

Computer-aided design optimisation and analysis of salient pole alternators

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ABSTRACT

A computer-aided design package for small, two-pole alternators is described. Synthesis and analysis are partly based on traditional techniques but also rely on specially developed algorithms, employed where demanded by the particular topology of the high-speed, salient-pole machines. The package is implemented on the IBM PC, or compatible, using Microsoft QuickBASIC and a windows type user interface. The design process is interactive, with user intervention encouraged at various junctures and the use of standard parts invited where appropriate.

1. INTRODUCTION

Computer aided design of electrical machines is by no means a novel process; virtually all design offices have employed the technique, in one form or another, for some years and, indeed, two of the authors of this paper were writing about the subject as long as 17 years ago [1,2]. However, the power of inexpensive modern micro-computers and the evolution of increasingly effective and convenient software techniques do provide incentive for a re-assessment of established procedures.

Conventional use, in the design office, of design synthesis and analysis packages, either driven by expert systems or incorporating a substantial element of designer intervention, is thus an obvious initial objective for any development or re-assessment. The package described in this paper is essentially interactive and its effectiveness will shortly be enhanced by incorporation of a graphical interface. Use of the package and the scope of its application are limited to the design and analysis of high speed, salient-pole alternators with either two or four poles and ratings up to 50 kVA. Machines of this size and type are not always, or even often, supplied with a comprehensive statement of parameter values and operational characteristics, but, under some circumstances, such information can be useful and perhaps essential to a customer and there is little excuse for a failure to provide this service. Whilst many of the equations and software algorithms employed are applicable to alternators with



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any pole number, the particular topology of the two-pole rotor presents its own unique problems. Certain aspects of the well-established design process are no longer entirely appropriate and the same is true with regard to parameter estimation. Where necessary, therefore, the effects of the two-pole construction have been accommodated by specially developed algorithms and analysis.

2. DESIGN PHILOSOPHY

2.1 Design Objectives

The primary objective, as always, is a "good" design but, though the engineer may wish otherwise, this will probably be far removed from the most elegant solution in strictly technical terms. The final design must, of course, satisfy the specification but for alternators with ratings within the range considered here the specification is rarely stipulated by the customer, being more usually defined by the manufacturer to satisfy a perceived range of applications and users.

Though the machine parameters and operational characteristics may not be of critical significance to every customer, the price almost certainly will. It is acknowledged that price and cost of manufacture are not always directly related but it is certainly true that a low cost design with satisfactory performance will maximize profit margins. A good design will thus seek to minimize cost. This could be achieved by the use of a cost function requiring large amounts of data relating to materials, manufacturing costs for the various processes involved and the availability and cost of standard parts, with appropriate physical dimensions. The alternative is an interactive process where the knowledge, experience and flair of a designer can be fully exploited, and it is this latter option which has been utilized in the current approach.

Though cost is of major significance, and it is assumed that a user of the package will be disposed to make suitably appropriate decisions during the interactive process, there is a second essential property of a good design for an alternator. This is that the machine should, as far as is possible, have inbuilt protection against operational faults or misuse in service. Typical design objectives would be that the machine should be capable of sustained operation with a 3-phase short-circuit at the stator terminals, or that the stator windings might be connected in delta without damage from circulating triplen harmonic currents. These requirements are met by suitable prompts and suggested default values for relevant quantities, as described in section 3.2.

2.2 Design Synthesis

The design process is based on traditional techniques with the operator invited both to specify the machine ratings and to impose values for the fundamental dimensions, constraints for the specific magnetic and electrical loadings and limits for the current and flux densities in the various parts of the machine. Information is also requested for secondary quantities such as slot number, winding type, lamination packing factors and magnetic materials. This last is hardly of secondary importance but there is the facility to store all relevant information pertaining to a number of standard products in a data base, the expectation being that the operator will select from the materials available. Failing this, a suitable product will be chosen by default.



A similar resort to default values is used throughout, the principal being that a design will emerge however limited the experience of the operator. Any decisions made by the operator which lead to constraint violations, excessive loadings or mutually exclusive dimensional combinations are disregarded and prompt a comment statement indicating the nature of the problem and its immediate ramifications.

The stator is, as usual, designed first, with the operator being allowed (or encouraged) to request preferred values for the outside diameter and length of the core. If there are no resulting prohibitions the results are displayed, with internal diameter, slot dimensions, winding details, and actual loadings of particular interest. At this stage the designer can interrupt and replace the computed internal diameter and slot dimensions with those of an available standard lamination, it being assumed that the outside diameter is already incorporated. The results are then displayed with emphasis given to the new flux and current densities, and specific loadings.

Alternatively, the programme is allowed to progress to the rotor design, again with boundaries imposed by the various constraints, loadings, etc. The airgap length is computed from the specified short-circuit ratio and the rotor mmf required at rated output is then calculated. The rotor field current follows from the specified wire size and preferred current density. More significantly, the area required to accommodate this rotor winding and the actual area available between the poles are displayed with an invitation for the designer to respond. There are three possible responses: (a) accept the result, (b) make minor adjustments to the airgap and accept the consequences, or (c) have recourse to a review of the stator and rotor design data.

On satisfactory completion of the rotor design, the user can again replace the designed stator lamination with a standard component, the result of this exercise, in terms of loadings, densities and rotor design details, being displayed for assessment.

2.3 Analysis

With the completion of satisfactory stator and rotor designs the programme progresses to the analysis stage. The modelling techniques and equations employed are an amalgam of tradition with specially developed analysis appropriate to the 2 and 4-pole configurations. All parameters are calculated, as are the operational characteristics of the machine. The former include the steady-state, transient, and subtransient (when a damper winding is employed) reactances in both the d and q axes, and corresponding time constants. The latter includes the actual short-circuit ratio, the efficiency and an assessment of the harmonic content of the stator output voltage.

3. SOFTWARE IMPLEMENTATION

3.1 Language Choice

For flexibility and wide accessibility of the software, a decision was taken to implement the package on the IBM PC, or compatible, using the Microsoft QuickBASIC programming language. Convenience and the ease of maintenance of programmes developed in the QuickBASIC integrated environment are allowed to override the relative inefficiency of the language in the light of the power of modern microcomputers. Running on a 33 MHz, 486 PC, a complete alternator design, incorporating multiple iteration, with typical operator intervention and appropriate



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expertise, can be achieved in a matter of a few minutes.

The use of a windows type user interface was a perceived prerequisite and QuickBASIC allows easy implementation of this format in addition to permitting the incorporation of complex numerical algorithms. Additionally, QuickBASIC readily permits interfacing with assembly language routines which were most suited to implementation of mouse handling.

3.2 Data Input

The top level window permits a choice of two possible mechanisms for data input. Essential data embodied in the specification, dimensional constraints and specific loadings may be entered via an introductory series of three windows in which information is requested. These are the *General Specification*, *Stator Specification* and *Rotor Specification* windows, respectively. Alternatively a previously generated data set may be imported from disk.

The user is generally allowed to move forward or backward between the top level window and the General, Stator and Rotor specification windows during the data input phase of the programme. Selection of individual items within a window may be achieved either by moving a highlighted bar via the keyboard or by the use of a mouse. The data input window presented in response to an item selection invites the designer to input a value, the permitted range for that input, or a typical value, being indicated to the designer.

If the user fails to provide an essential item of data a default value is provided based on the range of ratings and constructional features to which the programme has been limited. Conflicting requirements and mutually exclusive aspects of a proposed design are brought to the attention of the designer and further progress to the design phase of the programme may be inhibited, dependent upon the extent to which the design rules have been violated, until a satisfactory data set is assembled. An assembled data set may also be saved to disk, via an option in the top level window.

3.3 Programme Operation and Output

The design phase of the programme is initiated by selection of the "Design" option in the top level window. A simplified flow chart of the alternator design and analysis programme is shown in Figure 1.

The stator design is both an interactive and an iterative process, the iteration being deemed to be complete when the outer diameter of the stator is the value requested in the specification. At this stage, the designer is presented with a summary of the main stator dimensions and loadings and is allowed to impose a preferred stator core length. Slight alteration of this latter dimension can produce significant changes in the number of stator turns and hence to various other related quantities. Imposition of a stator core length other than the calculated value initiates further iteration around the stator design loop. To ensure convergence a relaxation upwards of the stator back iron flux density (a stator design constraint) is allowed if necessary. The extent of the relaxation is strictly limited to 0.1% and has no perceivable effect on the ultimate performance. Typical stator design output is shown in Figure 2.



Rotor design is embarked upon in accordance with input data, an MMF table being presented to the designer to allow a review of the magnetic condition of the various parts of the magnetic circuit. It may, at this stage, be deemed wise to modify aspects of the stator or rotor data sets and this option is provided. The design proceeds with an invitation to select a suitable diameter for the rotor conductor, whereupon the programme calculates the number of turns required to produce the required mmf. One of the most demanding aspects of small alternator design is to ensure that there is sufficient space on the rotor pole to accommodate the field winding. Should consideration of the rotor design details, summarised in the format of Figure 3, indicate insufficient space for the field winding there is the facility for adjustment of the airgap length. If this is prohibited or not sufficiently effective it may again be necessary to return to a review of the stator or rotor design data.

On completion of the design process a review of machine parameters and operational performance may be requested by selection of the relevant option from the top level menu. Typical parameter sets are displayed in Figures 4 and 5. If parameter values or performance are less than satisfactory the designer must again review the design data and make considered adjustments to dimensions, loadings, etc., as a prelude to further iteration.

4. DISCUSSION & CONCLUSION

The design and analysis package described is operating successfully and the format adopted makes good use of the accumulated wisdom of an experienced designer. On the other hand the use of default values, prompts and comment statements allows the production of a perfectly respectable design by almost any operator with a basic understanding of the topology, construction and functioning of an alternator. This also raises some interesting possibilities regarding the use of the package as a teaching aid.

All design should be evolutionary and the work described achieves this by being an obvious case for optimisation. Various routines are under development for cost, efficiency, weight, etc. and the incorporation of expert system techniques as an alternative to designer input is envisaged.

5. ACKNOWLEDGEMENTS

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6. REERENCES

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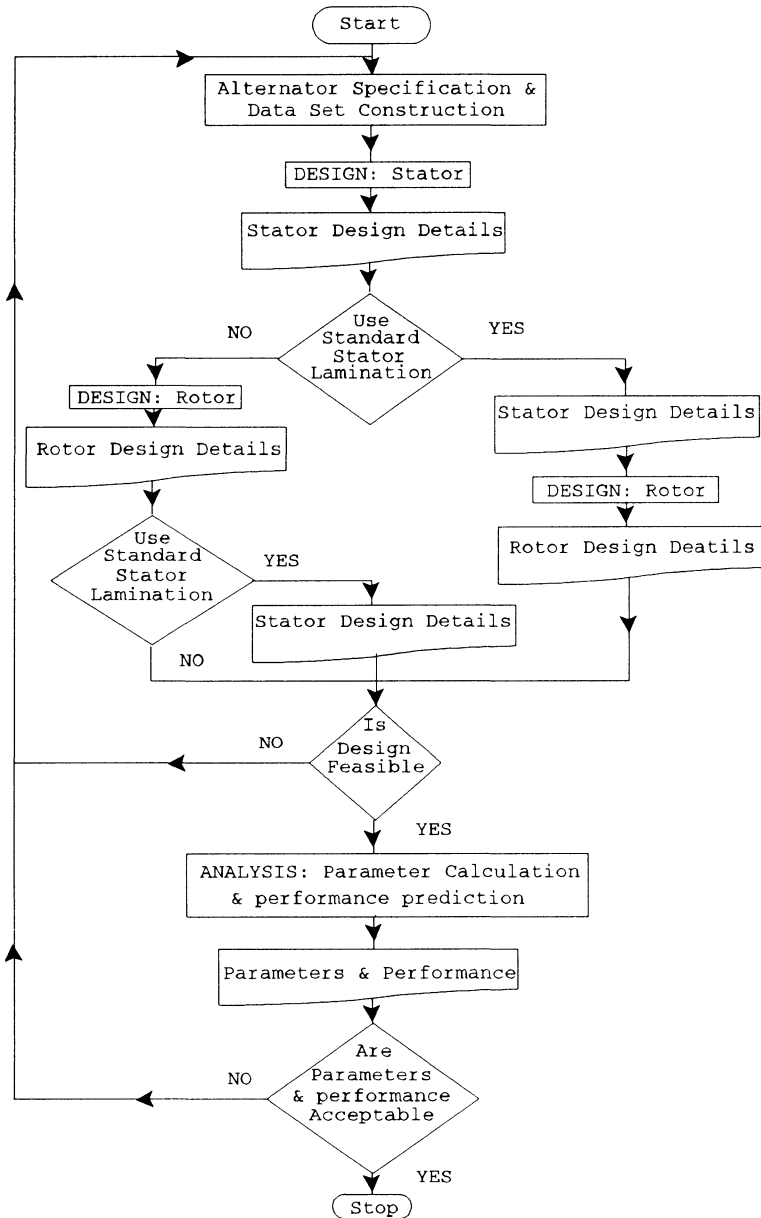


Figure 1: Alternator Design and Analysis Programme

**STATOR DESIGN :**

The Stator inner diameter is	=	0.181	m
The Net stator core length is	=	0.110	m
The number of Slots/Pole/Phase is	=	4	
Flux per Pole in the airgap	=	0.0163	Wb
Turns per phase (calculated min = 75.45)	=	80	
Turns per coil (calculated min = 9.43)	=	10	
Phase Current	=	34.78	A
Coils per phase	=	8	
Winding type	=	Double layer	
Conductors per slot	=	20	
Calculated Specific Magnetic Loading (Bav)	=	0.519	T
Calculated Specific Electrical Loading (AC)	=	29280.92	Amp Cond/m
Required slot area	=	148.29	mm sq
Wire size (Current Dens. = 6.86 A/sq mm)	=	2 off 1.5	mm diameter
	=	1 off 1.4	mm diameter
Stator tooth pitch	=	23.76	mm
Stator tooth width	=	10.27	mm
Stator slot width at the top	=	13.49	mm
Net Stator slot depth	=	12.05	mm
Gross Stator slot depth	=	18.05	mm
Actual slot area calculated	=	148.45	mm sq
Min back Iron thickness required	=	46.21	mm
Calculated Min Stator OD	=	310.00	mm

Press any key to continue or click left mouse

Figure 2: Stator Design Output

ROTOR DESIGN :

Number of poles	=	2	
Pole pitch	=	285.074	mm
Pole arc	=	190.049	mm
Pole shoe width	=	154.052	mm
Pole shoe depth	=	46.471	mm
Pole body width	=	86.988	mm
Pole body depth (for winding)	=	19.971	mm
Net rotor pole length	=	0.110	m
Airgap length	=	1.000	mm
Carters Coefficient	=	0.296	
Rotor Field Current	=	3.927	A
Turns per Rotor Pole	=	1142.09	
Diameter of Rotor winding conductor	=	1.000	mm
Rotor Coil available area	=	1369.86	sq mm
Required Rotor Coil area	=	1366.89	sq mm

Press any key to continue or click left mouse

Figure 3: Rotor Design Output



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PARAMETERS :

Rotor Winding Resistance :

Rf20 = 28.950 ohm
Rf75 = 35.160 ohm

Rotor Damper Bar Resistance :

Damper.Rb20 = 2.506E-05 ohm
Damper.Rb75 = 3.044E-05 ohm

Rotor Damper Bar Shorting Ring Resistance :

Damper.Rc20 = 5.799E-05 ohm
Damper.Rc75 = 7.043E-05 ohm
Rd2d1 = 0.389 ohm

Stator winding Resistance (per coil & per phase):

R.coil.20 = 0.024 ohm R.ph.20 = 0.190 ohm
R.coil.75 = 0.029 ohm R.ph.75 = 0.231 ohm

Calculated Short Circuit Ratio

ShortCircuitRatio = 0.657

Press any key to continue or click left mouse

Figure 4: Parameters I

Reactances (ohmic & per unit values):

Xs = 0.271	Xs.pu = 0.039
Xe = 0.145	Xe.pu = 0.021
Xl = 0.416	Xl.pu = 0.060
Xad = 20.196	Xad.pu = 2.932
Xsd = 20.612	Xsd.pu = 2.992
Xsq = 11.231	Xsq.pu = 1.630
Xfl = 0.736	Xfl.pu = 0.107

Transient & Subtransient Reactances (Saturated per unit values):

Xsd'.sat.pu	= 0.144
Xsd''.sat.pu	= 0.059
Xsq''.sat.pu	= 0.201
X2.sequence.sat.pu	= 0.130
X0.sequence.pu	= 0.004

Time Constants :

Tdo' = 1.4973	sec
Td' = 0.0018	sec
Ta = 0.0123	sec
Tdo'' = 0.1756	sec
Td'' = 0.0715	sec

Press any key to continue or click left mouse

Figure 5: Parameters II and Time Constants