Design Approach To High Voltage High Power Steam-Turbine Driven Alternator

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ABSTRACT

The paper deals with the design methodology of high voltage high power alternators driven by steam turbines. These alternators run at a high speed of 3000 rpm in most part of the world (at 3600 rpm in USA) and are of cylindrical pole construction. The design procedure suggested in the text-books of design does not well-suit for large alternators of modern time. Modern high power alternators are designed with a low value of SCR to reduce the size, inertia and cost of the rotor. The diameter is limited by the consideration of centrifugal stresses. The no.of stator slots are determined by the no. of turns. The ventilating circuit has to be designed for hydrogen as coolant and in addition with water flowing through hollow conductors, if required. The data for the design variables and the design constraints are quite different from those for small power ratings. The materials to be chosen must be of very high quality. The computer programme has been chalked out and the case-study has been conducted keeping all these points in view.

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1. INTRODUCTION

D.C. generators were used in the earlier regime. They were in use upto first few decades of the 20th century. Later on they were replaced by A.C. generators for their various advantages. A.C. generators, particularly the synchronous type can be designed for high generation voltage (upto 33 KV) and for large rating (as high as 1250 MW) [1-2]. The voltage can be stepped up or stepped down using transformer which is not possible in case of d.c. generation. A.C. power can be transferred from one place to another by high voltage transmission links (up to about 1200 KV). These advantages of a.c. have led to the development of interconnected power system. High voltage d.c. links are used at places to avoid the difficulties associated with synchronous coupling but the generators are obviously a.c. generators [3]. There are three types of A.C. generators- synchronous, induction and inductor-type. The inductor-type generators are special purpose generators and are not used for bulk power production. Sometimes they find application in the excitation system of an alternator. Induction generators are cheaper compared to synchronous generators but they are incapable of producing their own excitation. They draw their magnetizing VAR either from the system or they are built up as self-exciting units with 3-phase capacitor-bank in parallel. They are used only for small rating e.g. as units coupled to wind-turbines etc. The bulk power is produced in a modern power station by synchronous generators [4-5].

2. CONSTRUCTIONAL FEATURES OF H.V. ALTERNATORS

Except for small ratings, the synchronous generators have a stationary armature and a rotating field. The field is housed in the rotor for technical and economic reasons. It makes the rotor light, reduces the size and losses in the bearing, makes the cooling simpler, and the response fast. Also, it is not possible to extract large power produced in a rotating armature through slip-rings and brushes. Therefore rotating fields are used from about a size of 500 Kw. The generators coupled to steam turbines in a thermal power station run at a high speed (3600 rpm in US, 300 rpm in other countries). It is convenient to use cylindrical poles for them, the number of poles being two. On the other hand, the generators coupled to water turbines in a hydro-electric power station run at a relatively slow speed- the speed depends on the height of the water fall and the quantity of water in the catchment area. Salient pole construction is conveniently used for them [6-8]. In a steam-generating unit, the turbine is generally Tandem-compounded having a high pressure, an intermediate pressure and a low pressure stage, with single or double reheat. The alternators are built in sizes up to 630 Mw in India, ratings of 210 Mw and 500 Mw being more common. Attempts are being taken to develop units of still higher rating [9]. The armature is housed in the stator of the alternators and the field in the rotor. Both turbo-alternators and hydro-alternators are of massive size and of high cost, the size and the cost increasing with the rating. So, the design must be made cost-optimally, fulfilling all technical requirements and without violating given constraints [10-11]. The turbo-alternators are characterized by large axial length and relatively short-diameter. The diameter is limited by the maximum allowable centrifugal stress. The stator is made up of sector-shaped laminations of best-grade CRGOS. These are stamped to produce a combination of radial and axial ducts to form a ventilating network. Hydrogen, for its various advantages is used as coolant. It is forced through the ventilating network and it carries off the heat produced. The outflow is externally cooled by Hydrogen-coolers. For a size of 200 Mw and more H-cooling is not sufficient. It has to be augmented with water-cooling of the conductors for which the winding has to be made using hollow conductors, partly of fully. Water-cooling of stator is enough up to a size of 500 Mw, above which the rotor has also to be water-cooled. In such cases (pure) water is inserted through hollow shaft at one end and taken out from the other after it has circulated through the ventilation network.

The rotor core is made up of forged or cast steel of high magnetic quality. The no of poles is two or four, mostly two. The rotor is made of solid iron to make it mechanically stronger so that it can withstand the high centrifugal stresses developed during rotation. It also adds to damping by induced eddy currents in the solid iron. The damping created by unconstrained eddy currents is often sufficient and a regular damper winding may be omitted. About two-third of the surface of the cylindrical rotor is slotted, leaving behind two big teeth opposite to each other. The d-axis passes through the axis of the big teeth. A little slot-saliency is introduced due to this. Hence it is better to make the analysis of the machine in 2-axis framework [12].

3. DESIGN APPROACH TO HIGH VOLTAGE ALTERNATORS

Alternators are designed to produce electrical power at a relatively high voltage e.g. 11 KV to 33 KV. Also the power rating of modern alternators is very high compared to those of earlier regime. Therefore great care has to be taken while designing them in respect of insulating the high voltage winding and cooling the machine while it is operating at continuous maximum rating (CMR). Best grades of insulation are used, both for slot-lining and for the conductors. The stator has to accommodate the H.V. winding. So its slots must be spacious so as to house the insulating troughs and the insulated conductors. Cooling is made by circulating hydrogen through the ventilating network. For turbogenerators, water-cooling is added if the rating is more than 200 Mw. Also the mechanical aspects are quite important viz. the diameter of the rotor and the shaft, radial forces and the width of the wedge, construction of the retaining rings etc. The retaining rings are made of copper bands. The whole structure is completely enclosed and air-tight. The peripheral speed of modern turbo-alternators may be as high as 220 m/s. For the hydrogenerators, the peripheral speed has to be limited to 80-100 m/s, in consideration of the centrifugal stresses that would be produced in case of run-away. The shaft may be horizontal or vertical, the horizontal configuration being more common. These are multipolar machines, the no of poles depending on the speed. The rotor core is laminated but the pole-shoe is of solid iron. An amortisseur winding is added for damping under conditions of oscillation. The function of solid iron pole-shoe is to add to damping produced by the regular damping winding.Single turn or bar windings have to be used for the stator. The stator conductors are sub-divided and transposed to reduce the eddy current losses. Single layer concentric winding is not used to avoid stray load losses though it has got the advantage of easier clamping. For large alternators it is a common practice to use a double layer winding with two conductors per slot and two parallel paths in the stator winding. This gives the advantage of chording to suppress some of the dominant harmonics. The stator overhang must be properly braced. Best grades of silicon steel stampings have to be used to limit the core loss. These are commonly of segmental type, fabricated in a way to provide for the cooling ducts. The bearings must be of high grade and provided with cooling arrangement.The rotor core has to be made of solid iron forging or casting for the turbo-generators and for hydro-generators, the pole-shoes must be of solid iron. This practice enhances the damping and reduces the oscillations. The design is made by using specially constructed computer programs [12-14].

4. DESIGN VARIABLES AND CONSTRAINTS

The design variables may initially be chosen from design data-book and from designers experience. But changes are to be brought about in the variables by the computer programme for making the design viable and for optimizing the design. Some of the design variables are continuous and some are discrete. Some of them are decision variables e.g. the choice of materials, whether water-cooling has to be added etc. The electric and the magnetic loading are two key variables. Depending on the size and the type of the alternator, the flux-density ranges from 0.52 to 0.65 wb/m^2, and Amp. Conductor/m ranges from 50,000 to 150,000 or more. The height: width ratio of the slot, core flux-density in stator and in rotor, the no. of stacks and no. of segments etc. are other variables. Another key variable is the length: pole pitch ratio which directly affects the over-all cost. However, for very large rating, the diameter is fixed by the allowable centrifugal force. Hence this ratio cannot be changed. The constraints are on maximum allowable temperature rise of stator and the rotor, temperature rise of other parts like bearings, the efficiency, the short-circuit ratio (SCR), critical speed etc.

5. PROCEDURE TOWARDS OPTIMIZATION

All machines should be designed for optimizing an objective function in presence of given constraints. The objective function may be the cost of production, or a weighted combination of the cost of production and the running cost. The later one is better from the point of view of over-all economy. Commonly used optimization algorithm like gradient search technique etc. cannot be gainfully used for the design of alternators as the practice violates the constraints. Therefore a heuristic search technique has been used for finding out the best values of design variables to match the specifications without violating any one of the design constraints [10-11].

6. CASE-STUDIES ON DESIGN OF ALTERNATOR

Two case-studies have been made in the field of alternator design viz.

a. Design analysis of a 210 Mw generator on the basis of detailed data collected from the manufacturer.
b. Design of a 120 Mw, 13.6 KV, 2-pole, 3000 rpm, 50 Hz. Turbo-generator.

7. DESIGN ANALYSIS OF A TURBO-ALTERNATOR

The details of construction, and tested parameters have been collected for a 210 Mw. turbogenerator set [9]. A computer program has been developed to find out the design variables and performance criteria of the machine from this collected data. The results give insight into the design details of large turbogenerators of modern times.

7.1. Rating

Active power = 210 MW; Power factor = 0.85 lagging; Line voltage = 15.75 KV, Reactive power = 130.15 MVAR; armature current = 9.0565 KA, No of poles = 2; Frequency = 50 Hz; Speed in RPS = 50, Given data:Stator/rotor/average diameter: 1.215m; 1.075m; 1.145m, Stator/rotor/average length : 4.4 m; 4.2 m; 4.3m, No. of stator/rotor slots: 60 / 36, No of conductors/stator slot/ No of parallel paths in stator winding: 2; 2 No of turns/phase of stator winding = 10 No of stator slots/pole = 30; Slot angle = 6^o ;Coil pitch in no. of slots = 27; Angle of short-pitching = 18^o Calculated values for the stator: Pitch factor, K_p = .98769; Breadth factor, K_b = 0.95535; Winding factor, K_w = 0.94359, Phase voltage = 9093 V; Average flux-density = 0.56122 Tesla, D^2L-product = 5.6374 m^3; Output coefficient = 876.5, Amp-conductor/m = 150467; Length of air-gap = 70 mm, Stator slot-pitch = 63.626 mm, Base impedance, ohm= 1.0041, Armature resistance, pu/ohm: 0.00189 ; 1.8977E-03. Depth of conductor and non-conductor portions in stator slot in mm: 195; 10 Depth of wedge and lip in stator slot in mm: 10; 5 Slots are parallel-sided with width = 22 mm; Stator slot-opening = 10 mm, Depth of stator slot = 220 mm, Length of mean turn = 14.29 m, Cross-section of stator conductor = 866 mm^2, Current density in stator conductor = 5.229 A/mm^2. The conductor has 16 sections, each 7x11 mm^2, Alternate sections are hollow with gap 5x9 mm^2, The conductor C.S. = 872 mm^2. The actual C.S. is a little less due to rounding effect.No of ducts, width of duct in mm: 90; 5 Stacking factor of stator core = 0.97 Net length of iron = 3.8315 m; Diameter at slot bottom = 1.655 m Stacking factor, Effective length of stator, m: .97, 3.8315, Flux-density in stator core = 1.15 tesla. Depth of yoke, outer diameter, m: 0.4926 ; 2.6402 Calculated values for the rotor: The peripheral velocity of the rotor = 168.88 m/s, No of rotor slots under a pole = 18, leaving behind two big teeth. Rotor slots are of open type and parallel, slot width = 28 mm, Rotor slot-pitch = 64 mm ; No of conductors/slot in the rotor= 7, No of turns of the field coil = 126 , Depth of conductor & non-conductor portion in the rotor slot,mm: 120 ; 10 Depth of wedge and lip in the rotor slot, mm: 15; 5 Total depth of rotor slot,mm: 150, Performance analysis: Carter's coefficient taken as: 1.3, AT consumed by the air-gap = 60979, Assuming AT for iron path as 32.5%, total field AT = 80797, Field current at rated voltage = 916.07 A (Test value in OCC =917 A) , Parameters and variables are in p.u., Armature leakage reactance = 0.152 (calculated from Potier's triangle on OCC, SCC & ZPF), d-axis synchronous reactance (from OCC & SCC) = 2.225, q-axis synchronous reactance (given) = 2.11, d-axis magnetizing reactance = 2.073, q-axis magnetizing reactance = 1.958, the power angle at CMR = 40.34^o. The d- & q-axes components of terminal voltage: 0.64738; 0.76217, The d- & q-axes components of terminal current: 0.95177; 0.30681, Induced voltage = 2.88. It is found from the above analysis that the flux-density to be used for the design of a large turbo-alternator is within the bounds specified by text-books but the amp-conductor/m is far beyond the specified range. A much higher value has to be chosen for large rating. It does not pose any design difficulty as the cooling conditions are far better. Also, the maximum diameter is limited by the peripheral velocity (about 170 m/s) not by the consideration of best possible value of length/pole pitch.

7.2. Construction of Turbo Alternator

Now we shall take up the design and performance analysis of a turbo-alternator of large rating. Using a specially constructed program, the turbo alternator has been designed. The ratings and specifications are given below. 120 Mw, 0.85 lagging p.f., 2-pole, cylindrical construction, 50 Hz, 3000 r.p.m. The leakage reactance 0.14 p.u., the unsaturated synchronous reactance 1.9 p.u., the efficiency > 98% at CMR. The rating is same as that of the units Santaldihi TPS. The design details are given below:

7.2.1. Rating

The rated power of the generator = 120 Mw; The rated power factor = 0.85 lagging, Frequency = 50 Hz; No of poles= 2, Chosen design variables: Average flux-density = 0.55 tesla; amp.conductor/m= 140000, Approx. winding factor = 0.93; Output coefficient = 787.71 Maximum allowable peripheral speed = 155 m/s

7.2.2. Computation

The rated KVA = 141176.5; Speed in rps = 50; Speed in rpm= 3000, Diameter of rotor = 0.985 m; Inner diameter of stator = 1.129 m; Length of stator = 2.81 m. The generator is Y-connected. The phase voltage = 7852 V, The pole pitch = 1.76715 m; Flux/pole = 2.7506 Wb. No of turns/phase = 14; No of stator slots= 84; Slot angle = 4.2857$^{o;}$ The coil pitch in no of slots = 35; Angle of short-pitching = 30^o, Pitch factor = 0.9659; Breadth factor = 0.95515; Winding factor = 0.9226. Phase current = 5993.3A; Base impedance = 1.31 Ω. Area of stator conductor = 499.44 mm^2, There are two conductors/slot. The no of parallel paths = 2, Armature AT, No load field AT, Airgap AT: 123700.5; 64324.26; 51459.4, Length of airgap = 72 mm; Stator slot pitch = 42.075 mm, Area of conductor, Area of slot in mm^2: 504; 3330, Conductors are ofelectrolytic ally pure copper. There are 12 sections for each conductor (Conductors are sectionalized to reduce the skin effect). Water-cooling of stator is not required below a size of 200 Mw. So there is no hollow conductor. Width and height of conductor-sections in mm: 7 ; 12 Height occupied by the conductor portion = 144 mm Height occupied insulation (non-conductor) portion = 15 mm Height occupied by wedge and lip in mm: 8 ; 3 Width of slot, depth of slot in mm: 21 ; 170 Length of mean turn of armature coils = 7.744 m ; Armature resistance/phase = 0.002474 Ω ,Flux density in stator core = 1.3 tesla; Depth of stator core = 0.426 m ; Outer diameter of stator = 2.317 m , Area of rotor conductors/pole = 92775 mm^2, No of rotor slots must be an odd number having no common factor with stator no of slots. There must be two big teeth occupying ⅓ rd. of the rotor periphery.No of rotor slots/ wound no of rotor slots: 57 ; 40 Length of rotor = 2.81m, keeping 10 mm gap between the end of stator and end of rotor to avoid centering of flux. Exciter voltage is taken as: 720 V. Voltage across each field coil 288 V, keeping 20% as reserve.Rotor pole pitch/ slot pitch: 1.5472 m ; 54.29 mm, Mean length of turn of field coil = 9.4186 m ; Cross-section of field conductor = 139.57 mm^2. No of conductors/rotor slot = 17; No of field turns/pole = 340; Field resistances/pole, ohm= 0.5277 Ω; Field current at full load = 545.74 A, Slot dimensions of rotor- rotor slots are parallel-sided.The depth of conductor and non-conductor portion, mm: 119; 10 The depth of wedge and lip, mm: 10; 3; Total depth of rotor slot = 142 mm, Effective area of rotor slot = 3501.6 mm^2.

7.2.3. Efficiency, Leakage and Synchronous Seactance

Field copper loss in Kw and in % : 314.34 Kw ; 0.22266 % , Armature copper loss in Kw and in % : 266.58 Kw ; 0.18883, Volume of stator iron/ weight of stator iron: 7.2768 m^3 ; 55668 Kg, Width of stator teeth at 1/3 rd height, mm= 25.314 mm , Flux-density in teeth at 1/3 rd height = 1.4875 Tesla, Iron loss/Kg for this flux-density = 14.383 W/kg , Weight of teeth/ Core los in teeth: 21136.36 Kg ; 304002 W, Iron loss/Kg for chosen stator core flux-density = 7.943 W , Weight of stator core / Stator core loss: 47887.84 Kg ; 380373 W , Total iron loss in stator: 684376 W ; 0.48477 % , Estimated friction and windage loss inclusive of fanning & circulation = 0.6 % , Total % loss/ Efficiency at CMR: 1.496 ; 0.9827 , (as compared to 0.985 for the 210 Mw-set).Leakage reactance (estimated) = 0.135 p.u. Unsaturated value of d-axis synchronous reactance (estimated) = 1.92 p.u.Computation on cooling, ducts etc. have not been made as the focus is on H.V. phenomena. It may be noted that the dimensions and parameters are similar to that of the 210 Mw set.

8. CONCLUSION

The design of a high voltage high capacity alternator is not at all an easy task. Many of the usual procedures for designing a small rating alternator does not hold good for alternators of large rating. In this case the electric and magnetic loading must be very high to keep the size of the alternator reasonably small. The peripheral capacity has to be kept within a specified upper bound. The diameter of the shaft has to be determined from the point of view of strength of materials. Both torsion and bending need be considered. There is no key. The rotor-core-shaft structures are integrally forged. The structure is of solid iron. Often a regular damping winding may be omitted. The stator core laminations are sector-shaped. They are assembled in a manner to provide a ventilation network. The whole structure has to be sealed against leakage. Hydrogen gas has to be used as coolant for its much better heat transfer capability. Moreover water-cooling of stator as well as rotor may have to be added for very large sizes to keep the temperature rise within reasonable limit. To gain an insight into the numerical values of design variables used for large alternators, a design analysis has been made. The results of the analysis have given the required data-base (not available in standard data-books), and further work has been made on its basis. The design of a 120 MW, 15 KV turbo-alternators has been taken up. The rating is same as that of Santaldi TPS-units. For such alternators of large rating, generally more attention is paid towards technical feasibility rather than on economic optimization. The important points under consideration are the losses and efficiency, the temperature profile at rated load, the vibration, the critical speed, the thermal expansion, the bearings and lubricants etc. All large turbo alternators are characterized by a large axial length and a relatively short diameter (to keep the centrifugal force within limit). The rotor core is of solid iron and the retaining rings are of metal. The solid iron adds to damping. More and more difficulty is experienced as the rating becomes higher. It is difficult to reach a feasible design in presence of several geometrical constraints. The program has been maneuvered to reach the best possible solution through heuristic search and the results have been given.

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