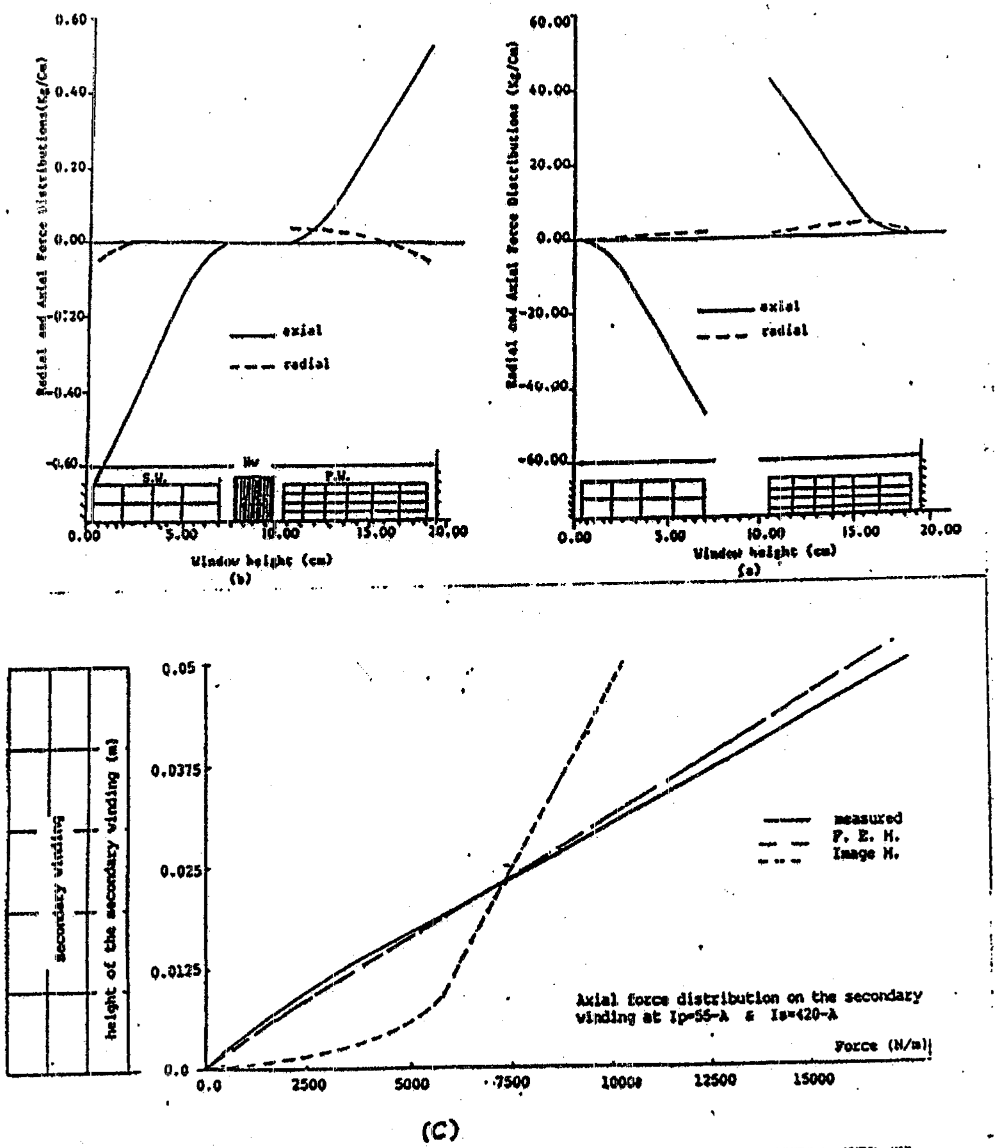

Fig. (9) Force distribution of E-405
(a) without moving limb using FEM. (b) with moving limb using FEM.
(c) the axial force on the secondary winding at max. currents using FEM, IRM and measured values.

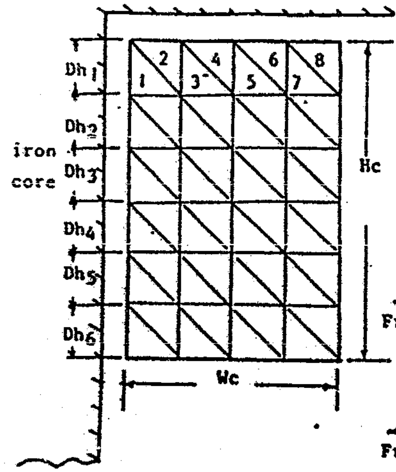

Fig. (11). Finite element grid of a transformer winding (NOD = 6 divisions, NOEPD = 8 elements, NOEPW = 48 elements).

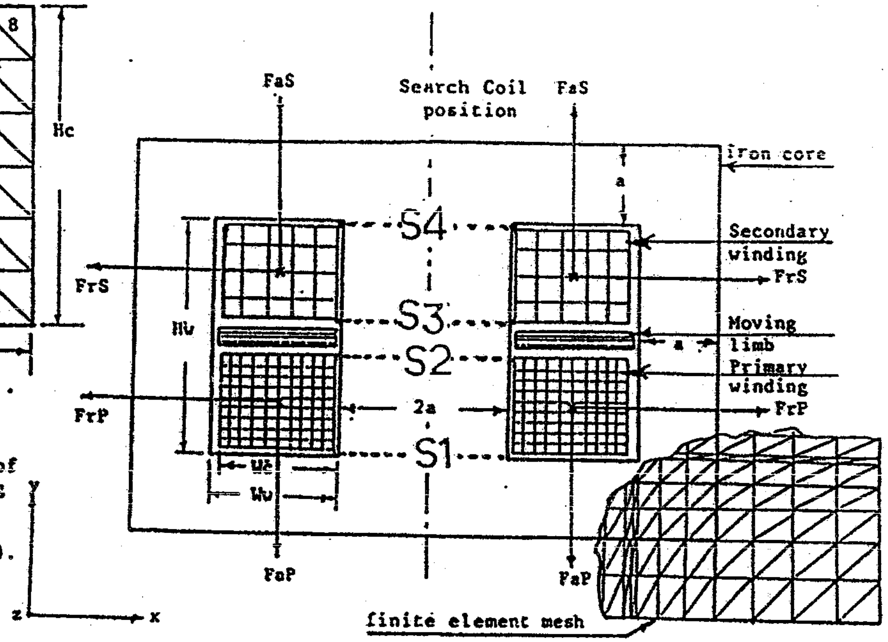

Fig. (10) Section plane of a shell type moving limb welding transformer.

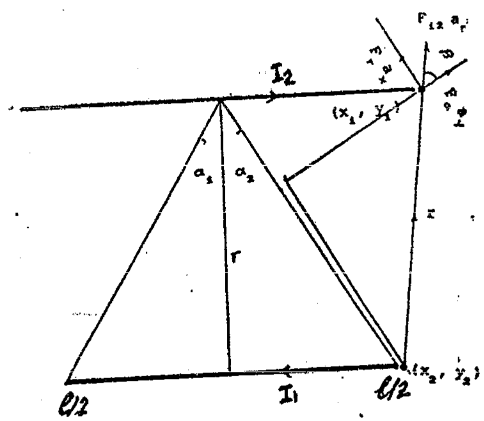

Fig. (14) the force between two parallel filaments.

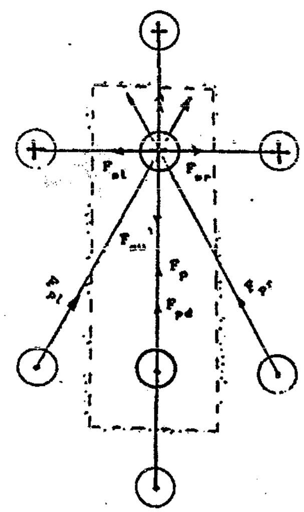

Fig. (13) the total forces on the secondary winding.

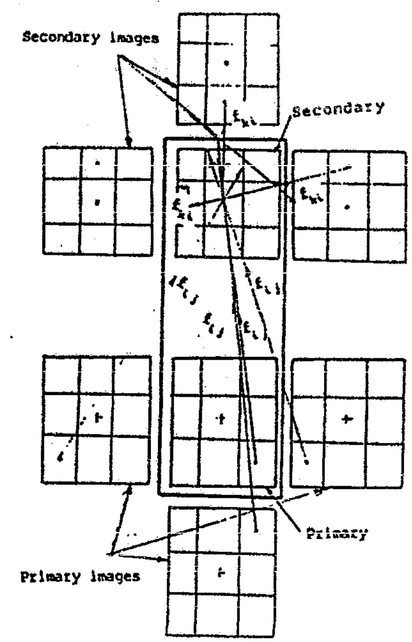

Fig. (12) the representation of the welding transformer for IRM.

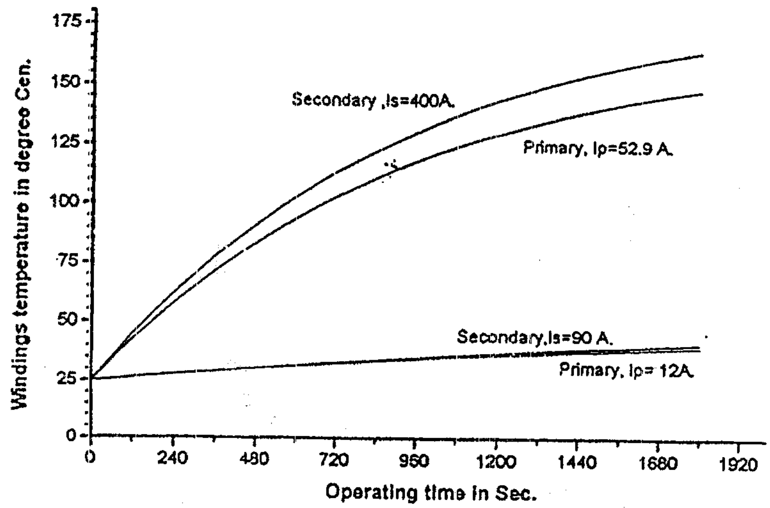

Fig. (15) Temperature rise of transformer windings for continuous operation.

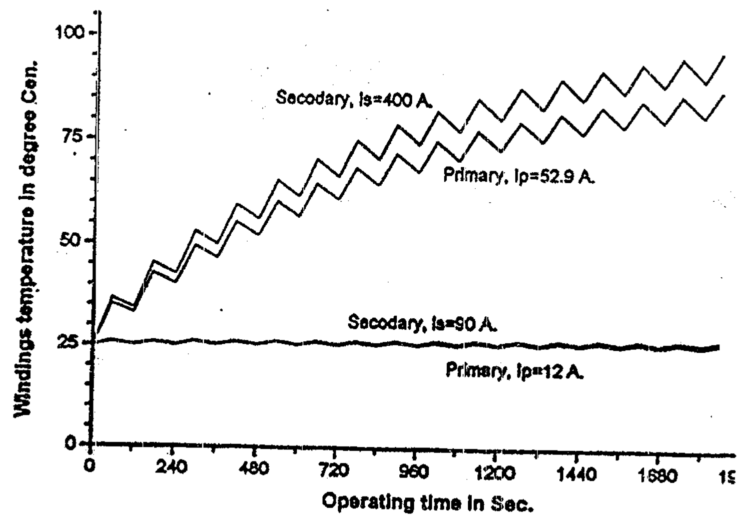

Fig. (16) Temperature rise of transformer windings for discontinuous operation. (55% duty cycle)

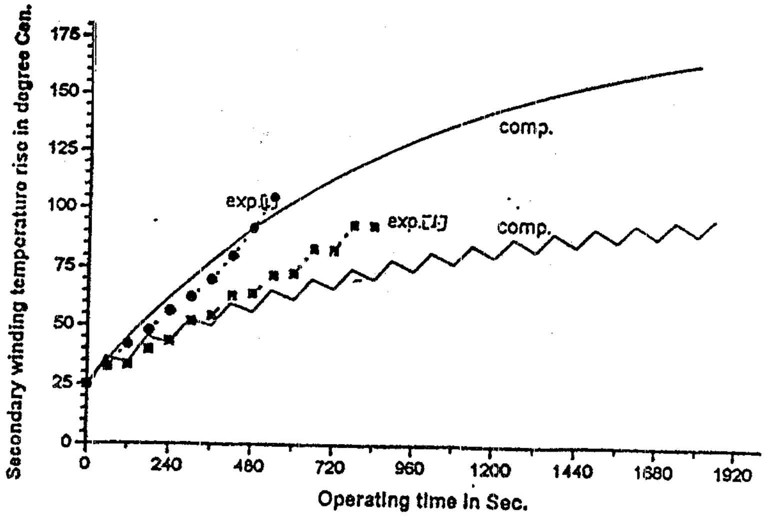

Fig. (17) Temperature rise of secondary winding at maximum current (Is=400A) for continuous and 55% duty cycle operations.

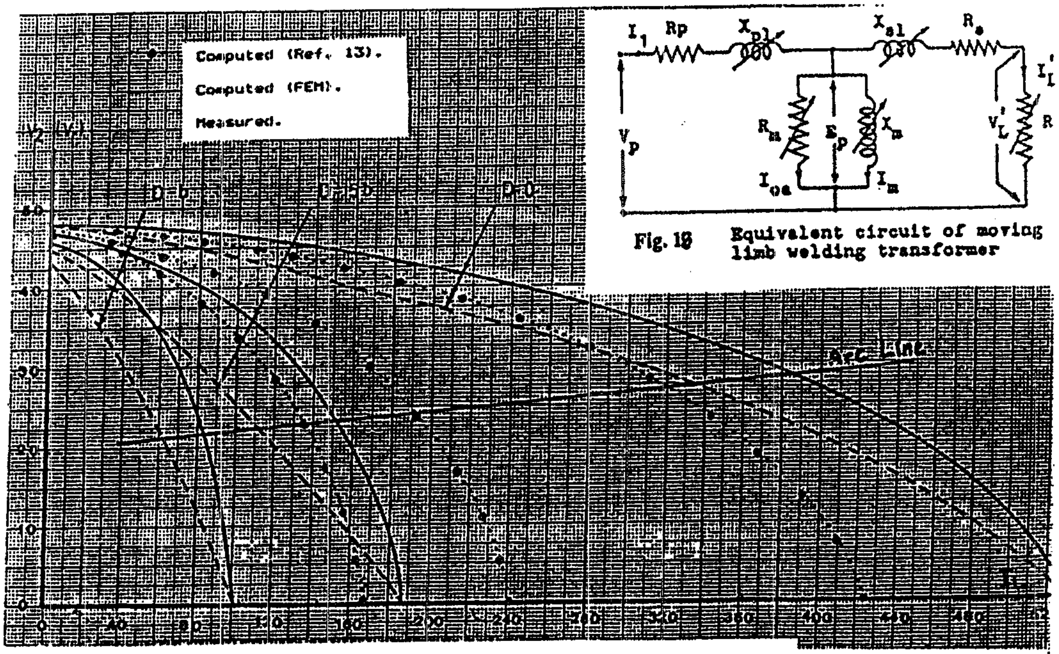

Fig. 18 Equivalent circuit of moving limb welding transformer

Fig. (19) the secondary voltage versus the load current of E-405 at 380v.

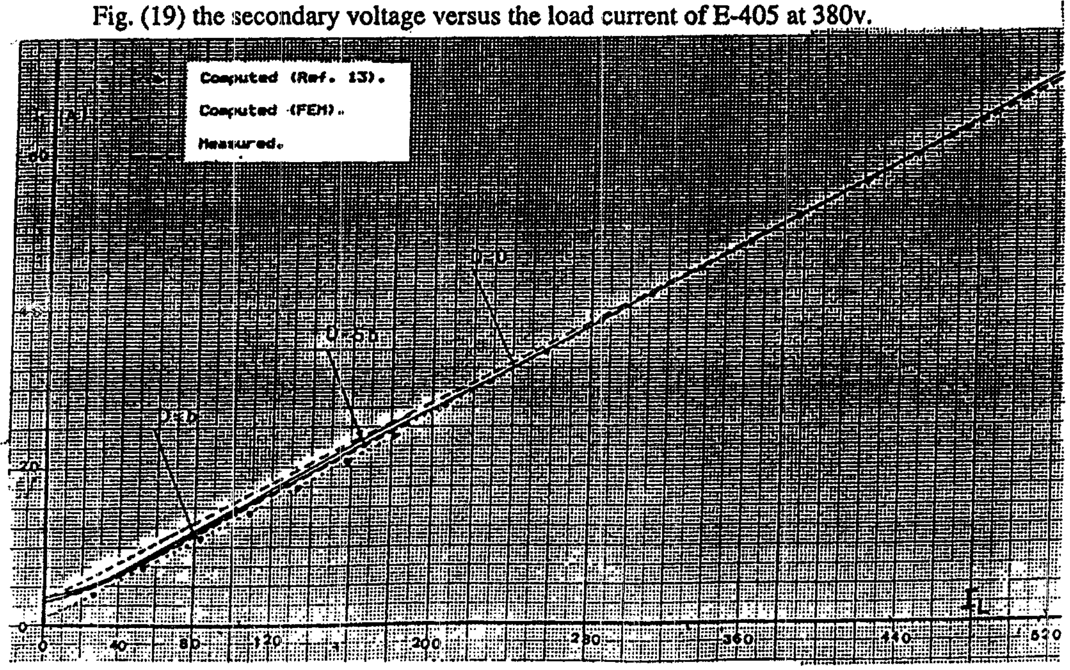

Fig. (20) the primary current versus the load current of E-405 at 380v,

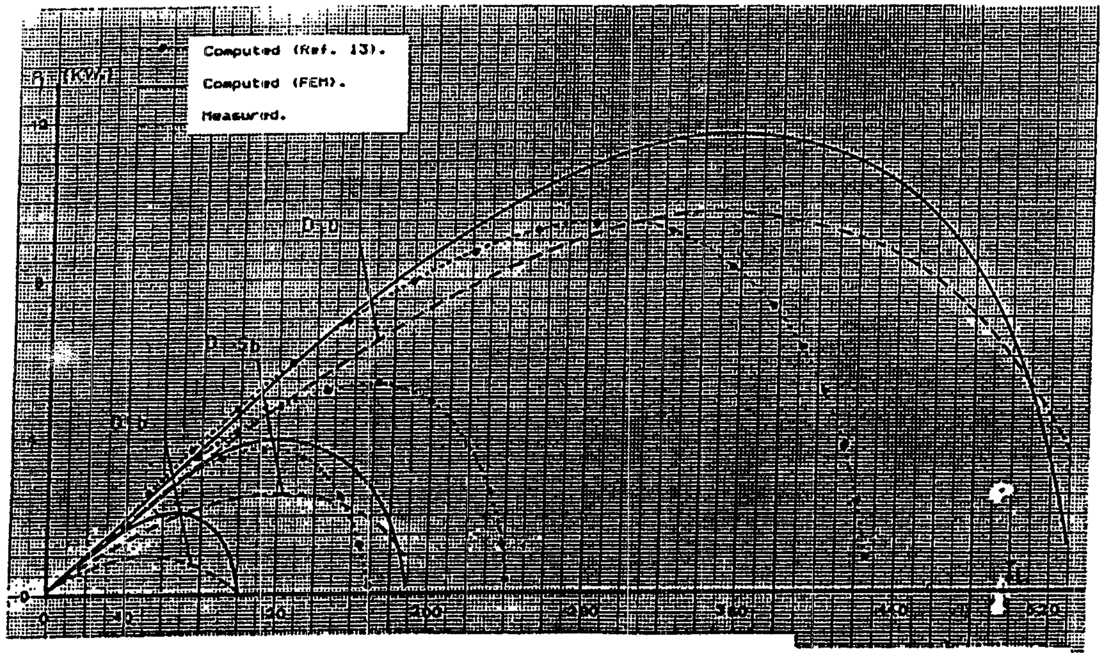

Fig. (21) the input power versus the load current of E-405 at 380v.

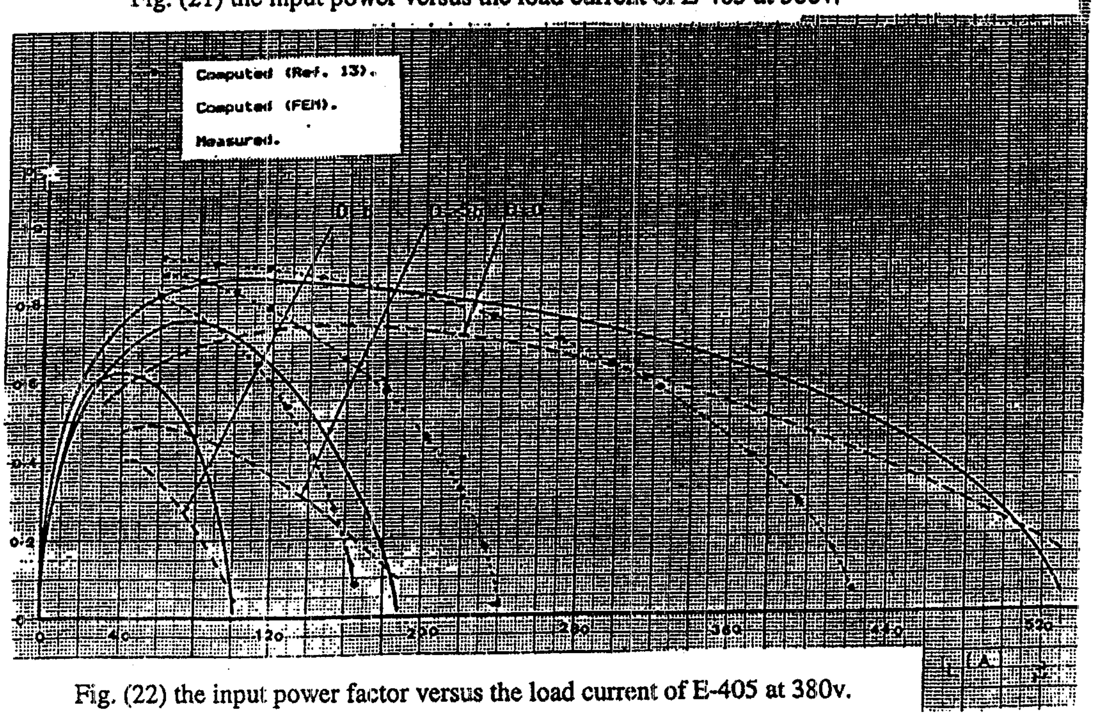

Fig. (22) the input power factor versus the load current of E-405 at 380v.

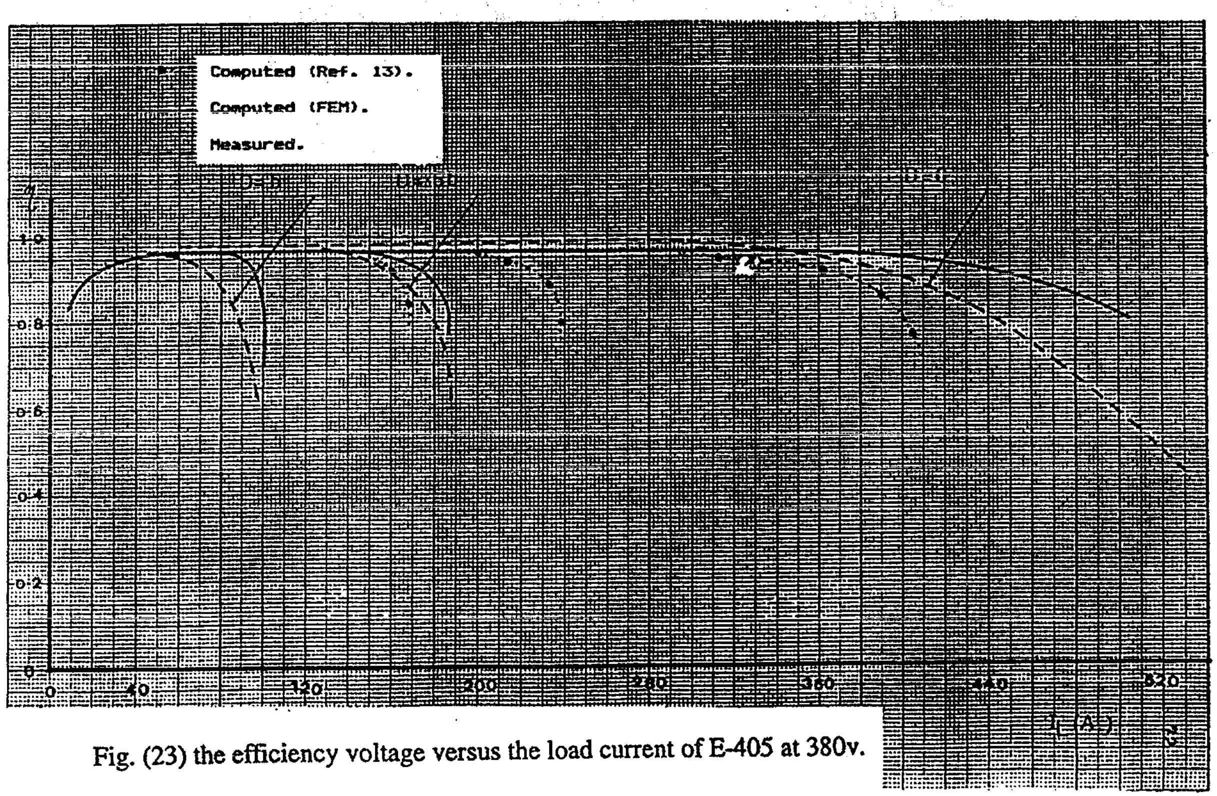

Fig. (23) the efficiency voltage versus the load current of E-405 at 380v.

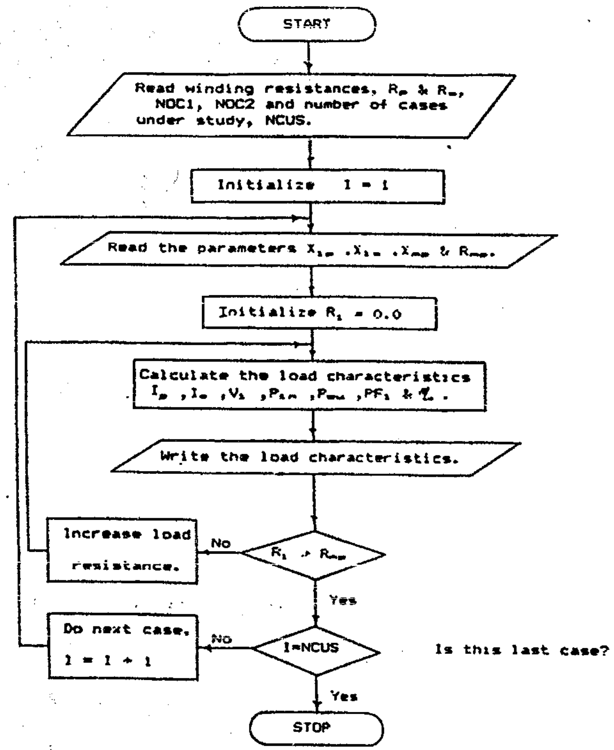

Fig. (25) A flowchart for the load characteristics calculation.

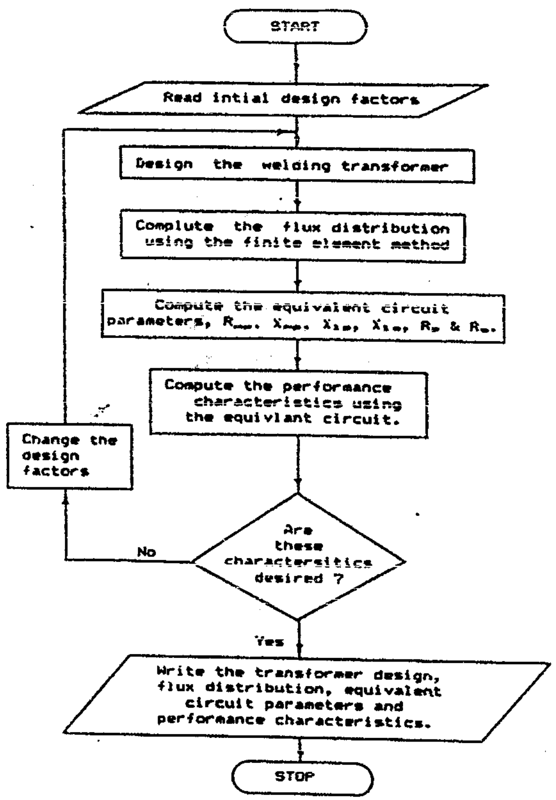

Fig. (24) A flowchart for designing the welding transformer using the FEM.

تصميم محولات اللحام الكهربية

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هذه المقالة تقدم عرضا مرجعيا مفصلا عن تصميم وتحليل محولات اللحام الكهربية ذات الذراع المتحرك والتى تبرد بالهواء حيث تم سرد طريقتين استخدمتا فى هذا المدمار وهماطريقة تحليلية وطريقة رقمية. الطريقة التحليلية تعتمد على التحليل النظرى للمجال المغناطيسى فى شباك وقلب المحول للحصول على معادلات تحليلية لحساب التدفقات الهاربة و التدفق المتشابك. أما الطريقة الرقمية تعتمد على حل معادلة بواسون للمجال المغناطيسى بالمحول باستخدام طريقة التقسيم الى عناصر محددة فى بعدين للحصول على قيمة هذا المجال فى كل جزء من أجزاء المحول والحيز المعتبر.

تبداء الطريقتين بتصميم نموذج مبدئى للمحول المطلوب باستخدام معادلات التصميم الكهربية الخاصة بهذا المحول ثم يتم حساب المجالات الكهرومغناطيسية وثوابت الدائرة المكافئة للمحول.ومن ثم يمكن حساب المفاقيد الكهربية (نحاسية وحديدية) وتوزيعها ؛ القوى الكهرومغناطيسية على الملفات وتوزيعها ؛ ارتفاع درجة حرارة المحول ؛ منحنيات الخواص لهذا النموذج فان كانت هذه الحسابات مقبولة تعتمد أبعاد هذا النموذج و إلا فيعاد تغير ثوابت التصميم فى حدود المدى المسموح به للحصول على نموذج جديد وهكذا حتى نصل الى التصميم الأمثل.
تحصى المقالة المعادلات التفصيلية للطريقة الرقمية لبناء الشبكة تلقائيا وبأقل عدد من المعطيات ، ولحساب التدفق المغناطيسى فى المحول وحيزه ، ولحساب المفاقيد الحديدية والنحاسية وتوزيعها ، ولحساب القوى الكهرومغناطيسية (المحورية والقطرية) على الملفات وتوزيعها على طول محور الملف ومقارنتها بالطرق الأخرى المستخدمة فى هذا المجال ، ولحساب الزيادة في درجة حرارة المحول في ظروف التشغيل المستمر والمتقطع ،ولحساب ثوابت الدائرة المكافئة للمحول وأخيراً حساب الخواص الكهربية ومقارنتها بالطريقة التحليلية والنتائج المعملية التي أجرت على المحول قيد البحث .

امتازت الطريقة الرقمية عن الطريقة التحليلية بالدقة حيث أخذت في الاعتبار التشبع والخواص اللاخطية لحديد القلب كما يمكن باستخدامها الحصول على حسابات تفصيلية عن كل عنصر محدد في حيز المحول .