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Effects of Lamination Packs in Induction Heating Work Coil Design by the Superposition Method

Dr. A.K.M. Al-Shaikhli
Prof, Electrical Engineering DEPT, University of Technology
Baghdad, Iraq

Mustafa F. Mohammed
Assist. Lecturer, Ministry of Higher Education & Scientific Research
Baghdad, Iraq
Email: mfmfzy@yahoo.com

***Abstract*— In some induction heating applications, lamination packs are installed around the coil. The main reason for using them is to channel the flux in the region outside the coil so that it does not link the surrounding metallic objects, which will heat these objects and, also, might result in sparking. The efficiency will be improved also by the employment of these flux guides due to the reduction on the stray losses and the magnetizing current. The object of this paper is to inspect the applicability of the superposition method in a system containing laminations, before this technique can be recommended as a coil design method to installations involving the laminations. This is to be done by studying the effect of the laminations on the power density induced on the work piece due to single conductor and number of conductors.**

Keywords—Induction heating; lamination packs;Superposition.

I. INTRODUCTION

The employment of the ferromagnetic materials in induction heating as a flux guide to protect the surrounding metal work from being heated by the stray flux is well known. Packs of low-loss materials, such as nickel-iron or silicon-steel, are usually placed on the outside of the coil of a vessel heater or melting furnace, so as to confine the magnetic field close to the outside of the coil. This prevents the flux from spreading away from the outside of the coil and linking with surrounding metallic objects.

The superposition method has been applied, to rectangular and cylindrical work pieces [1] successfully. The aim of this paper is to assess the applicability of the superposition method on applications whereby ferromagnetic laminations exist in the system. This is done by investigating the influence of these laminations on the distribution of the power density induced on the load and, also, to inspect the validity of the superposition method with existence laminations.

II. SUPERPOSITION METHOD

This method considers the effect of each turn of the coil, then applying the superposition principle to determine the performance of the coil. This method can be used to design a coil for applications requiring non-uniform power density distribution along the load. The theory of superposition method is described in [2] and [3] and with the applicability of it on a load of aluminum but without the effect of the laminations. This paper is to show of applicability of the superposition method on applications of

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induction heating work coil design whereby ferromagnetic laminations exist in the system.

If a circular conductor of radius (a) carrying current (I) , at a distance (h) from the surface of semi-infinite, good conductor slab, will induce magnetic field strength at any point (P) along the surface of the slab, given by:

$$H_P = \frac{I}{\pi} \times \frac{h_e}{h_e^2 + z^2} \qquad (1)$$

Where:

h_e: The effective height = $\sqrt{h^2 - a^2}$

Z: The distance along the slab, beneath the conductor to point p

If there are (N) identical conductors instead of one conductor, and the distance between the conductors are constant and equal to d, i.e. uniform coil, then

$$H_P = \frac{I \cdot h_e}{\pi} \sum_{x=0}^{x=n-1} \frac{1}{h_e^2 + (z_1 + xd)^2} \qquad (2)$$

Also, it can be noticed that the magnetic field intensity at the surface of the slab is equal to the linear current density, A, induced per unit length of the slab, see figure-1, i.e.

$$A_P = H_P \qquad (3)$$

It was found empirically, that the magnetic field of equation (2) should be amended to the practical equation below:

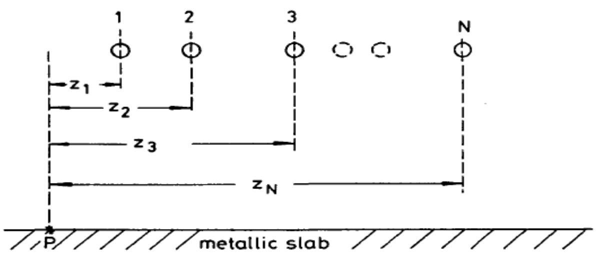

Figure-1 *Number of identical conductors at a specific air-gap from a metallic Load*

$$H = \frac{\beta \cdot I}{\pi} \times \frac{h_e}{h_e^2 + \frac{\alpha}{\cos\sigma} z^2} \qquad (4)$$

Where:

σ: The angle between the line joining the conductor and point P and the perpendicular line from the conductor to the slab.

Also, αandβ are constants found from practical measurements and they are functions of the effective heighth$_e$. αis a straight line represented by:

$$\alpha = 10^{-2} h_e \qquad (5)$$

The application of the closet fit computer routine was found to produce the equation of the other constant β, where:

$$\beta = -(2.642 + 10^{-1}) + (7.736 \times 10^{-2}) h_e - (1.539 \times 10^{-3}) h_e^2 + (1.31 \times 10^{-5}) h_e^3 - (3.968 \times 10^{-8}) h_e^4 \qquad (6)$$

Where h_e in (mm)

The variation of α and β is shown in figure-2 for simplicity and within the accuracy levels required the use of graphical results given in the figure is preferred. From equation (3), it can be concluded that the equation of induced current density is:

$$A = \frac{\beta \cdot I}{\pi} \times \frac{h_e}{h_e^2 + \frac{\alpha}{\cos\sigma} z^2} \qquad (7)$$

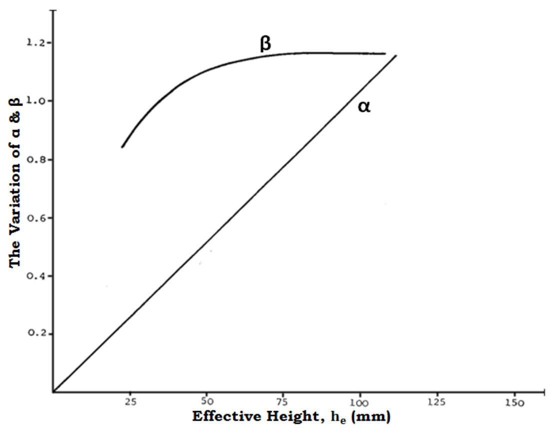

Figure-2 *the relations of h_e for different values of α and β*

III. EXPERIMENTAL WORK

The experiments were carried out on the same aluminum slab employed in [1], and by using the experimental rig as shown in figure-3 and its circuit diagram as shown in[1],with the addition of the laminations. The configuration of the system is shown in figure-4. A pack of nickel-iron laminations was used in the experiments; contained 250 sheets of the followingdimensions 45 ×280 × 0.15mm. It was supported by 2 stainless steel bolts.

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The pack was then covered with a Fiber glass tape to maintain Proximity between the laminations and to protect their edges. A Circular conductor of 28mm diameter and a rectangular conductor were used in order to investigate the laminations effect on a single conductor.The air gap g between the aluminum slab and the conductor was held constant at 40 mm. The current in the conductor was permanently fixed at 1000A. The voltage induced at different points on the load was measured by the current density probe and the current distribution on the conductors was also recorded, so that the effect of this distribution could be assessed. When investigating the effect of the laminations on the power density induced on the load a pack of laminations was positioned above the conductor at distance h1 = 5, 11, 20 and 35mm respectively. The pack was above the center of the aluminum slab, where the induced surface power density was measured. Figures (5 & 6) show the measurements of the induced surface power density without the effect of lamination for circular and rectangular conductors respectively while, figures (7, 8 , 9, & 10) show these measurements together with the calculated values according to equation (7). The differences between the two values did not exceed 5%; this proves that the practical equation (7) can be used even when there are laminations above the conductor. The constant α is the same as in the case of no laminations, while the other constant β increases when decreasing the distance h1, see Table-1, Decreasing the distance h1 increases the power density induced on the load i.e. increases the coupling. Also, Table-2 shows the values of the power density induced on the loaddirectly beneath the conductor for different values of h1.

The next stage was to investigate the current distribution on the conductor itself in order to find out whether the change in the distribution of the induced power density was due to a variation on the conductor current distribution or not. The surface current density distribution on the circular and rectangular conductors was measured with the laminations pack 5mm above it. It was found that laminations do not have an important effect on the distribution of the current on the conductor where, this effect did not exceed 5% & 7% for circular and rectangular conductors respectively. So it can be conclude that the power induced on the load was due mainly to the presence of the laminations. As the power density induced underneath the pack has already been investigated. It is important to know the effect of the laminations on the parts of the load which are not exactly beneath them. One lamination pack was placed above one edge of the load and the induced voltage distribution was measured at both edges of the slab. The distance h1 was 5, 11, 20 and 35mm respectively.Figures (11, 12, 13, & 14) illustrate the power density distribution for h1 = 35mm and h1 = 5mm only. The other results are not shown because they lie between the limits of these two cases. These curves show the power density induced on two parts of the load, near the two edges, one is covered with one pack of laminations and the other edge is left exposed.

Figures (11 & 12) show that, within the range of the experiments, the laminations do not have an important effect on the distribution of the current on the conductor. This effect did not exceed 5% for the circular conductor and 7% for the rectangular conductor. As the change in the conductor current distribution was small; its effect on the power induced on the load would also be small. Hence the change in the power induced on the load was due mainly to the presence of the laminations.

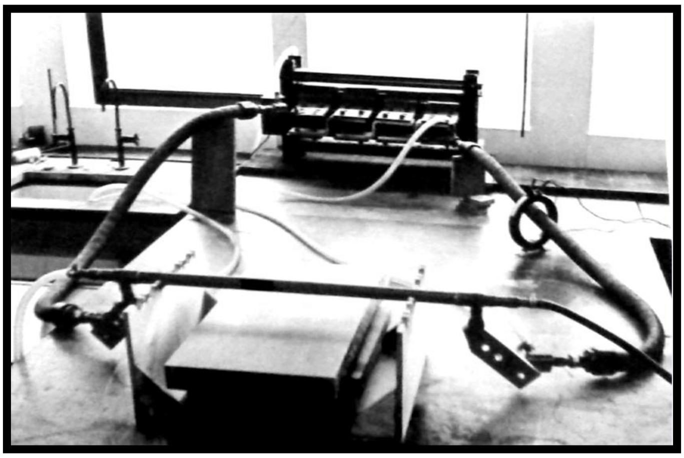

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Figure-3 *the experimental rig*

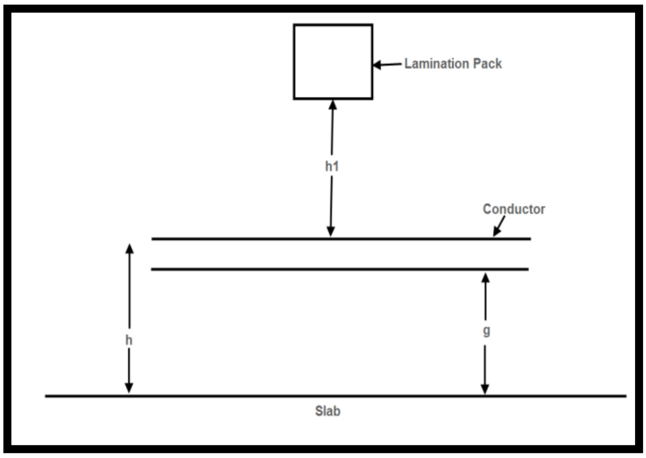

Figure-4 *the load, conductor and the lamination*

h1	β for circular conductor	β for rectangular conductor
(no lamination)	1.13	1.07
35	1.39	1.16
20	1.46	1.19
11	1.51	1.25
5	1.58	1.3

Table-1 *the variations of β with h1*

h1 (mm)	The load surface power density induced from circular conductor (W/m^2)	The load surface power density induced from rectangular conductor (W/m^2)
35	170	200
20	189	213
11	203	233
5	223	256

Table-2 *the power density induced beneath the conductor*

Table - 3 shows the power density induced on the load at those two parts directly beneath the conductor. From this table it can be seen that the power density induced on the other end varies only slightly with h1 and can thus be regarded as constant.

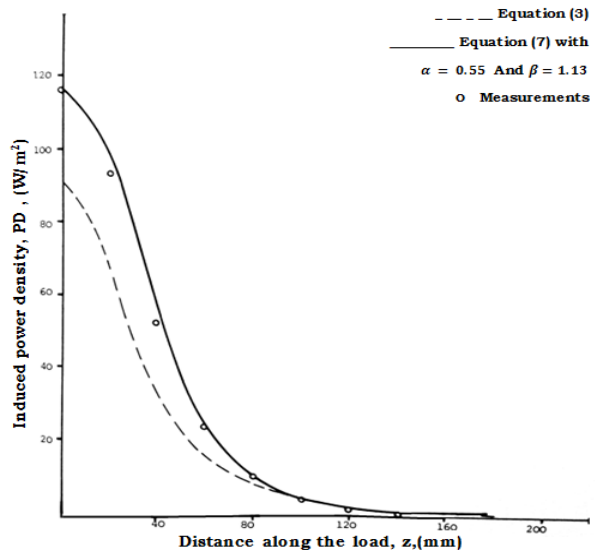

Figure – 5 *Surface power density distribution along aluminum slab due to 1000A flowing through circular conductor of 28mm diameter at h = 54mm*

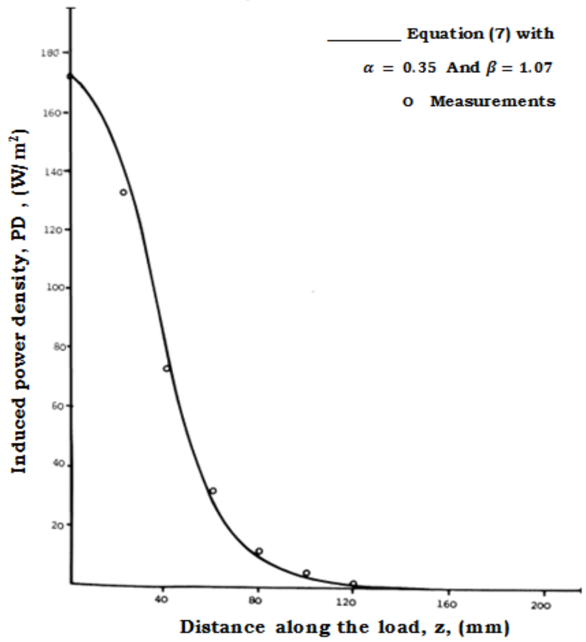

Figure – 6 *Surface power density distribution along aluminum slab due to 1000A flowing through rectangular conductor at g = 40mm*

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When investigating the effect of the laminations on the applicability of the superposition method it proved necessary to measure the voltage distribution, induced on the load, when 1000A flowed through the single rectangular conductor, whichwas above the slab and below the lamination pack when h1 = 5mm. These readings were combined with the computer program "W-SC-FIT" to predict the induced power density from 5 similar conductors which were parallel to each other and positioned at 31mm intervals. These 5 conductors operated under identical conditions to those of the single conductor with the exception that a current of 600A/conductor and not 1000A was applied. The results are shown in Figure – 15. The existence of the laminations did not affect the applicability of the superposition method. The discrepancy

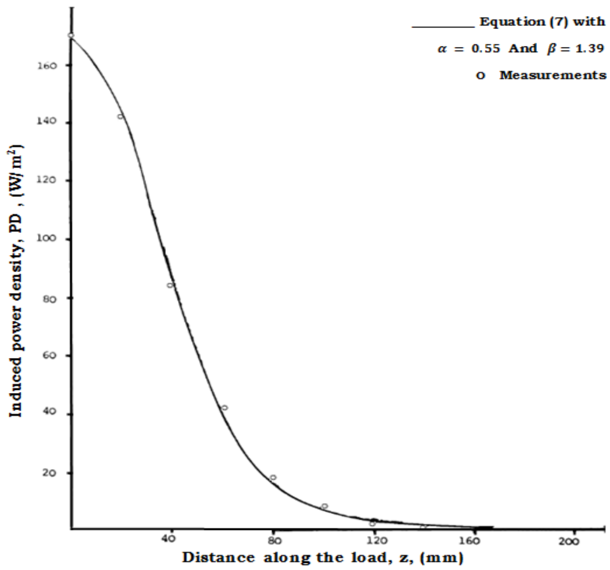

Figure – 7 *Surface power density distribution along aluminum slab due to 1000A flowing through circular conductor of 28 mm at h = 54mm with lamination pack at h1 = 35mm*

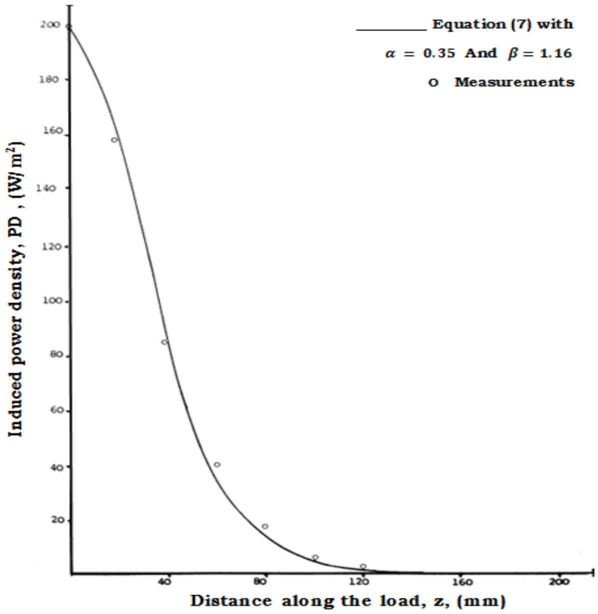

Figure – 8 *Surface power density distribution along aluminum slab due to 1000A flowing through rectangular conductor at g = 40mm with lamination pack at h1 = 35mm*

between the measured power density and that predicted by the superposition method is less than 7%. This small difference is an acceptable experimental error and proves that this technique can be used in the relevant applications.

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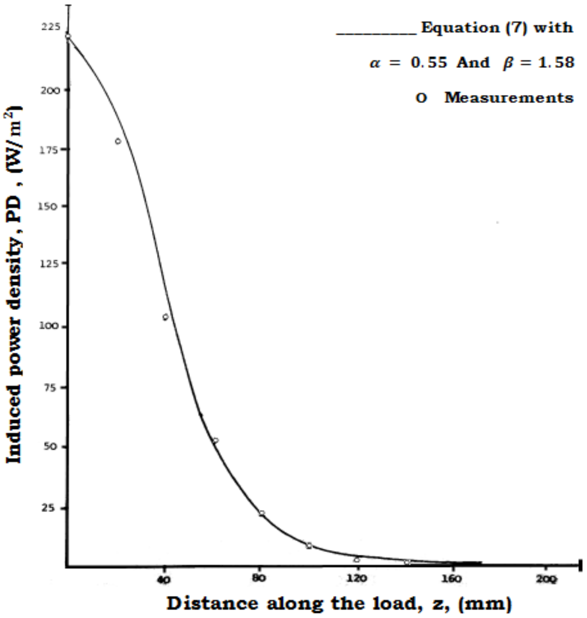

Figure – 9 *Surface power density distribution along aluminum slab due to 1000A flowing through circular conductor of 28 mm at h = 54mm with lamination pack at h1 = 5mm*

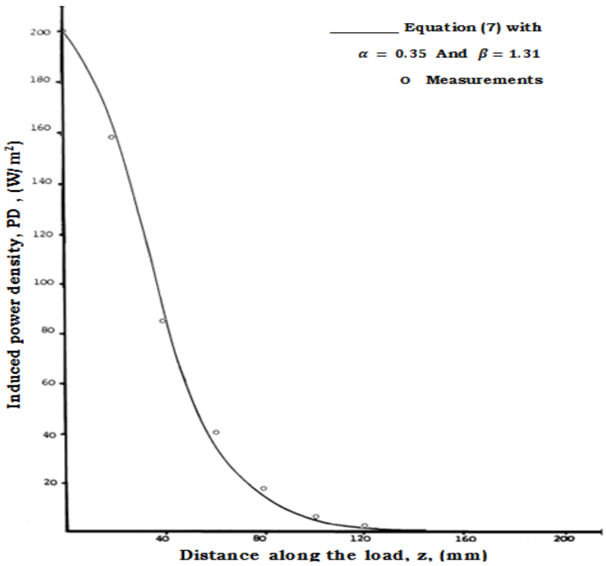

Figure – 10 *Surface power density distribution along aluminum slab due to 1000A flowing through rectangular conductor at g = 40mm with lamination pack at h1 = 5mm*

	Circular Conductor			Rectangular Conductor		
Distance h1 (mm)	PD under	PD on the other	%Diff	PD under lamin.	PD on the other part	%Diff
35	170.	153.45	9.92	199.02	165.25	16.9
20	34	157.97	13.7	219.08	179.11	7
11	183	153.07	6	234.53	180.0	18.2

Table - 3 the power density on the load directly beneath the conductor

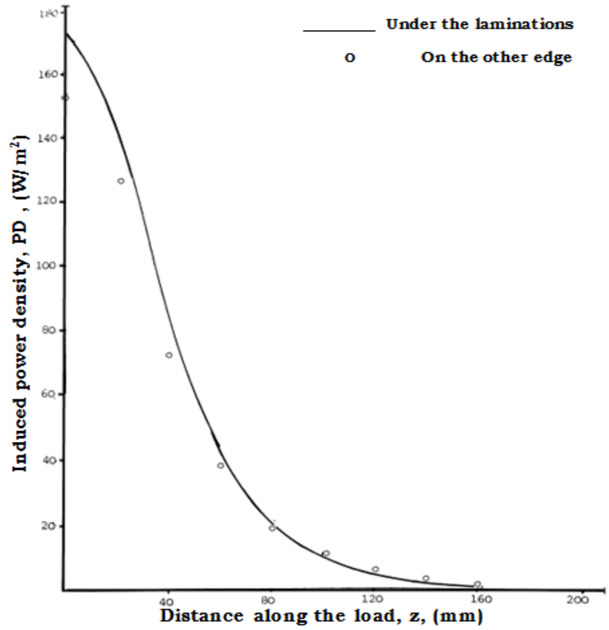

Figure – 11 *Surface power density distribution along aluminum slab due to 1000A flowing through circular conductor of 28 mm at h = 54mm with lamination pack at h1 = 35mm above one edge of the slab*

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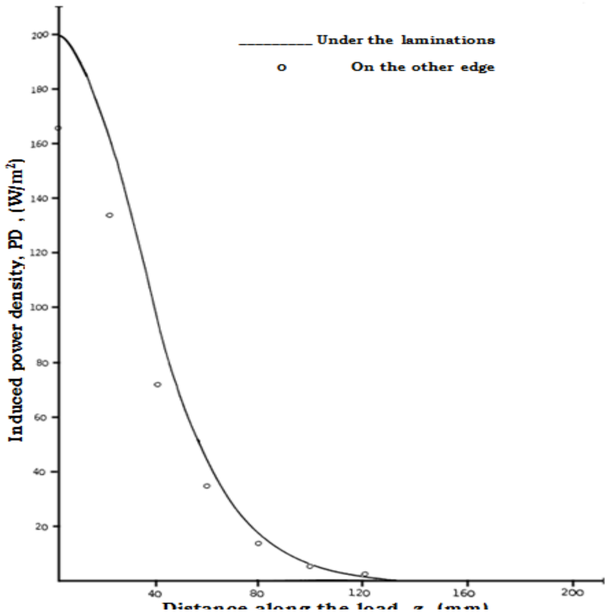

Figure – 12 *Surface power density distribution along aluminum slab due to 1000A flowing through rectangular conductor at g = 40mm with lamination pack at h1 = 35mm above one edge of the slab*

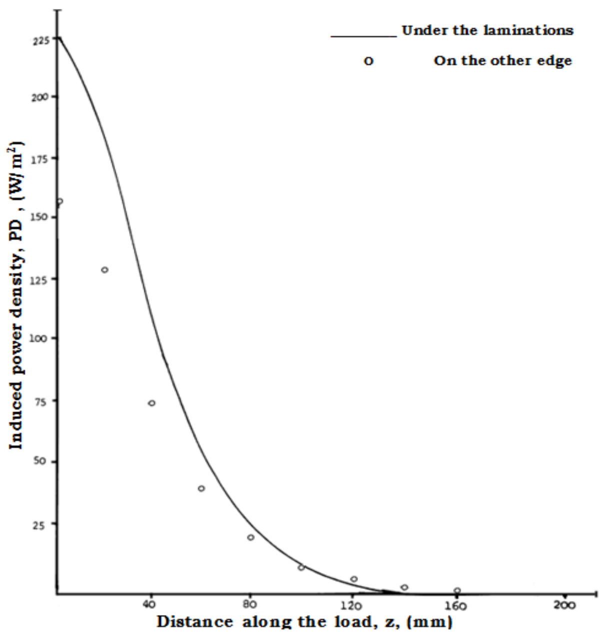

Figure – 13 *Surface power density distribution along aluminum slab due to 1000A flowing through circular conductor of 28 mm at h = 54mm with lamination pack at h1 = 5mm above one edge of the slab*

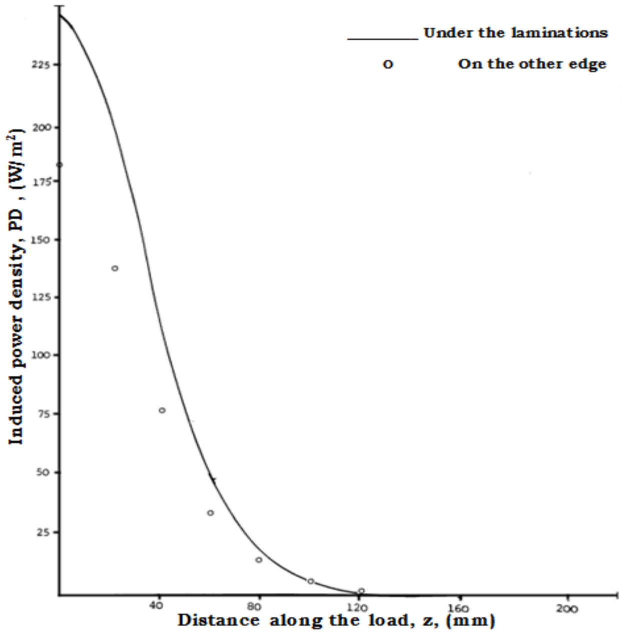

Figure – 14 *Surface power density distribution along aluminum slab due to 1000A flowing through rectangular conductor at g = 40mm with lamination pack at h1 = 5mm above one edge of the slab*

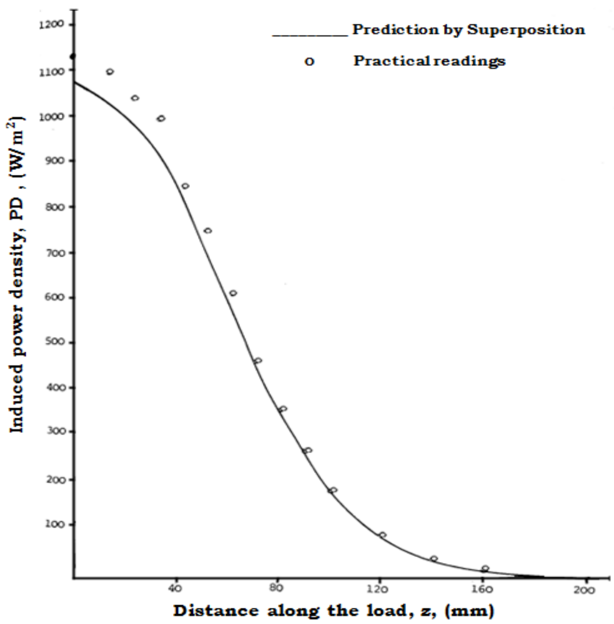

Figure – 15 *Power density distribution along aluminum slab due to 5 rectangular conductors at*

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air gap of 40mm,coil pitch of 31mm and current of 600 A/conductor with lamination pack at h1 = 5mm

IV. CONCLUSION

The superposition method can be applied to magnetic and nonmagnetic loads and to a system containing laminations. Also, the applicability of this method is not affected by the current distribution on the conductor which depends on the position of the conductor among other conductors. The use of laminations increases the power density induced on the load beneath the lamination packs. This power density is inversely proportional to the distance between the laminations and the conductor. The accurate calculation of the power density induced on a ferromagnetic load requires the variation of the permeability to be taken into account. Finally, the work with lamination packs proves that the superposition method is suitable to applications involving laminations such as metal melting and vessel heating. Hence it is conceivable to employ the superposition method on different applications.

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