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Derived Functions for MATLAB Non-linear Solvers – an optimal Stator Slot Design Stopgap

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

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ABSTRACT

In the three-phase squirrel cage induction motor (SCIM), like other rotating electromechanical machines, the active length of the stator windings lies in the slots. The proper dimensioning of the slots is therefore critical to the design of both the windings and the stator core, so as to attain a high performing machine. The preliminary stage of the SCIM design, if well done, facilitates the refinement and optimization stages; serving as a good take-off point for that final state of the art design. The aim of this article isn't to come up with a novel optimization method for the SCIM, but to provide another way of obtaining an initial stator slot design template, from where proper design refinement/optimization techniques could obtain very good starting values and be facilitated. Therefore, an attempt is being made here to derive relevant design functions that could be fed into the algorithms of various non-linear solvers such as the Genetic Algorithm (GA), to output the main stator slot dimensions for the SCIM. The final designed SCIM obtained from implementing the derived equations, when compared with the appropriate reference datasheets, showed only minor deviations from the expected performance indices – an outcome deemed satisfactory for a preliminary design attempt. These initial dimensions may in practice be subjected to the appropriate refinement. Depending on the target performance requirement of the motor.

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1. INTRODUCTION

The three-phase Squirrel Cage Induction Motor (SCIM) is widely used in domestic, commercial and industrial applications due to its simplicity, robustness and low maintenance cost. However, these motors consume large quantities of power. The reduction in electric energy consumption in SCIM's through a better motor design should always be a welcome option. The aim in motor design is to manufacture motors that have the desired characteristics with low financial cost values [1]. In order to analyze the performance of induction motors, the equivalent circuit parameters is usually calculated [2]. There is no unique solution to a design problem, and designs for the same specification will differ because of different emphasis being placed on each requirement by the particular designer [3].

In order to eliminate the few drawbacks of the SCIM, the designer should make a preliminary modeling and determine the physical size via parametric optimization with modern software in accordance with the requirements of the application [4]. The induction motor design is considered a nonlinear programming problem, where one or more objective cost functions of the design are minimized. In the design of induction motors, motor geometry and winding types which are effective in desired performance values are determined. One of the most important parameters in the design of electric motors is the determination of stator and rotor slot geometries [5-7]. The use of different slot geometries in motors significantly changes the motor performance via the variation of equivalent circuit parameters. For this reason, it is of great importance that the slot geometries are properly selected when designing the motor [8].

The slot geometry depends mainly on the SCIM power (torque) level and thus on the type of magnetic wire (round or rectangular cross section) from which the coils of windings are made. With round wire (random wound) coils for small power IMs, the coils may be introduced in slots wire by wire and thus the slot openings may be small. For preformed coils (in large IMs), made, in general, of rectangular cross-section wire, open or semi open slots are used. In an IM, only slots on one side are open, while on the other side, they are semi open. Electric conductors for stator windings are made of pure (electrical) copper, the slots containing a polyphase AC winding. The flux density in a tooth is affected by the shape of slot. For a wider slot, tooth width is narrow, giving higher flux density in a tooth; it leads to more iron loss [9,10]. The computation of flux density within an electrical machine forms the basic principle behind the machine design process [3].

References [11-14] are some recent and readily available articles that have accomplished objectives that are similar to that of this present treatise, making use of CAD tools like Visual Basic Artificial Neural Networks, finite element etc. However, none of them actually went on to derive relevant customizable functions that are executable by MATLAB nonlinear solvers. In this paper, some pertinent equations specially tailored to the stator slots geometry were derived from the design experience of various authors and suitably formatted for compatibility with common nonlinear optimization tools or solvers that are usually employed in SCIM design. The nonlinear solver to be illustratively employed is the MATLAB based Genetic Algorithm (GA). The GA is a potent tool to optimize the design of electrical machinery. One of the merits of the GA is that it is useful for solving nonlinear equations or complex optimization problems where the number of parameters is large, and it finds the global minimum for a wide range of functions, instead of a local minimum, without the need for the starting points to be close to the actual values [15]. Another advantage is that it does not require the use of the derivative of the function, which is not always easily obtainable or may not even exist [16].

This work hopes to serve as a valuable piece of reference in various modules of SCIM design classes in tertiary institutions. And for the design engineer in practice; it promises to be a rough and ready take off point for the optimization of the stator slot geometry. The author will attempt to treat the rotor version in a later publication.

2. MATERIALS AND METHODS

In fulfilling the aim of this study, various electromechanical equations or expressions directly or indirectly pertaining to slot dimensioning were identified from seasoned machine design literature, and mathematically formatted to be machine readable/executable by the GA routine in MATLAB, as well as by other solvers/techniques akin to the GA. Form wound chorded coils made of square magnetic wire in open slots having 3 slots per pole per phase was used in the stator of a standard efficiency100HP SCIM. The pole pitch was such that exceeds the coil span by one stator slot. It is assumed that the SCIM main dimensions and other design variables of the stator as well as the rotor are fully designed for the given rating, and are all functionally integrable to the stator slot design. The geometry of the stator slot is shown in Fig. 1.

For simplicity here, all slots and slot components were assumed to be in the form of simple geometric shapes, and the laws of geometry and trigonometry were thus assumed to apply accordingly. Thus, for a stator slot of roughly rectangular cross section as in Fig 1: Top width b_{s1} ≈ bottom width. For a rated ampere of the motor I_s, number of current paths in parallel *a,* and current density of the stator winding $ð_s$; the rectangular cross sectional area of the stator conductor could be sized as Ac = $\frac{I_s}{a ð_s}$ (1)

If the depths of conductor occupied portion, slot wedge and tooth lip are respectively d_{slot}, d_{sw} and d_{sl}; then, the total slot depth $d_{ss} \approx d_{slot} + d_{sw} + d_{sl}$ (2)

The area of the conductor occupied portion of stator slot could be taken as:

$$A_{sc} = b_{s1} d_{slot} = \frac{C_s A_c}{s_F} \quad (3)$$

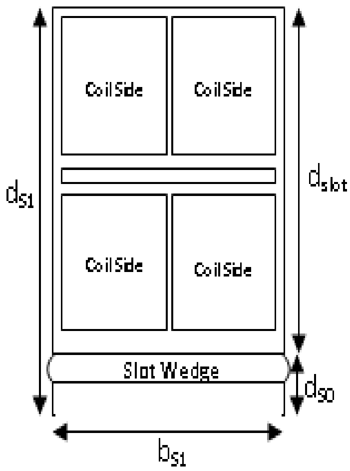

Fig. 1. Stator slot geometry

s_F and C_s being the slot fullness factor and number of conductors per stator slot respectively.

Appropriate values for the stator slot opening w_o (approx. equal to b_{S1} of Fig. 1), as well as the wedge height d_{sw} and lip height d_{sl} may be got from various empirical tables in literature e.g., from the design experience of [9]. The GA GUI was called to calculate suitable values of the main stator slot parameters such that both the teeth and the core may not attain an unacceptable level of magnetic saturation.

Table 1. Test Machine specifications

Specifications of Test Machine	Values
Power rating (HP)	100
Voltage L-L (V) volts	400
Number of poles (p)	8
Number of rotor slots (Sr)	55
Number of stator slots (Ss)	72
Conductors per slot (Cs)	4
Number of current paths in stator (a)	1
Stator winding factor (kws)	0.945503085
Bore diameter (D) mm	480.6338126
Stator core outer diameter (Do) mm	693.2980318
Core axial length (L) mm	188.7444569
Airgap length (lg) mm	1.140636642
Mean length of turn (MLT) mm	500.4526867

The following outlines the Matlab syntax by which GA finds the minimum of a function:

[x,fval] = ga (fitnessfcn, nvars, A, b, Aeq, beq, LB, UB, nonlcon, options) (4)

Where,

'x' is the best point that GA located during its iterations.
'fval' is the fitness function evaluated at x.
'fitnessfcn' is the handle to the fitness function.
'nvars' is the positive integer representing the number of variables in the problem.

'A' & 'b' is the matrix & vector respectively, for the linear inequality constraints of the form

A*x ≤ b (5)

'Aeq' & 'beq' is the matrix & vector respectively, for the linear equality constraints of the form

Aeq*x = beq (6)

'LB' & 'UB' are the vectors of lower & upper bounds respectively.

'nonlcon' is the nonlinear constraint function handle that returns two outputs:

[c, ceq] = nonlcon (x) (7)

'options' is the structure containing optimization options.

And from the LHS of equation 4, as got from [17]; three variables (nvars = 3) were outputted by the GA i.e., (B_t, A_{slot} and d_{slot}). B_t is the stator tooth flux density corresponding to the computed slot dimensions. A_{slot} and d_{slot} being respectively the area and depth of the conductor occupied portion of the stator slot.

2.1 Deriving the Objective Function

From [18,19], it could be gathered that:

Stator minimum tooth width $b_{ts}(\text{min}) = \frac{p\phi}{Bt_{max} L S_f S_s}$ (8)

Minimum depth of stator core $d_{cs}(\text{min}) = \frac{\phi}{2Bc_{max} L S_f}$ (9)

L is the core axial length, S_S is the number of stator slots, ϕ is the air gap flux per pole, number of poles is given as p, S_f represents the stator core stacking factor, while Bt_{max} and Bc_{max} are the maximum tooth flux density and maximum stator core flux density respectively.

ObjFcn is the objective/fitness function got with equation 8 from Nene in [18]; and properly formatted for GA thus: $k_3/w_t \le B_t$ (10)

Where, by modifying for the peak value, $k_3 = \frac{\frac{\pi}{2} p\phi}{L S_f S_s}$ (11)

But since the slot pitch (ƛ) is the sum of the widths of both the tooth (w_t) and slot (w or b_{s1}), then:

$w_t = \lambda - w$. (12)

And equation 10 gives: $k_3 - B\lambda + Bw \le 0$ (13)

Reference [20] gave an estimate for the area of the conductor portion of a rectangular slot as:

$A_{slot} \approx \frac{\pi D Q}{s_s s_f \eth_s}$. (14)

Where the specific electric loading $Q \approx \frac{6 N_{ph} I_{ph}}{a ƛ s_s}$. (15)

From equations 14 and 15, $ƛ = \frac{6\pi D N_{ph} I_{ph}}{a s_s^2 s_f A_{slot} \eth_s} = k_2/A$ (16)

Where, $A = A_{slot}$ and $k_2 = \frac{6\pi D N_{ph} I_{ph}}{a s_s^2 s_f \eth_s}$ (17)

D, N_{ph} and I_{ph} are respectively the stator bore diameter, number of turns/phase and current per phase.

Therefore, equation 13 becomes: $k_3 - B\frac{k_2}{A} + Bw \le 0$ (18)

This simplifies to give the fitnessfcn as:

$$Adk_3 - Bdk_2 + BA^2 \le 0 \quad (19)$$

Where, as in fig 1, $B_t = B$, $d_{slot} = d$, and w = A/d. (20)

2.2 Deriving the Constraint Function

References [19,3] also gave the approximate relationship between the stator tooth flux density B and the airgap average flux density B_{av} over one slot pitch for the case where saturation is neglected i.e.

$$\lambda B_{av}/w_t \le B \quad (21)$$

This ideal case was used as the nonlinear constraint (nonlcon) to guide the GA towards a suitable solution. But from Nene in [18], and again modifying for peak value,

$$B_{av} = k \approx \frac{\frac{\pi}{2} p\phi}{\pi D L S_f} \quad (22)$$

Therefore, equation 21 becomes $\frac{kƛ}{w_t} \le B$ (23)

After substituting equations 12 and 16, and the geometrical equivalent of w, equation 23 gives the nonlcon as: $kdk_2 - Bdk_2 + BA^2 \le 0$ (24)

2.3 Deriving the Function for the Bounds

Reference [21] gave the relation between the stator slot width w (approx. same as A/d) and stator slot pitch ƛ, and this was used as the linear constraint. i.e

$0.5ƛ \le w \le 0.6ƛ$ (25)

The lower limit is: $0.5d\lambda - A \le 0$ and the upper limit is: $A - 0.6d\lambda \le 0$. (26)

Reference [22] also gave the expression for the minimum and maximum depth of stator core.

$$d_{cs}(\text{min/max}) = \frac{\phi}{2Bc_{max/min}LS_f} \quad (27)$$

Which was used to derive an estimate for the upper bound (UB) and lower bound (LB) of *d*. The maximum and minimum values for the core flux density was taken as 1.7Tesla and 1Tesla respectively. i.e., with a stator core outer diameter D_o:

$$d_{max} = \frac{1.7s_f L(D_o - D - 2d_{s0}) - \phi}{3.4Ls_f} \quad (28)$$

$$d_{min} = \frac{s_f L(D_o - D - 2d_{s0}) - \phi}{2Ls_f} \quad (29)$$

d_{s0} being the sum of d_{sw} and d_{sl}.

The UB for A was derived from appropriate expressions got from [20], by equating expressions for the specific electric loadings i.e.,

$$A_{max} \approx \frac{\lambda\theta}{\rho c s_F \eth^2} \quad (30)$$

The expression for the stator phase current together with the knowledge of slot space factor and current density ð was used to derive the LB for A:

$$A_{min} = \frac{p_o c_s}{(\sqrt{3}) \text{ x } \eth \text{ x } a \text{ x } s_F \text{ x efficiency x power factor x } V_{L-L}} \quad (31)$$

Where, P_o, θ and ρ are the SCIM power output, maximum envisaged temperature rise (say, 75^0C) and the corresponding conductor resistivity respectively. S_F and c are the space factor (say, 0.4) and cooling coefficient (say, 0.02 ^{o}CW-m^2) respectively. Appropriate values from [23] were also used as the UB and LB for B (2Tesla and 1.4Tesla respectively).

2.4 Estimating the Area of Cross Sections

From Fig. 1 the total slot depth $d_{ss} \approx d_{slot} + d_{sw} + d_{sl}$ (32)

Therefore, the total slot area $A_{SS} \approx A_{slot} \left(\frac{d_{ss}}{d_{slot}}\right)^2$ (33)

The slot opening was taken as $b_{S1} \approx A_{slot}/d_{slot}$ (34)

Using a stator slot fill factor of 40%, the cross-sectional area of each coil conductor Acc according to [19], could be taken as: Acc ≈ $0.4A_{slot}$/Cs (35)

Equations 19, 24, 26 through 31 are the proposed formatted design equations for driving the GA or any similar optimization tool/solver, to obtain the main stator slot initial sizing parameters prior to refinement or optimization procedures.

Table 1 gives the specification of the test machine whose output is compared with the technical datasheet of the standard efficiency class of SCIM's as archived by seasoned international industrial leaders involved in the commercial production of electrical machinery in compliance with the IEC guidelines.

3. RESULTS AND DISCUSSION

The GA outputted main stator slot dimensions are given in Table 2.

Table 2. GA output

GA output and related parameters	Values
stator slot width (bs1) mm	10.45889169
Stator slot depth (ds1) mm	41.83556678
Stator tooth width @ max. Bst (ts1) mm	10.51271462
Statot tooth lip depth (dsl) mm	1.5
Slot wedge height (dsw) mm	4
Approx. area of a coil conductor (Acc) sq mm	38.00297576
Area of conductor portion of stator slot in (Asl) sq mm	380.0297576
Maximum Stator tooth flux density (Bst) T	2.015163386

It is necessary to compare the performance of the SCIM realized from implementing the stator slot derived functions, with those of salable prototypes in relevant catalogues; so as to ascertain how close to real life the test machine is, and thus, ascertain the suitability of the derived functions as reliable providers of pre-refined dimensions for the stator slot; when the said functions are run in compatible Matlab solvers. This comparison was done in Table 3.

It may be observed from Table 3 that, despite the fact that the test machine houses a rough and ready stator slot design, it does appear to perform impressively in the area of power factor and capacity for short time overload (as the Maximum to Full load torque ratio tends to indicate). The designs also seem good in the area of low slip operation (as the full load data illustrates). However, minor deviations are most obvious in the ratios – as seen in Starting to Full load torque ratio. Overall, the performances of

Table 3. Comparison of SCIM performance with that of standard prototypes

Parameters	ABB Motors (M2QA Series)	Vemat Motors (3VTB Series)	WEG Motors (W22 Series)	OMEC Motors (OMT1 Series)	Test Machine
Full Load Efficiency	0.93	0.93	0.91	0.93	0.91
Full Load Power Factor	0.82	0.82	0.8	0.81	0.86
Full Load Current (AMPS)	142	142	149	144	138
Full Load Speed (RPM)	740	737	740	740	739
Starting to Full load current ratio	7	6.2	5.3	6.6	6.5
Starting to Full load torque ratio	1.8	2.5	1.6	1.8	1.3
Maximum to Full load torque ratio	2	1.9	2	2	3.5

the test machine appear adequate for the machine stator slot dimensions and derived functions to be adopted as a good takeoff point to facilitate subsequent design refinement/optimization, depending on target performance or application.

4. CONCLUSION

With the primary objective of providing handy equations/functions for realizing good starting values in the stator slot dimension search space for various 3ph SCIM optimization programs, relevant design functions have been derived and formatted for driving nonlinear solvers or optimization tools such as the GA and the likes, as far as the preliminary stator slot dimensioning in a typical SCIM design program is concerned; and the algorithm have been integrated into an existing SCIM program in Matlab for proper overall machine performance assessment. The machine performance has been assessed against frontline industrial prototypes. The results obtained show that though the stator dimensions, in particular, are yet in their unrefined state, the test machine in which they feature, could arguably pass for a final salable prototype. Therefore, designers, students, and researchers are herein provided with handy equations and formatted functions to possibly kickstart and facilitate their design and optimization routines, with relevant modifications possible where necessary; to capture the peculiarities of other stator slot geometries.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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