COMPUTATIONAL AND FEM BASED ANALYTICAL ASPECTS OF MEDIUM CAPACITY-TURBO ALTERNATOR DESIGN

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***Abstract:**Today most of the electrical power in the world is generated by synchronous machine (alternator). Regarding to the cost, durability, stability, security; a design of synchronous machine is very important. Various constrain like processes, availability of magnetic material, quality aspects and cost aspects are considered during the design of synchronous machine. In practical design, a number of designed parameter of the machine is so high such that hand calculation is so tough and takes a long time. To satisfy all constrain and get realistic design, an iterative approach is required and that can be done by computer programming. This paper represents a design process with flowchart for the synchronous machine and a finite element method for the magnetic analysis.*
***Keywords:**Design of synchronous machine, Electric loading, FEM-Finite Element Method, Magnetic loading, SCR-Short Circuit Ratio.*

I. INTRODUCTION

Design may be defined as a creative physical realization of theoretical concepts. Engineering design is an application of science, technology and invention to produce a machine which performs specified tasks with optimum economy and efficiency. For any synchronous machines which are used in the power system must be designed with reliability and durability in operation as a major consideration, with less emphasis on initial cost [1].According to the rotor construction, a synchronous machine (alternator) having two types such as Salient pole rotor machine and Cylindrical pole rotor machine. In thermal power plant and nuclear power plant, a high speed synchronous machine which having a cylindrical rotor construction and in hydro power plant, a low speed machine which having a salient pole rotor construction are used. The speed of the machine is dependent on the number of machine poles and the supply frequency, which is defined by following equation:

$$N_S = \frac{120 \times f}{P} \qquad (1)$$

Where, N_S = Synchronous speed
f = Frequency of the system
P = Number of pole

For starting the design of an alternator, it is necessary to assume certain parameters within limit and according to that calculate the other parameter of the machine which is represented in the fig. (1) and Fig. (2). After getting realistic design which having all the designed parameter within limit is used for magnetic analysis by the finite element method with help of MAGNET software.

The aim of this paper is to represent a computational and FEM based analytical aspects of designed Medium capacity Turbo alternator. This paper represents design concepts, design procedure, data sheet winding for the machine and finite element analysis. This paper is structured as follows: In Section II, a basic idea for the selection of certain parameter which is necessary for the starting for the design of synchronous machine is discussed. In Section III, flowchart which gives the basic idea to making the computer program for the analytical calculation is introduced. In Section IV, different specification of the synchronous machine and design sheet with various designed parameter are given. In Section V, the detail of stator and rotor winding through which current flow in distributed winding and alternating voltage is available at the armature terminal is given. In Section VI, basic of FEM and also a verification of the analytical design with help of MAGNET software by comparing the value of flux density are discussed.

II. DESIGN CONCEPTS

There are set of equations for completing a design of synchronous machine, but following are two main equations which are necessary for the starting of the design [3].

$$Q = C_0 \times D^2 L \times N_S (2)$$

$$C_0 = 11 \times B_{av} \times ac \times K_W \times 10^{(-3)} \qquad (3)$$

Where, Q = Output power rating
C_0= Output coefficient
D^2L = Main dimension of the machine
B_{av} = Magnetic loading of machine
ac= Electric loading of the machine

Equation No. (2) and (3) also relates the output power rating, speed and size of the machine. For the same output power rating, the size of the machine can be reduced by increasing the output coefficient and speed of the machine. But in the case of designing an alternator the cost is not only important; but the performance, efficiency and temperature rise of the machine are also important during the design of synchronous machine. Initially it is required to assume the magnetic loading and electric loading of the machine in such a way so that design of the synchronous machine become optimum and all the parameter like efficiency, temperature rise and losses are in limits (4).A value of magnetic loading also affects the iron loss, voltage rating, transient short circuit current, stability and parallel operation of the machine. A value of electric loading affects the copper loss, temperature rise, voltage rating, synchronous reactance and stray load losses of the machine. Short circuit ratio also affects the performance parameters of machine like voltage regulation, short circuit current and self excitation of the machine.

III. DESIGN PROCEDURE

Basically a design involves calculating the dimension of various component and parts of the machine, weight, material specification, output parameter and performance in accordance with specified international standards (5). A practical method in case of large machine is to develop coding for the total design incorporating the constrain parameter and executing the coding for various alternatives from which final design is selected.

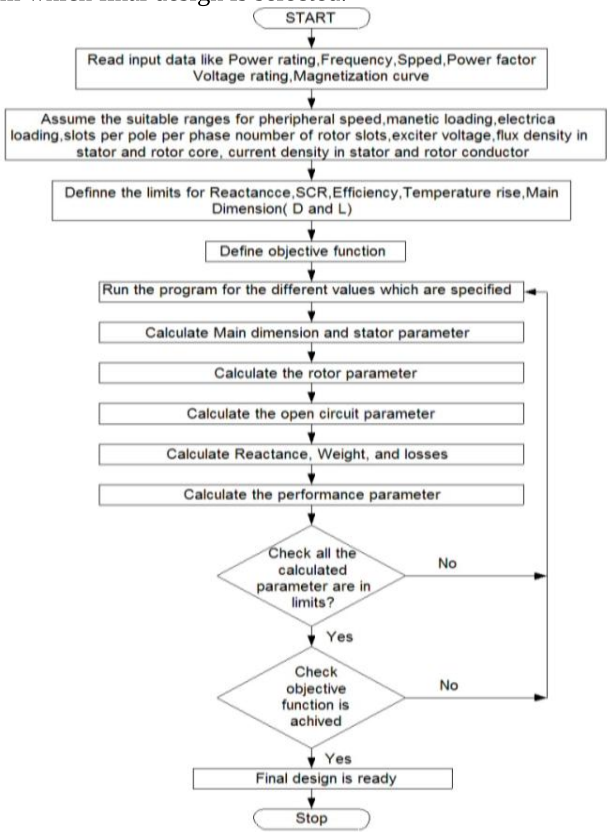

Fig (1): Flow chart for the total design calculation

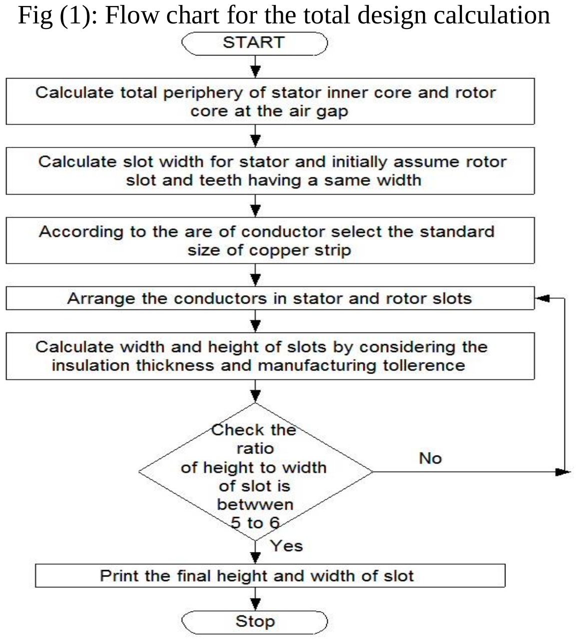

Fig (2): Flow chart for stator and rotor slot dimension

To get realistic design, a main objective is to achieve higher efficiency, lower temperature rise, lower weight for given power rating and lower cost.

Fig.1 represents a flow chart for the total design of synchronous machine in which initially assumes certain parameters which are necessary to start a design process and latter check whether the objective function is achieved or not. And if not then run the program for next iteration which are specified in suitable range.Fig.2represents a flow chart for a calculation of the dimension of stator and rotor slots. For stator slots dimensions, calculate the slot pitch and teeth width from the Fig.1, then calculate total periphery of the stator inner core at air gap and subtract the total width of all slots. Similarly rotor slots dimension calculate rotor periphery and initially assumes the rotor slots and teeth having a same width and find the width of one slot. According to the area and number of parallel path of conductor, chose the size of copper strip from the standard and arrange in the slots. For particular arrangement the rotor slots width is varied and final width of rotor slots are achieved.

IV. DESIGN SHEET

Here designed parameter of the synchronous machine with different number of stator slots are given in the Table I, Table II, Table III and Table IV. By comparing all three designed parameters, design with 84 slots is physically near to the main dimensions according to the Indian standard. [5]

Table I.Synchronouys Machine Specification

Machine Rating	
Power rating	5 MW
Voltage rating	11000 V
Speed	1500 R.P.M
Number of poles	4
Types of rotor	Cylindrical
Frequency	50 Hz
Power factor	0.8 Lagging

Table II.Various Designed Parameter For Stator

Stator Parameters for Different No. of slots			
Number of slots	84	72	96
Magnetic loading (Wb/mm^2)	0.55	0.60	0.58
Electric loading (ac/m)	60000	51000	71000
Stator current/phase (Amp)	328.4	328.4	328.4
Core length (mm)	945.15	999.18	799.82
Core OD (mm)	1450	1495	1496
Core ID (mm)	874	883	850
Turns/phase	84	72	96
Core depth (mm)	207	230	210
Slot width (mm)	16.05	17.02	13.02
Slot height (mm)	82	78	113
Flux/Pole (Wb)	0.35	0.41	0.30
Bare conductor size (mm)	1.4×10	1.3×11	2.2× 7

Mean turn length (m)	4.30	4.42	3.96
Air gap length (mm)	10	8	11
Armature reaction	17783	15243	20234
Leakage reactance (P.U)	0.121	0.093	0.167

TABLE III.VARIOUS DESIGNED PARMETER FOR ROTRO

Rotor Parameters			
Peripheral speed (m/s)	67	68	65
Number of slots	60	60	60
Rotor diameter	853	867	829
Slot width (mm)	22.30	18.72	20.22
Slot height (mm)	98.05	99.25	112.85
Bare conductor size (mm)	4×4	3.2×4.5	3.5×5
Turns per pole	64	60	66
Length of mean turns (m)	3.70	3.83	3.37

TABLE IV.VARIOUS PERFROMANCE PARMETER GETTING AFTER DESIGN

Performance Parameters			
Armature reaction field current (amp)	111.84	100.28	122.43
Field current on short circuit (amp)	118.52	104.90	132.13
SCR (P.U)	0.46	0.47	0.44
Voltage regulation	30%	29%	35%
Voltage across rotor winding at rated load and power factor (V)	53.44	47.68	58.05
Temperature Rise (℃)	30.07	25.10	33.64
Losses	170.82	160.17	169.80
Efficiency	96.69	96.89	96.71

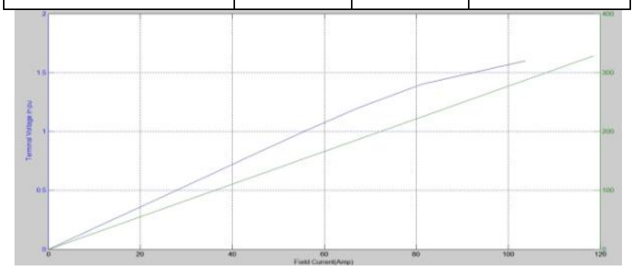

Fig (3): OCC and SCC for 84 Slots

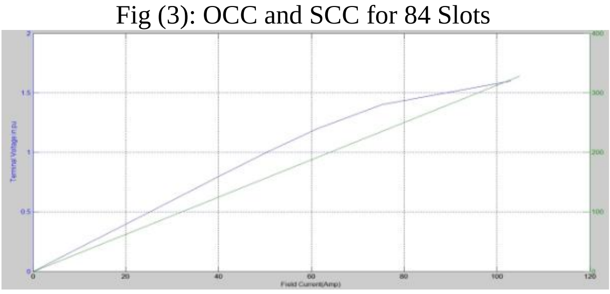

Fig (4): OCC and SC C for 72 Slots

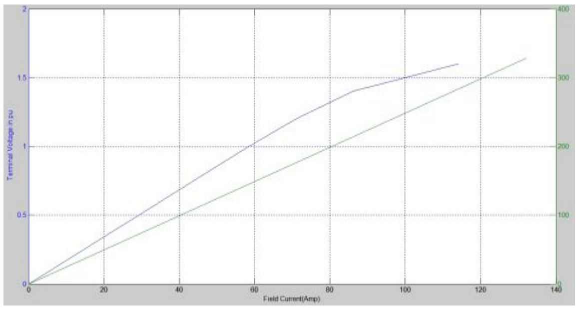

Fig (5): OCC and SCC for 96 Slots

V. MACHINE WINDING

Winding of the machine is defined as an arrangement of conductor to produce electromagnetic force by relative motion in a magnetic field. Electrical machine employ groups of conductor distributed in a slot over the periphery of stator and rotor. The conductors are connected in series to increase the voltage rating while conductors are connected in parallel to increase the current rating [2].

A. Stator winding

TABLE IV.ARRENGEMENT OF THE STATOR WINDING IN STATOR SLOTS

Phases	Winding accommodate in stator slots			
	N Pole	S Pole	N Pole	S Pole
R	1,2,3,4,5,6,7	22,23,24,25,26,27,28	43,44,45,46,47,48,49	64,65,66,67,68,69,70
B	8,9,10,11,12,13,14	29,30,31,32,33,34,35	50,51,52,53,54,55,56	71,72,73,74,75,76,77
Y	15,16,17,18,19,20,21	36,37,38,39,40,41,42	57,58,59,60,61,62,63	78,79,80,81,82,83,84

The double layer integral lap wound short pitched winding is used for stator winding. Total number of slots are 84 and poles are 4, therefore pole pitch is equal to 21 slots, but here short pitch winding by 3 slots is used therefore coil span is equal to 18 slots. I n one full revolution of rotor, a conductor in any slots are travels by 360° mechanical is equal to the 720°electrical, since there are 84 slots therefore slot angle is equal to 8.57. There are three phases R, B and Y and separated by 120°. If R phase start at 0° at slot number 1, then B phase start at 120° later from R phase at slot number 8 and Y phase start at 240° later from R phase at slot number 15.Slots/Pole/Phase=7,Back pitch=37, Front pitch=35. Following Table V represents the total number of slots and the winding arrangement of three phases.

B. Rotor winding

The double layer simplex lap winding is used for rotor winding. Total numbers of rotor slots are 60, but for cylindrical rotor 1/3 of the total slot are provided for the pole portion [4]. So rotor winding is accommodate in the remaining 40 slots in such way so current in both conductors in one slot in same direction to ensure that the produced resultant magnetic field is in the require direction for the rotation of the rotor. Back pitch=21, front pitch=19. Following Table VI represents the brushes, commutator segments arrangements, No. of coils and winding arrangement.

TABLE VI.ARRANGMENT OF THE ROTOR WINDING IN ROTOR SLOTS

Pole No.	Polarity-slots No.	E.M.F	No. of coils	No. of Comm. Segment	No of brush
1	North 1,2,3,4,5,6,7,8,9,10	+ve	10	10	1
2	South 16,17,18,19,20,21,22,23,24,25	-ve	10	10	1
3	North 31,32,33,34,35,36,37,38,39,40	+ve	10	10	1
4	South 46,47,48,49,50,51,52,53,54,55	-ve	10	10	1

VI. FINITE ELEMENT ANALYSIS

Finite element analysis is a numerical technique for finding approximate solution of a partial differential equation as well as an integral equation. The FEM is a good choice for solving partial differential equation over complicated domains, when the domain changes, when the desire precision varies over the entire domain (6). The FEM is essential based on subdivision of the whole domain in a fixed number of subdivisions. A FEM analysis is done by using MAGNET software, which having a main three domains. In pre-processor domain model of synchronous machine is created, assign the material of various part of the synchronous machine like stator, rotor, winding of the machine etc, and also specify the electrical circuit for the synchronous machine. In solver domain model is solved by solving the integral equation. Postprocessor is an interactive module that displays field quantities like flux density, magnetic field intensity, energy, torque, voltage, current etc.

A. Creation of the model of synchronous machine

The model of synchronous machine is created in the post processor according to the dimensions which are specified in the design sheet. After creating the drawing, the various materials for the various parts are assigned which are shown in the Fig.6.After assigning the material, the whole model is converted into 3D drawing; Fig.7 shows the 3D view of stator and rotor individual.

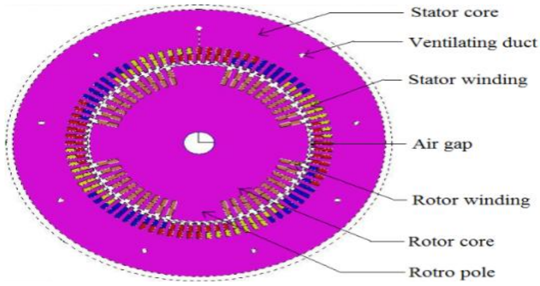

Fig (6): Solid Model of Synchronous Machine

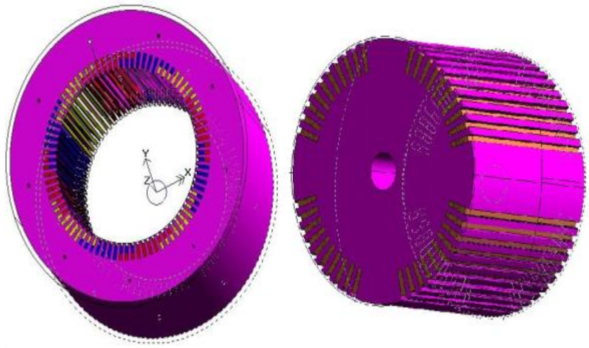

Fig (7): 3D Model of stator and rotor with winding

B. FEM simulation

To get the result, meshing and refinement of the model is carried out. When increasing the meshing of the model, the accuracy of the result is increased but time for solution is also increasing. Meshing of the synchronous machine is shown in the Fig.8. By performing static analysis there is creation of the 4 poles which having a positive and negative value of flux alternatively is shown in Fig.9 and Fig.10. By this analysis we also get the flux density at various part of the synchronous machine. Here the value of flux density in analytical design is very near to the flux density which getting by the MAGNETsoftware. So, analytical design is verified by the MAGNET software which is represented in Table VII and Fig.10.

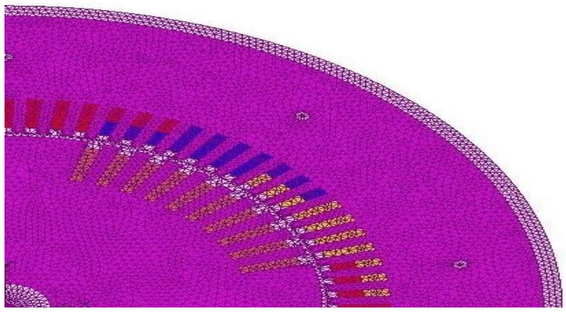

Fig (8): Meshing of the synchronous machine

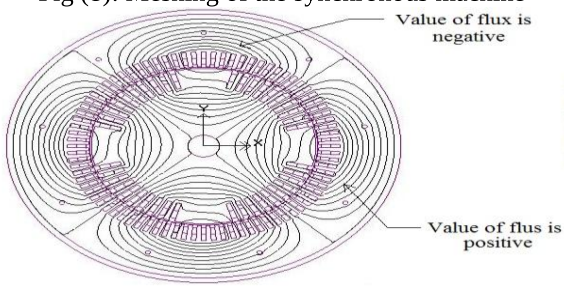

Fig (9): Physically and Graphically Creation of

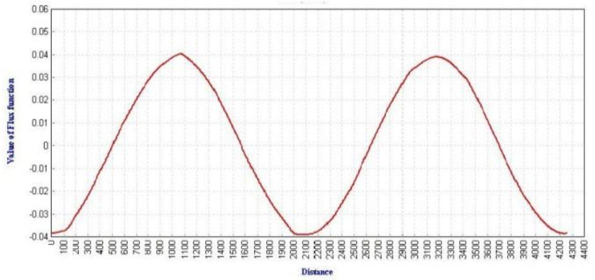

Fig (10): Physically and Graphically Creation of Pole

TABLE VII.VALUES OF FLUX DENSITYAT VAROIUS PART

Flux density (Wb/m^2)	Analytical values	FEM values
Stator core	1.098365	1.09971
Stator teeth	1.300000	1.48175
Rotor core	0.459115	0.452041
Rotor teeth	1.042466	1.044849
Air gap	0.825	0.75208

Flux density at the stator core is represented by the Fig.11 in which there is sudden drop in the value of flux density at the ventilating ducts. In ventilating ducts, an air provide high reluctance path to flux, therefore a flux density is reducing to zero. Maximum flux density is at stator and rotor teeth, but in rotor there is a maximum flux density at the middle teeth between the poles and reducing its value near to pole center because the interaction between stator and rotor flux. Flux density at stator teeth and rotor teeth is represented by Fig.12 and Fig.13respectively.Magnetic field intensity is maximum in the air gap at center teeth of the rotor between two poles, which is represented by Fig.14.

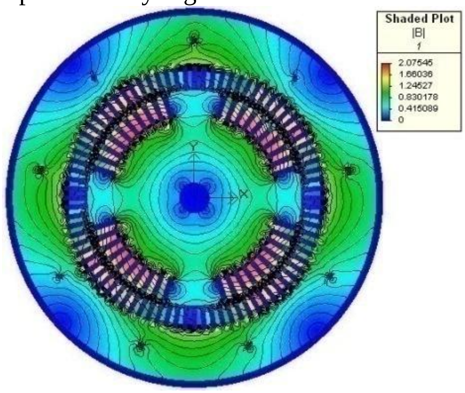

Fig (10): Flux density plot

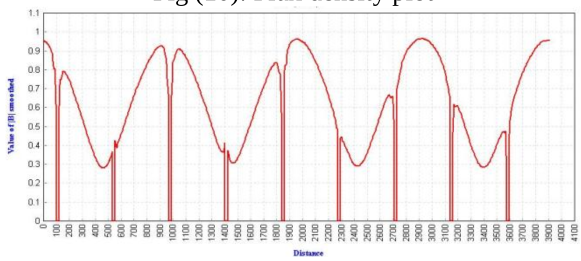

Fig (11): flux density at ventilating ducts in stator core

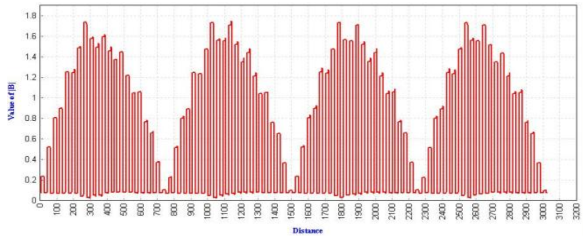

Fig (12): Flux density at stator teeth

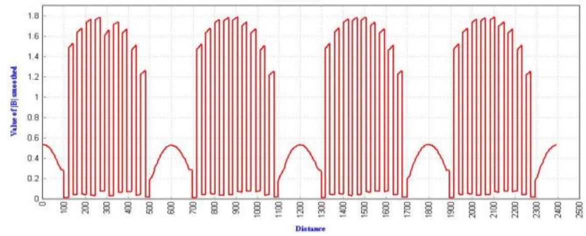

Fig (13): Flux density at rotor teeth

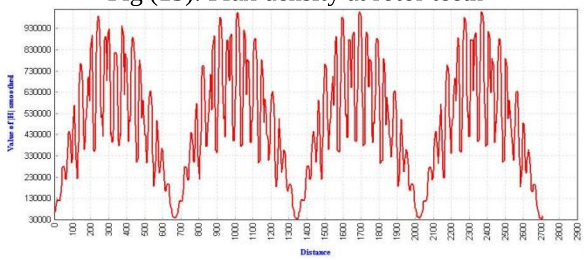

Fig (14): Magnetic field intensity(H) at air gap

VII. CONCLUSION

During design of synchronous machine, choice of specific magnetic loading and specific electric loading is very important. Ones turns per phase is achieved according to the conductor per slot and if a ratio of length to pole pitch is between 1.0 to 2.25 then and then a calculation for the other parameters have to be carried out; otherwise a loading of machine has to be selected properly. The design with 84 slots is very near to standard; therefore this design is chosen for FEM analysis. The result of software can be increased by increasing the meshing of the synchronous machine model.

REFERENCES

[1] W.L.Waters, A paper presented at the 20th annual convention of American institute of electrical engineering, Niagara Falls, N.Y.June,29,1903.Commercial alternator design.

[2] K.M.Vishnumurthy, B.S.Publication, Computer aided design of electrical machie.

[3] A.K.Sawhney and A.Chakrabarti, Dhanpatrai and co, Acourse in electrical machine design.

[4] Ju-Lee, Yong-Sik Jo, Jung-Pyo Hong, IEEE transaction on applied superconducting, Vol. 10, No.1, March 2000, An approach to shape optimum design of superconducting synchronous generator.

[5] IS-4722,2003, for rotating machine.

[6] Nicola Binachi, Taylor and francisgrop, Electrical machine analysis using finite element method.

[7] J.H.WALKER, Bharat heavy electrical limited, Large A.C. machine design manufacture and operation.

[8] Michael D. Werst, Jonathan J. Hahne, Hsing P. Liu, and Charles E. Penney, IEEE Transactions on magnetics, Vol. 39, No. 1, January 2003, Design and Testing of a High-Speed Spin Test for Evaluating Pulse Alternator Windage Loss Effects

[9] M.V.Deshpande, Design and testing of electrical machine.

