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Aluminum Conductor Theoretical Design and Economy for Variable Speed Drives

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Abstract: Copper has been the only material with good conductivity and easy availability and methods of design of copper conductors motors are based upon more than half a century of years of experience. Economy variable speed drives might use aluminium conductor in the stator also so as to minimise costs ,but this has to be studied in detail and designs tested by actual construction. Now the time has come, at least in this country, to try to exploit materials other than copper towards this purpose, and we have the next best in the list as Aluminum, the metal which is available in plenty in this country and almost everywhere in the world. Already the use of Aluminum has found a place in overhead conductors, cables and for domestic wiring. But the use of aluminum winding material in electric machines has not been taken considerably and there are reasons. This paper provides simple and economical procedure for the operation of AC induction motors for small and medium sizes and therefore, the use of aluminum conductor for stator winding was considered as important.

Keywords*: motor stampings, Aluminum motors, specific heat per unit volume*

I. INTRODUCTION

The electrical machine is made up of the two essential pieces of material namely copper and steel. Speaking in physical terms, we require one material to conduct the current and another to conduct the magnetic flux so that they react and produce power.

Mariana [1] has investigated the rated and starting torque for both the copper and aluminium conductors for stator windings and have analysed the mechanical characteristics such as temperature and noise effects during the operation of the motor. There has always been a tendency to get better materials, particularly with the steel, so that machine size can be reduced. Though generally speaking silicon steel is the best suited for electrical machines, a very vast category of varying types of sheet steel have been produced throughout the world. The increasing use of grain oriented low loss steel types have found a place in large machine sizes to increase their efficiency. On the other hand there had never been any step taken towards the electrically conductive material either to improve upon it or substitute other materials for it.

E.C.Hartung[2] Fabricated aluminum rotor construction for induction motors. He presented a new process of construction of aluminum conductor rotors and reviewed rotor construction in a slightly different manner .W.R. Finley et al. [3] devised a choice between utilizing a lower cost die cast or fabricated aluminum rotor versus expensive copper bar rotor and analyzed , the effects of various materials and types of rotor construction on motor performance .Rahul Tiwari,, Dr.A.K.Bhardwaj, [4] analyzed motor performance with die cast rotor, and managed to prove that Using copper in place of aluminium would result in a motor efficiency higher than that of the original aluminium-based motor. E.F. Brush et al [5] showed that Performance of several motors where copper has been substituted for aluminum in the rotor squirrel cage resulted in higher electrical energy efficiency, slightly higher rotational speed, lower operating temperature, higher pumping rates and volume pumped per unit of input energy. D. T. Peters and J. G. Cowie[6] worked on improved efficiency and cooler running temperatures for copper rotor motors and they too suggested Design modifications to better utilize copper in the rotor and resulting motor performanceC. Stark et al. [9] suggested modification of the conductor bar shape to control in-rush current and starting torque to accommodate copper in the rotor. S. Bauer et al.[10] found that usage of copper as squirrel cage material substituting aluminium could result in ca. 15-20 % overall motor loss reduction.The use of aluminum in place of copper in motor windings, however, presents certain problems, which have to be faced before some experience is gained in its use. The problem is two fold; for, in the first place, a design with aluminum conductors presents considerable difficulties and as the second, winding of motors with aluminum wire has some differences. It is with this idea in mind that this problem was taken up and definite results have been obtained in the construction of aluminum conductor induction motors for the small and medium capacities.

The significance of this problem, however, has an important bearing in India. India's copper resources are limited. Already we have replaced copper in so many uses as line and cable material, in order to conserve copper and try to use indigenously available aluminum as substitute for copper. However, we know that is still a very large amount of copper is employed for drawing into wires suitable for its uses in winding electrical motors. If methods are obtained to utilize aluminum successfully in place of copper, a considerable saving of foreign exchange can be realized

II. DESIGN PROBLEM OF THE INDUCTION MOTOR WITH ALUMINUM CONDUCTORS

The one important drawback of aluminum is its increased resistance compared to copper. If we like to have the same resistance as a copper motor, then we must increase wire size by 60%. However, if we use wire of the same size, then the motor has 60% more copper loss. With so much of loss we will fail to comply with the normal specifications of performance demanded of such machines. The aim is therefore neither to increase wire size so much as to have the same resistance, nor to be satisfied with the increased resistance and poor performance, but to obtain a compromise between the two. It is therefore certain that we have to increase the volume of metal (aluminum) in the motor in order to obtain a reduction in resistance.

The thermal problem too is unfortunately more troublesome in the case of aluminum. Aluminum has a lower specific heat per unit volume, than copper. This means that with the same wire-loss, Aluminum rises to a higher temperature than copper. To add to this the thermal conductivity of aluminum is also only a little more than half that of copper. Hence the hot-spot winding temperature will be higher and this will have to be taken care by proper built-in cooling.

. Thus, it is important that we have more volume of space in the slots of the motor to accommodate the aluminum wires and the increase required may be about 40 to 50% depending upon motor size.

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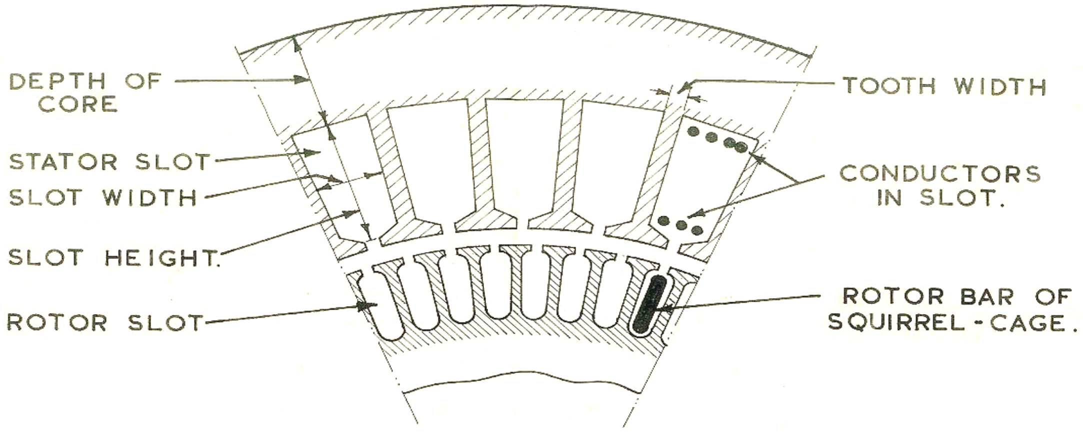

Fig.*1. Sketch showing a portion of the motor stampings, both Stator and Rotor.*

Supposing we take a motor stamping used for a copper motor and increase the slot height in order to obtain increased slot volume, then we are at a great disadvantage. For, when slot height is increased, we have increased tooth height and this results in increased tooth volume. Since in an electric machine the teeth are the highly stressed portions magnetically, when the teeth volume increases, teeth loss also increase considerably. In addition, the magnetizing current of a motor is dependent very much up on the m.m.f. required to pass flux in the teeth and with increased teeth length, the magnetizing current of the motor is more.

When magnetizing current increases , the power factor on load falls down and thus we will be falling out of the specifications required. Moreover when we increase slot height we will be increasing the facility for flux to leak inside the slots and hence the leakage reactance is increased. In an induction motor, the increased leakage reduces the maximum available torque and the starting torque. Thus the results are that the motor will have poor power factor, efficiency and starting torque.

The alternative to increasing slot height is to increase the slot height is to increase the slot width. (Fig.1). If we have to increase the slot width, then we have to reduce teeth width, because for a certain bore diameter having N slots, the length of the periphery will be N times the sum of teeth and slot widths. Therefore, we must simultaneously increase gap diameter in order to increase slot width. This means that we increase machine size and use more steel. So it is not very advisable to increase core diameter alone to obtain increased slot width. The other method to reduce tooth width would be to reduce the mean flux density B. If we reduce this B, then we will have to increase either the number of conductors per slot or increase core length or both suitably. For, if we reduce B, we get a corresponding decrease in the tooth width, which gives us more width of slot.advisable to increase core diameter alone to obtain increased slot width. The other method to reduce tooth width would be to reduce the mean flux density B. If we reduce this B, then we will have to increase either the number of conductors per slot or increase core length or both suitably. For, if we reduce B, we get a corresponding decrease in the tooth width,which gives us more width of slot.

III. DESIGN OF ELECTRIC MOTORS

Design of electric motors is usually given by [M.G.Say] the following equation which gives the relationship between KVA per rotation of the motor in terms of size.

$$KVA = C_o D^2 l \ldots\ldots(1)$$

where D is the diameter of the air gap and l is the core length.

C_o is a coefficient in Watts per rotations per minute and per unit volume (c.m). and is usually chosen for good silicon (4%) sheet steel as 2.5-3×10.[6]

We find that the parameters involved in the variation in order to procure more slot area are :

Gap diameter
Core Length
Teeth width
Height of slot
Gap density B and
Number of Conductors per slot

There is another variable viz. the maximum tooth flux density Bt. In fact the value of Bt is often chosen to be corresponding to the point on the knee of the saturation characteristic of steel. We see that all these six parameters, together with the current density chosen for the Aluminum, will have to determine the design of the motor. The output equation for a machine is given in terms of KVA per r.p.m.

$$KVA = GD^2LN$$

$$G = \frac{1.11 \times \pi^2 B_{av} \times ac \times K_w}{60 \times 10^3} \qquad ....(2)$$

where G is called the output coefficient in KVA/c.m./RPM.

The best value of Bav, which is known as the specific magnetic loading, and ac, which is well known to be the specific current loading, are not established for the aluminum conductor motors.

The values of Bav and ac are known as the design coefficients and are usually known for copper conductor motors, because values of the above two for various machine sizes have been found by experience in design. But we are lacking design experience with Aluminum conductor motors. Therefore we will have to try all combinations of the above variables and try to obtain designs for motors which not only comply with the standard specifications but can also compete fairly with the present copper conductor motors both in cost and in performance.

It is with these in view that a method of design, which could take into account all possible variations and obtain the motor of required performance and minimum total cost was programmed for working on the computer. The method of design is an "optimum design" for these motors of H.P. from 3 to 50 and this involves the continuous variation of parameters such that the requirements are fulfilled and also the cost is minimized. A number of modifications had to be done during the working of the solution since there were many unanticipated troubles in the working of the solution by the computer. This means to say that there should be a definite order in which the different parameters are to be varied, and if the order is changed, there is a possibility that no design is obtained which could comply with the requirements. The flow diagram of data for such a final programme is shown in Table 4-1.

IV. DESIGN INVESTIGATIONS

The Horse power or KVA rating is chosen. The Speed of the motor at mains frequency is given. Then a range of diameter values normally known for that rating are given. The current density of Aluminum conductors is also assumed.

The number of slots per pole per phase should be at least *2* and most small motors have *3* as the value.

Starting from the smallest value of diameter of air gap from the range given we calculate the pole pitch as πD / Poles and the slot pitch as pole pitch divided by slots per pole

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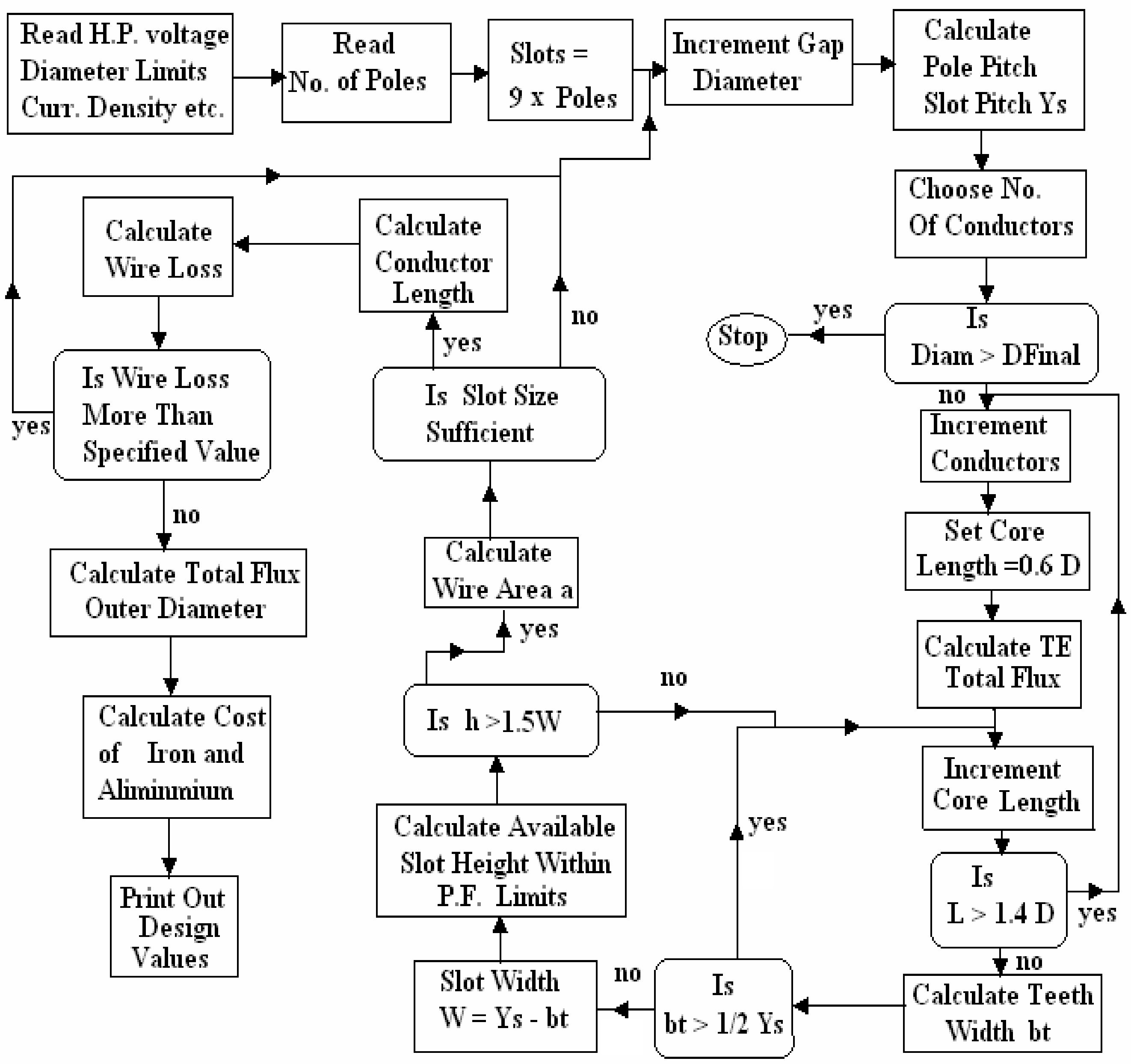

Fig.2 Flowchart of Computer Programme

Pole pitch$=\frac{\pi D}{P}$

We start choosing the diameter of the core as if it were for copper motor design.

From design data for such motors, we use (2) above, which gives

Slot pitch $Y_s = \frac{\text{Pole pitch}}{\text{Slots per pole}}$.....................(3)

.

$$KVA = GD^2LN$$

$$G = \frac{1.11 \times \pi^2 B_{av} \times ac \times K_w}{60 \times 10^3}$$

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So, values of Winding factor K_w of 0.9 is chosen, B_{av} (the average flux density under the pole) and *ac*(amp. Conductors/ cm. of armature periphery) are as 6800 Gauss and 250.

With these values, for a 7.5KVA motor, say, we can substitute and get the value of G as 2.95×10^{-6}. Dividing by N, the speed of motor at rated frequency as 1000 r.p.m., D^2l =2540.

Thus, an initial D is chosen and the core length *l* found from D^2l by division.

The diameter value is varied step by step. The length is assumed first as 0.6 D

$$l(\text{intial choice}) = 0.6D \ldots\ldots\ldots\ldots(4)$$

Then the flux per pole Φ is to be found from

$$\text{Flux per pole} = \emptyset = \text{pole pitch} \times B_{av} \times l = \pi D B_{av} l/P \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The next calculation is the number of conductors. For this the EMF Equation is used:

$$E_{phase} = 4.44 f \times \emptyset \times T_{ph} \times K_w \ldots(6)$$

This equation relates induced stator voltage (per phase) with the frequency, flux per pole and turns per phase. K_w is a pitch factor and distribution factor combined quantity depending on winding.

From the frequency value and Voltage of the motor, this equation enables winding number of turns per phase (T_{ph}) to be calculated.

Conductors per slot can be found as

$$Z_s = 2T_{ph}/(SPP \times P) \ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Because the conductors will be two for each turn; further per slot means we divide by the no. of slots per phase which is *P* times the SPP, the term used for Slots per pole per phase.

The core length can be varied from 0.6 to 1.4 *D*. For each of these, the flux per pole, the number of conductors per slot are to be found.

1. Calculating teeth width

The width of stator tooth adjacent to the slot is an important parameter. In variable speed inverter drive for these motors, since they are higher frequency flux components (in space vector method, DTC ,FOC methods particularly), the teeth losses will become abnormal causing over heating. Teeth saturation should be avoided due to excess flux value in addition to ensuring a lesser flux density to cope with the higher than nominal (i.e., mains supply) frequencies being applied to the motor.

$$\text{Slot pitch at the air gap} = \frac{\pi \times D}{P \times 3 \times SPP}$$

We choose an average tooth density value B_t. The flux density values can be told in Tesla or in lines/s.cm. The value for Stalloy sheet steel laminations is 11,700 (1.17 Tesla) is recommended for 50Hz motors. For this density of flux, the ampere turns to magnetise is obtained from the Stalloy steel magnetizing curve as 12 at/cm. This fact is used for calculating the current of the motor on no load.

So, the value of b_t is found as

$$b_t = \frac{\text{Flux per pole } \emptyset}{\text{Slot per pole} \times \text{Core length} \times 1.17} \ldots(8)$$

because all flux mostly pass through the total number of slots which form a pole Since b_t times core length gives the area per slot, the flux density of the chosen value (which can also vary) is used to determine the tooth width of stator slots.

Then the slot pitch is calculated Y_s. This is just the pitch of the slot. We cannot have too small a slot width and a large tooth width. Therefore, a check is made if the tooth width is more than half the slot width. Then, we have to reduce the flux per pole. So the program loops back to increase the core length *l*.

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Then the slot width is calculated from

$$W_{slot} = Y_s - b_t \quad \ldots\ldots \quad (9)$$

Calculating the width of slot, it can be chamfered at the edge to give a small opening or lip, about 2 -3mm only for wire entry. For small size motors, it is usual to have parallel teeth and trapezium slot shape.

Conductor current has to be found. This is the same as the phase current I_{ph} of the motor given from

$$I_{ph} = \frac{KVA}{3V_{line}} \ldots\ldots\ldots\ldots\ldots\ldots(10)$$

This assumes Delta connection which is usual when a star-delta type of starter is to be used. But with variable speed inverter drives, they prefer star winding because the motor's starting with star to delta change over is not done with such drives.

2. Current density of wire and size

From this current in the conductor, we decide the area of wire by

Wire Area = Current in conductor/ Current density.

The copper conductor value normally used is 400 Amperes per square cm. This is high with aluminum wires. A lesser value is to be chosen. Variation from 250-300 is chosen by computer. For each choice, of course, the motor performance is assessed and then choice is made.

A standard gauge wire is anyhow to be chosen, since wire sizes are given in Gauge numbers. (The no. of dies the metal is drawn through to reduce the area).

Then from the wire area, we calculate the slot area and depth of slot. This is given by

$$\text{Slot depth } h_s = \frac{Z_S \times \text{Wire Area}}{\text{Slot Opening} \times \text{Space factor}} \ldots(11)$$

The slot opening has been found from W_s in (4.9). The Space factor can be about 0.4 to 0.5 depending on wire insulation. It is only 0.4 for Double cotton or polymer fiber insulation or 0.5 for enamel insulated wires. The slot lining insulation is also taken into account in the factor.

The slot depth having been found, one has to determine the reactance to leakage flux and estimate what the motor power factor will be on load. When the depth of slot increases, the X_1 value increases and hence the Cos φ decreases.

Therefore a check initially is to look if $h_s > 1.5W_s$. This will take the program loop back to the point earlier in the program, where either core length or even the next diameter is chosen.

3. Conductor length and wire resistance

The conductor length is found taking into account the pole pitch for the overhang length of wire. Then, knowing resistance of wire chosen, the total stator winding resistance R_s is calculated.

The wire losses on full load is given as

$$= 3{I_{ph}}^2 R_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots(12)$$

This has to be within limits; usually not more than 3% of rating. Otherwise, the diameter of motor is changed and design is re-started from the beginning.

4 .Total Flux and outer diameter

Since the pole flux is known, from the chosen flux density for the bulk sheet steel, we can have a depth of metal below the slot equal to the slot height or somewhat less. This decides the outer diameter of the motor stator. Then, the stamping size is sketched and has to be used for making the laminated stampings.

$$D_{outer} = D_{inner} + 2h_s \quad \ldots\ldots\ldots\ldots(13)$$

The volume of material for stampings can now be determined from

$$Volume\ of\ Stampings = \pi(D_{outer} - D_{inner})^2 l \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(14)$$

Cost of Iron = Cost per volume of stamping X Volume of Stampings.

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To this, the cost of stamping die making has to be included in any new design.
The cost of aluminum wire used is calculated from the length of wire and Cost per meter.

The total cost figure is only used to compare between the several choices of design made by the program.

The performance of the motor is estimated from the values of magnetizing current determined as well as the leakage reactance values.

5. Economics of Aluminum motors

Nothing definite can be mentioned at present as to the economics of these motors. To bring this into line we should consider the following. Even though large deposits of aluminum are available in this country, much remain to be mined. At present, the demand for aluminum in the country is so high that unless more refining plants are set up in India, we will have to be continuing to import aluminum. The cost of indigenously produced aluminum is low compared to Czech, Russian and Canadian imports. In fact, the cost of aluminum is widely fluctuating for the pure metal. It need not be said that with imported Aluminum we will incur a loss in the construction of these motors. However, with Indian Aluminum we can save more than 10% for each motor.

V.CONCLUSION

However, the importance of this problem is more than the economy drives. Our requirements of copper are mostly by import. With the use of aluminum for small motors, which are ever being made use of in this country in very large numbers, we will be effecting a positive saving of copper and foreign exchange. Aluminum conductor motors are particularly suitable as agricultural pump-motors, since design can be less rigorous with them thereby bringing about an additional 3% saving. Aluminum lends itself particularly suitable for die casting applications and the idea of utilizing aluminum for casting the squirrel cage of motors, together with the fan blades, though not a novel one is very noteworthy. And the saving of copper so contrived can be concentrated into the use of higher rating machines and d.c. machines and other special applications

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