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Discrete Design Optimization of 3-Phase Induction Motors Using Standard Lamination

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***Abstract*—3-phase squirrel-cage type induction motors are very widely used as industrial drives. They have outpaced their predecessor the d.c. motors for various advantages they have. Slip-ring or phase-wound types are used as adjustable-speed drives. Cage-type motors are also being used as adjustable-speed drives after the advent of power-electronic devices. The single-phase motors are also widely used for running small machineries and domestic appliances. The total expenses for these motors constitute the largest fraction of the total investment at the consumer end. Therefore, they must be designed cost-optimally. At the same time, they must conform to the standards specified by the customer or the statutory regulations imposed by the authorities. We can expect to arrive at a feasible but not cost-optimal solution if the design is made according to textbook guidelines. Standard stampings are more cost-effective for job work because they do not require the purchase of expensive dies. Using commercially available standard stampings, the paper presents an iterative procedure for obtaining the most cost-effective solution under typical design constraints. On this foundation, a case study was developed.**

Keywords— Boost converter, Grid-connected, Photovoltaic (PV), PWM inverter, Transient current limiter (TCL), Stability analysis, Total harmonic distortion (THD)

I. INTRODUCTION

Standard laminations are typically used in the job manufacturing of transformers or induction motors, but they can also be customized. The practice is more advantageous in terms of economics. If laminations are constructed in a free-form manner, the die-set necessary to fabricate the laminations will be prohibitively expensive. Purchasing die sets for laminations is not an economically viable option if the order is for a small number of machines. Nowadays, induction machines (IMs) are commonly employed in variable-speed drives due to their simplicity and resilience, as well as the fact that they are made using mature manufacturing technology and control methods. Furthermore, IM is less expensive than a permanent magnet machine, which is one of the reasons why it is so widely used [1]. Variable-speed IM has received a great deal of attention since its introduction in the 1990s. It is important to note that the primary distinctions between variable-speed induction motors and line-fed induction motors are that (a) no particular design for high self-starting torque is required and (b) the input voltage/current and frequency can be changed for a given operation point. Therefore, the deep slot or double cage that was required for a line-fed induction motor is no longer required for this type of motor. The conventional procedure is to employ standard stampings for the purpose of duplication. Standard stampings in a variety of sizes are readily available on the Indian market for purchase. At one time, the Shankey wing of M/S Guest, Keen & Williams was the dominant force in the market for stampings. Several additional enterprises, such as M/S Debidayal and others are now engaged in the mass manufacture of stampings. The upshot is that induction motor systems often have high losses, low efficiencies, a low power factor, and a low inverter use factor, which is particularly problematic for motors operating at high speeds and with big output powers. As a result of a substantial study undertaken on the design principles of induction motors used in hybrid electric vehicles [1]–[6], this issue was resolved after the 1990s.

Designs conforming to standard stampings and standard frames cannot be made by following the test-book procedure. Specially constructed programs are required for their design.

II. CONSTRUCTIONAL FEATURES OF INDUCTION MOTOR

Inclined motors can be broadly divided into two types: squirrel-cage type and phase-wound type (also known as slip-ring type). Compared to other types of cages, squirrel cages are more durable and sturdy, as well as being less expensive and less maintenance intensive. As a result, they are more frequently encountered. They were, however, unsuitable for use with variable speed transmissions (until the advent of power electronic control). In addition, because they operate at a low power factor, they consume an excessive amount of VAR, resulting in an excessive voltage drop on the system bus. They are also unsuitable for loads that necessitate a large amount of beginning torque. Despite the fact that they are more expensive and suffer from issues coming from rotating contacts, phase-wound or slip-ring types of motors are employed for such drives.

A. Cage-type motors

Stator construction: The main parts of the stator are the stator core and the stator windings. The core-coil structure is assembled in the frame. The frame sizes are standardized. The stator core is made by assembling stampings of Si-steel (Lohys or special Lohys) having one or two coats of varnish. Different grades of materials are available in the market. Semi-closed slots, either parallel-sided or rectangular, are commonly used. Depending on the size of the motor, a no. of radial and axial ducts is provided while cores are assembled, for adequate cooling and if necessary a cooling fan is also added. The slots are lined with insulating paper and coils made of insulated conductors are placed in slots to form the

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windings. The individual phase windings are similar to each other- they are internally separate but externally connected in star or delta according to the designer's choice. Copper conductors of the appropriate cross-section are used. Aluminum conductors are used for transmission lines but are not suitable for rotating machines as they take more space which offsets the overall economy.

Rotor Construction: The rotor core is also made of laminations of the same material, with coats of varnish to limit the eddy current. However, solid cores are also used for large machines to get a mechanically stronger rotor. As the rotor frequency is much smaller than the line frequency, the rotor iron loss is negligible. The no. of slots should not equal to that of stator- also a no. of unfavorable combinations of stator and rotor slots are to be avoided so that vibration, noise, cogging, and crawling may not occur.

The cage-type rotor is made by placing bars of copper or aluminum in the slots and brazing them to two end-rings. Presently die-cast rotors are used which are mechanically stronger, aluminum is being the commonly used material. The cage-type rotor is short-circuited in itself. Hence no resistance can be inserted in the rotor circuit of a cage-type motor to limit the starting current and increase the starting torque. Larger starting torque may be realized by using deep and narrow slots or by using double squirrel cage construction.

The rotor core & winding structure is keyed onto an M.S. shaft of required diameter which is placed on ball/roller bearings in end-plates bolted to the stator frame on its two sides. The diameter is determined by the consideration of torsional and bending stresses. The enclosure is to be chosen according to the environment and the mounting according to the specific use.

III. Phase-wound motors

The phase-wound or slip-ring type motors are used for adjustable speed drives. Their stator construction is similar to that of the squirrel-cage motor. But the rotor construction is different- it houses a polyphase winding wound for the same no. of poles (but maybe of different no. of phases) as for the stator. The windings are connected in star and the terminals brought to slip-rings. Variable rheostats are connected to the windings through slip-rings and brushes. Their function is to limit the starting current and to increase the starting torque. They may also be used for rheostatic speed control. However slip-power recovery schemes employing power-electronic devices are better options as they do not waste power in the rheostats and hence they are power-economic. They can be used also in the VAR-compensating mode by injecting EMFs with q-axis components.

A. *The Design Procedure*

Four different approaches are made for designing engineering equipment viz. analytic, synthetic, optimal, and standard. The analytic procedure is very common and easiest. It starts from identifying the design variables and assigning appropriate values to them. These values are obtained either from the experience of the designer or from design data books. Then data entry is made for the equipment to be designed. The program runs through multiple steps for calculating the dimensions of the machine and for computing the performance variables. There is no feedback from the output or the results in the input section. So one must be content with whatever results he gets or he may take another chance changing the values of the design variables.

The shortcomings in the analytic approach can be partially offset by following the synthetic method in which specifications and constraints are given. The program is designed to give multiple feedbacks from the output in respect of the constraints and to bring forth necessary changes in the variables to conform to the specifications.

B. *Design variables*

- There are many variables in a 3-phase induction motor. Some of them are continuous variables, some of them are decision variables and some of them are integer variables. The variables that have a large influence on the cost-function are called key variables. In an induction motors, the continuous variables are: i) length/pole-pitch ratio, ii) average flux-density in the gap, iii) flux-density in the stator/rotor core iv) teeth flux-density in stator/rotor v) amp-conductor/m of periphery, vi) slot depth/slot width, etc. The decision variables are: i) single layer or double layer winding in the stator, ii) configuration of slot, iii) conductor material for the rotor, iv) type of bearing iv) laminated or solid rotor, etc. The integer variables are i) no of stator/rotor slots, ii) no of slots/pole/phase (generally integral slot winding is used in induction motor, iii) no. of conductors/slot (even integer for double layer winding) iv) no of ducts, etc.

C. *Design constraints*

- The optimization has to be sought in presence of a no of inequality and other constraints viz.

  a) Full voltage starting torque/full load torque must be more than a pre-defined value e.g. 1.75.

  b) Maximum torque/full load torque must be more than a pre-defined value e.g. 2.25.

  c) The efficiency must be more than a pre-defined value e.g. 85%

  d) The power factor must be more than a pre-defined value e.g. 0.8 lagging

  e) The no. of stator slots/ rotor slots must be integers

  f) No. of slots/pole/phase must be an integer.

IV. Algorithm

A Delphi high-level programming language was used to construct the software for induction motor design optimization. Analyze and improve motors using this program or assess design costs and performance with this software. The motor or the materials may be simply changed to see how they affect performance. The user has a degree of control over the selection and optimization types (such as torque, cost, and so on). A roulette wheel selection, a single point crossover, bit mutation, and elitism were used in the GA optimization process. The flowchart in Figure 1 illustrates the process of design optimization. Each block contains several subroutines. Once the program has established and run the fundamental motor design factors, such as the number of generations, population size, crossover rate, and mutation rate, it begins executing the performance criteria. The user may specify the

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population's characteristics, including its size, number of generations, crossover rate, and mutation rate.

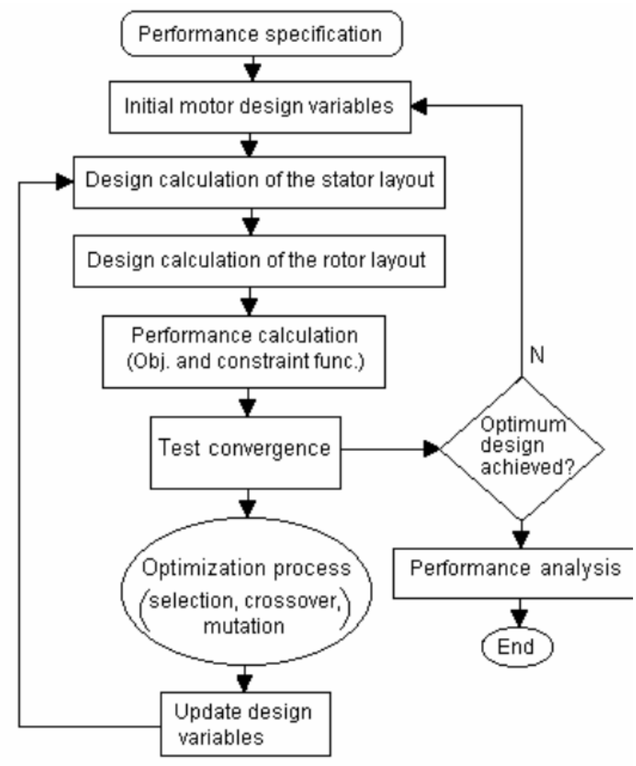

Fig.1 The flow chart for the design optimization process

The algorithm for optimal design with standard laminations is given below:

1. Read data on design variables ( ), specific cost etc.
2. Read data files on SWG no of wires, the thickness of insulation, etc.
3. Read the specifications of the motor.
4. Check the validity of the specifications. For invalid specifications go to step 2
5. Find the output coefficient. Find input power/apparent power from assumed values of efficiency & power factor.
6. Find the approximate friction & windage loss by using a data file on the same.
7. Find no. of poles, synchronous. speed and the D2L-product.
8. Find shaft diameter from mechanical considerations.
9. Choose length/pole pitch ratio as 0.8 and find the stator bore diameter.
10. Open the data file for standard laminations available in the market and keep the data in an array. Compare the calculated diameter with the diameters of standard laminations and choose the frame size of the nearest available diameter.
11. Read the details of the lamination. Check the feasibility of accommodating the shaft. If the inner diameter of the lamination is less than the shaft diameter then go to step 33.
12. Find the length of the stator from D2L product, net length of iron, number of ducts, pole pitch, flux per pole.
13. Find pitch factor by short pitching the coil to about 5/6th. of the pole pitch. Find the breadth factor and the winding factor.
14. Find a number of turns/phases.
15. Find stator current, no. of conductors in parallel, and the cross-section of the conductor.
16. Open the data file for the SWG number and choose the appropriate conductor available in the market.
17. Find the depth of insulation and outer diameter of the conductor.
18. Choose parallel-sided teeth and semi-closed slots.
19. Find the depth of stator core and width of teeth for specified flux density of the core and the teeth.
20. Find the slot dimensions to accommodate the conductors.
21. Find the mean length of turn of stator and its resistance per phase.
22. Calculate iron loss in teeth & core of the stator by opening data file on special LOHYS.
23. Find the air gap, rotor diameter, and length.
24. Choose Aluminium as rotor conductor material. Find dimensions of the rotor bars and the end rings and dimensions of the rotor slots.
25. Find Carter’s coefficients from the data file and the total AT of stator, rotor & air-gap.
26. Find the magnetization current & the no-load current.
27. Find the slot leakage, overhang, and zigzag presences & the leakage reactance.
28. Find the rotor resistance & the short circuit impedance.
29. Make performance evaluation at full load - slip, efficiency, power factor, and temperature rise.
30. Find the critical speed and maximum torque.
31. Find starting current and starting torque, taking an increase in rotor resistance due to skin effect into consideration.
32. Calculate the weight of iron, copper, and aluminum and find the total cost inclusive of labor & overhead cost.
33. Keep all calculated values in the array.
34. Decrease the diameter by one step & go to step 11

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35. Examine the calculated values of the array and choose the lamination for cost-optimality.
36. Print the values corresponding to optimal design.
37. Stop
38. End.

In this work, the cost function includes the running cost of the motors in addition to its capital cost to preserve the interest of the customer

V. CASE STUDY

A program has been developed to design the motor using standard stampings, changing design variables like ratio, etc., and compute the cost function. This function is a weighted combination of the cost of production and the running cost to cover the interest of both the manufacturer and the customer. The design has been made following the algorithm given in the earlier paragraphs.

A. *The specifications*

Type of motor: 3-phase Squirrel Cage Induction motor
Type of starter: Star-Delta (Yd)
Frame Material: Normalised Grey C.I., with holes for axial flow.
Stator winding connection: DELTA; Type of stator winding: Double layer
Slot insulation: Bonded Polyester; Stator/ Rotor core material: Super-varnished Special Lohys
Class of insulation: B: Temperature rise as per grade
Type of enclosure: SPDP with fan-cooling
Stator conductor material: Synthetic resin-enameled copper
Rotor Material: Die-cast Aluminium; Roller bearings on both ends: Rotor to be dynamically balanced.

B. *The ratings*

KW/HP output: 30 / 40.2 ; Line voltage = 415 V; variation: -15% to +6%, Frequency = 50 Hz. ; variation: ± 4% ; R.P.M.= 1450 ; Duty: Continuous.

C. *Chosen design variables and assumptions*

Amp.-conductor/m = 35000; Average flux-density = 0.45 Tesla, Length/pole-pitch ratio varying from: 0.8 to 2 , Stator current density: = 6 A/mm2 ; Rotor current density = 4.575 A/mm2, Stator teeth/ core density in Tesla: = 1.2 ; 1.25 ; Rotor core density = 0.6627 Tesla , Copper space factor = 0.6 ; Assumed efficiency /power factor: 0.9 / 0.9.

D. *The specific costs*

Cost of iron = Rs. 120/ kg ; Cost of copper (nomex-coated) = Rs 720/ Kg ; Cost of aluminum = Rs. 180/Kg.

E. *The findings*

The program finds out the following possibilities:

Frame no.	Stator outer diam, mm.	Stator inner diam, mm.	Rotor inner diam, mm.	Stator no. of slots	Rotor no. of slots
144M	260.4	177.8	44.45	36	40
102M	304.8	190.5	50.8	36	40
146M	304.8	215.9	50.8	36	40
104M	366.6	228.6	50.8	36	59
103AM	355.6	254.0	50.8	48	59

Out of these, frame no. 104M of Shankey division of GKW gives the cost-optimal solution. So the design has been made based on this stamping.

VI. THE SOLUTION TO THE DESIGN PROBLEM

A. *Main dimensions*

i) No. of poles = 4 ; Synchronous speed = 25 R.P.S

ii) Approx. KW/KVA input: 33.333 ; 37.037

iii) Output coefficient =164.59 ; D2L-product = 0.00900 m3

iv) We choose standard stampings from table, but slots are freely designed.

v) The frame designation chosen by iterative procedure: 104M

B. *Stator design*

Stator bore diameter = 228.6 mm; Stator length = 170 mm ; Length/pole-pitch ratio = 0.947 ; No. of ducts = 1 :Width of ducts = 10 mm Net length of iron = 147 mm; Pole pitch = 179.5 mm; Flux/pole = 0.3740 Waber; No. of stator slots/ no. of rotor slots: 36 / 59 ; Stator slot angle.= 20o , No. of stator/rotor slots/pole/phase: = 3 / 4.917 ; Stator/rotor slot pitch in mm: 19.9 ; 12.1; Pitch factor of stator = 0.9848 ; Breadth factor of stator = 0.9598 ; Winding factor of stator = 0.9452; No of conductors/slot = 24 ; Total no. of conductors = 864 ; No of turns/phase = 144; No of parallel conductors in stator = 2; SWG No. of stator conductors = 15; Area of stator conductor = 2.627 mm2 ; Diameter of stator conductor = 1.8288 mm; Diameter of stator conductor with insulation = 2.059 mm; Total copper area/slot = 126.08 mm2; Parallal teeth & trapezoidal slots are used. ;Width of teeth = 8.5 mm ; Lip / Wedge in mm: 1 / 3 ; Width of slot over wedge = 12.1 mm ; Width of slot at bottom = 16.0 mm ; Depth of slot = 26.0 mm ; Actual copper space factor = 0.407 ; Depth of stator core = 37.0 mm ; Outer diameter of stator = 356 mm ; Clearance with frame = 4 mm.

C. *Rotor design*

Airgap length = 0.6 mm ; Rotor length = 160.0 mm; Rotor bar current = 370.6 A ;Rotor bar area = 81 mm2 ; Rotor bar width = 4.5 mm ; Rotor bar length = 160.5 mm ;Rotor bar depth = 18 mm ;Slip-ring width = 21 mm; Depth of rotor core = 70.4 mm ; Inner diameter of rotor = 50.8 mm = Shaft diameter ; Flux-density at 1/3 rd. tooth height of rotor = 0.999 Tesla ; Width of rotor teeth at 1/3 rd. tooth height = 6.3 mm ; Minimum width of rotor teeth = 5.7 mm; Rotor bars are skewed by one slot pitch. Ring depth is equal to bar depth. No load current calculation: Carter's coefficient: for stator slot = 0.637 ; for duct= 0.763 ; for rotor slot= 0.253; Gap contraction factor: for stator slot = 1.190 ; for rotor slot = 1.021 ; for duct = 1.047; Equivalent gap contraction factor = 1.272; Amp.turn required: for airgap = 372 ; for stator teeth = 92 ; for rotor teeth = 9 ; for stator core = 31 for rotor core = 4 ; Total Amp.turn required = 508 Magnetizing current = 6.37 A = 21.9 %Losses: Friction & windage = 522 W ; Stator teeth = 130.5 W; Stator core = 229.4 W; Stator iron = 359.8 W; % iron Loss = 1.1; Rotational loss current = 0.71 A 2.43 %; No load current = 6.41 A 22.04 %; Losses at full load:; Rotor ohmic loss = 867.6 W 2.64 %; Stator ohmic loss = 1088.3 W 3.31 % ; No load loss =

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881.83 W 2.69 % ; Total loss = 2837.7 W 8.6 % ; Parameter estimation: Stator resistance = 0.508 Ω 3.643 %; Rotor resistance referred to stator = 0.405 Ω 2.904% ; Eddy loss ratio = 5.724Leakage reactance: due to slotting = 1.15 Ω ; due to overhang = 0.40 Ω ; due to zigzag = 0.92 ΩTotal leakage reactance = 2.47 Ω 17.74 % Magnetising reactance = 65.13 Ω 466.84 %Iron loss resistance = 585.91 Ω 4200 %; Equivalent impedance referred to stator = 2.638 Ω 18.91 %

Full load condition: Full load torque = 202.12 N-m ; Full load stator current/phase = 29.09 A ; Full load line current = 50.39 A ; Full load power factor = 0.9309; Full load power input =32838 W ; Full load efficiency = 0.9136; Full load slip =0.0273 ; Full load speed = 1459 rpm; Starting current = 110.5 A ; Starting torque at full voltage = 540.31 N-m; Starting torque at reduced voltage (Y-D starter) = 180.1 N-m; Starting current/full load current for full voltage starting = 3.796; Starting torque/full load torque for full voltage starting = 2.673; Starting torque/full load torque at reduced voltage (Y-D starter) = 0.891; Critical slip = 0.16037 ; Maximum torque = 541.96 N-m ; Maximum torque /full load torque = 2.681; temperature rise:Copper loss in embedded portion of stator winding = 419.1 W; Total loss in embedded portion of stator winding = 778.9 W; Temperature rise of stator = 28.68 oC; Cost analysis:Weight of iron = 90.65 Kg ; Cost of iron = Rs.10877/-Weight of copper = 17.83 Kg ; Cost of copper = Rs.12841/-; Weight of aluminium= 2.87 Kg ; Cost of aluminium = Rs. 517/-Material cost including 20% auxilliaries = Rs. 29083/-Manufacturing cost inclusive of labour & establishment = Rs. 40716/-. The cost functions for all other feasible solutions have been found to be more.

VII. CONCLUSION

Optimization is the process of finding the best possible solution out of many feasible solutions. The feasible solutions of a design problem are found by varying the design variables within their normal bounds. The solution giving minimum cost may be found out either by exhaustive search in the parameter-space or by techniques like gradient search, method of random walk, etc. The advanced mathematical techniques need not be used for finding out the optimal solution using standard laminations, as the no. of solutions is few. Therefore the method of exhaustive search is acceptable in this case. The only thing of interest is to check the compatibility of the design with the chosen standard core and whether the specifications have been fulfilled.

It will be beneficial to the manufacturing process if we aim for the lowest possible cost of production. It will keep the machine's cost low while increasing sales. The machines, on the other hand, will be less efficient, will have higher ohmic and no-load losses, and will indirectly cause more pollution. As a result, the best practice is to create an objective function that accounts for both the capital and operating costs.

In this work, a computer program has been developed for the design of a 3-phase squirrel-cage induction motor. Provisions have been made for switching over to standard lamination available in the market after finding out the bore diameter. It has been repeated a no. of times changing the (length: pole pitch) ratio within its normal bounds. Also, changes have been made in the value of average flux-density and amp. Conductor/m. The best possible solution has been chosen from the set of solutions obtained by this process. The case study has been made on a 30 KW, 415 V, and squirrel-cage induction motor.

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