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DESIGN OF AN 8/6 SWITCHED RELUCTANCE MOTOR FOR 42V AIR-CONDITIONING COMPRESSOR AUTOMOBILE APPLICATION

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ABSTRACT
This paper presents a simple computer-aided design methodology of a four-phase switched reluctance motor (SRM) for an automotive application operating at 42V. The design procedure was entirely developed using Matlab in conjunction with a finite-element analysis method (FEA) for validation purposes. Design requirements for an air-conditioning automobile compressor are also introduced and briefly discuss. Characteristic analytical results of the flux linkage and inductances obtained for some rotor positions are then compared with values from the FEA analysis, showing acceptable margin of errors. These values are later used to calculate the analytical torque developed by the machine according to proposed requirements. Finally a FEA test has been carried out to verify performance and fine-tuning the final design.
Keywords: Switched reluctance motor, air-conditioning automotive compressor, 42V Power Net.

1. INTRODUCTION
Nowadays, the majority of motors used in automotive applications are simple DC-motors connected to a 12V bus. Important application examples of this philosophy are air-conditioning systems, which usually employ DC-brush motors embedded in a belt driven system. However it is well known that these motors have low efficiency and poor reliability. Therefore there has been a trend to replace DC-motors by more advanced AC-motors drives. A promising candidate to this technology is the switched reluctance motor (SRM). His advantages include high reliability, the ability to operate under fault conditions, high torque per ampere and excellent operation in harsh environments. These features make the SRM as a promising candidate for use in automotive applications, especially the air-conditioning compressor whose requirements will be shown in the next section. Nevertheless the design of an SRM machine is complex due to its multiple design parameters and its highly-nonlinear characteristics when operating with saturation currents.
Numerous authors have explored SRM design procedures in detail [1-2], although they require extensive knowledge or experience in the empirical design of such machines [3].
This paper presents a simplified computer-aided design (CAD) methodology applied for the design of a SRM automobile application. The procedure is based on a combination of different sources. They are: a systematic method for laminar and winding calculations [4, 5], basic principles from electromagnetism [1] and some empirical restrictions for the particular application [2]. Finally, the methodology develops an effective evaluation of the SRM torque, phase inductance, flux-linkage, phase currents and cooper losses, compared with results obtained from the FEA analysis.

2. DESIGN METHODOLOGY

2.1 Application Specifications
The minimum motor specifications for operating with an air-conditioning compressor are: 1) Operation in a wide speed range with overall system efficiencies of 70% or more. 2) Rated output

power in the range of 0.75 to 3.7 kW, with operation capacity in continuous mode at 1-2 kW. 3) Rated speed above 3500 rpm to 7000 rpm or more (operation at higher speeds are critical for fast cooling the automobile cabin). 4) Constant torque between 3.5 Nm to 6 Nm, from start to base speed *e.g.* 4000 rpm. Moreover the SRM motor must be small, compact and lightweight with a typical machine operation temperature of around 125ºC. Initial values utilised in this paper are specified in Table 1, while the nomenclature and cross section of 8/6 SRM are shown in Fig. 1.

2.2 Simplified design procedure

The SRM design method is depicted on the flow chart of figure 2, while the analytical CAD-simulation program is implemented using Matlab based on these steps. Beginning from the start, step 1 and 2, defines the electrical and mechanical specifications. Here parameters like number of phases (N_{ph}), number of stator and rotor poles (N_s, N_r) are selected. In our case we choose an 8/6 SRM configuration in order to decrease the torque ripple for the application [2]. Also the stator maximum outer diameter (D_{omax}) is associated to the compressor diameter (packaging). Step 3 corresponds to the laminar design which includes the internal sizing of poles height (h_r, h_s) and widths (t_r, t_s). Here flux densities and magnetic field intensities in the air-gap, rotor and stator are also obtained from the BH characteristic curve of the material. Turns per phase (N_N), rated current and aligned saturated inductances are calculated from the magnetic circuit equation at full load. Step 4 corresponds to winding design and includes the calculation of the required winding space and clearance (Cl), among other parameters. Between steps 2 to 5, the initial assumed parameters are recalculated and employed geometrical restrictions are also taken into account to avoid torque ripple [2]. In step 5, we estimate the phase inductance based on the rotor position. Flux-linkage characteristics, phase-resistance, motor weight and averages values of torque and power are also calculated. Finally, in step 6, the CAD program performs a single pole flux-linkage analysis with the purpose of finding motor torque based on the rotor position. Computation of turn-off angle and RMS-currents utilise an approximated procedure [1]. Waveforms for other phases are generated by symmetry, while the acoustic noise and thermal effects are not considered.

Table 1. Configuration, laminar and windings dimensions of the SRM designed

Configuration (Initial Values)	Dimensions Laminar Design	Dimensions Winding Design
P_{rated} = 1.5 kW	N_{ph} = 4; n_{par} = 1; n_{ser} = 1	C_l >= 2.5 mm
V_{DC} = 42V; I_{ph} < 65A	N_s=8; N_r=6	Cal AWG = 11
ω_{rated} = 4000 rpm	Lam. M19 SiFe	$Wire_{wrap}$ = 0.1mm
T_{rated} = 0, ω=3900 rpm	β_s = 17.98º; β_r = 20.4º	N_{LV} = 3 N_{LH} = 4
T_{rated}=4N.m, ω=3900 rpm	D = 71 mm; L_{stk} = 70 mm	h_w= 11.4 mm
T_{rated} = 0.2N.m, ω=16000 rpm	D_{shaft} = 25 mm; g = 0.2 mm	Turns per phase, T_{ph} = 24
D_o = 120 mm;	B_{sat} =1.75 Tesla;	
Tcu = 125ºC	y_r =6.96mm; y_s =11.14mm	

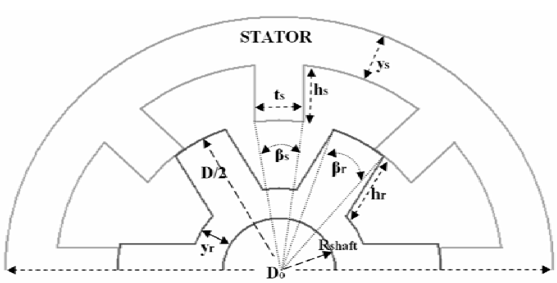

Figure 1. Cross section of 8/6 SRM in unaligned position

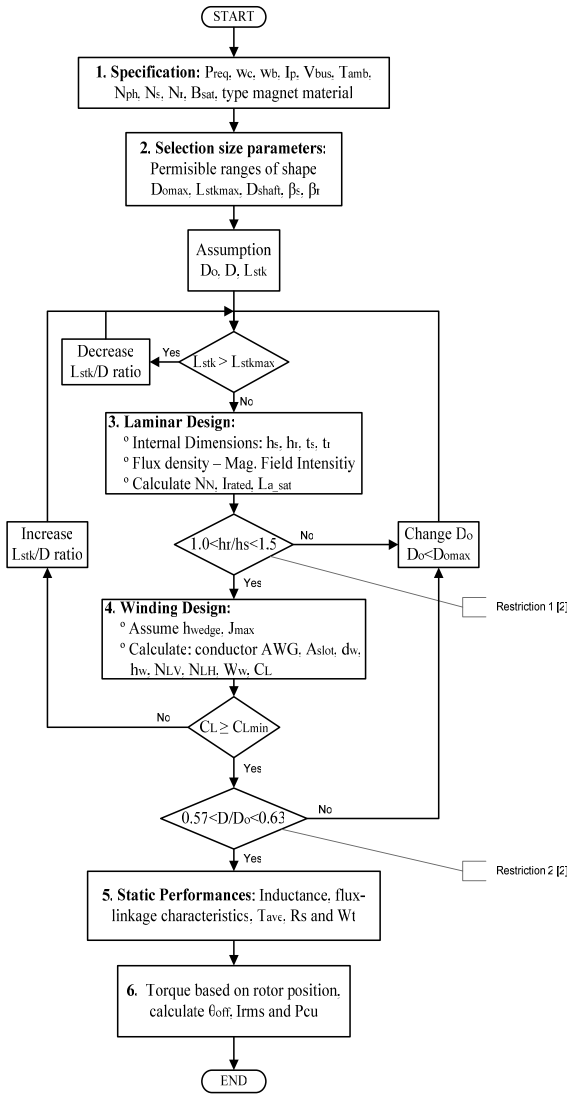

Figure 2. Flow chart of the CAD Program SRM

3. COMPARISON OF ANALYTICAL CAD-MODEL WITH FEA SOFTWARE

3.1 Determination of inductance and flux-linkage curves at different positions

The analytical computing of the flux-linkage curves for an SRM when the stator and rotor poles are overlap and non-overlap, including iron saturation, follows the approach of [6]. It is assumed that each phase is independent. This means that the flux linked by each phase depends only on the position of the rotor and current in that phase. The magnetic field is computed by means of the series expansion solution of Laplace's equation in a simplified rectangular geometry based on Fig.1. Geometrical parameters and the BH characteristic curve of material allow us to find the flux-linkage curves with high degree of accuracy in relative short times of simulation. The corresponding inductances calculated by Eq.(1) are shown in Fig. 3. Fig. 4 compares CAD flux-linkage curves using the analytical model and FEM flux-linkage results. Each curve represents flux linked by the phase at a fixed rotor position and phase current.

$$L(\theta, I_{ph}) = \left. \left(\frac{\Delta\lambda}{\Delta I_{ph}} \right) \right|_{\theta=\text{constant}} \quad (1)$$

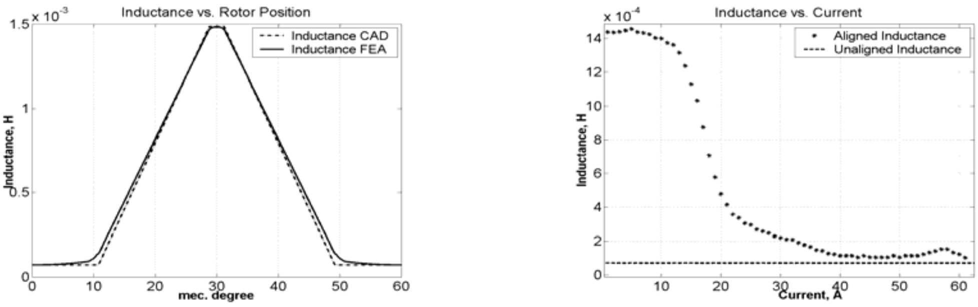

Figure 3. a) Comparison of aligned-unaligned CAD and FEA inductances versus rotor positions with current $\leq I_{sat}$ b) Aligned-unaligned inductance utilising SRM CAD

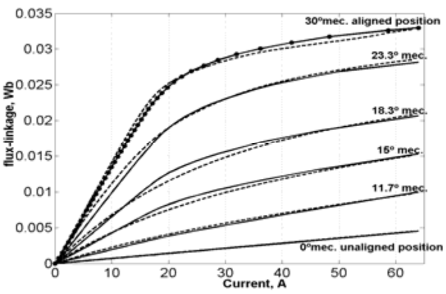

Figure 4. Comparison of the analytical CAD flux linkage curves and FEA flux result.

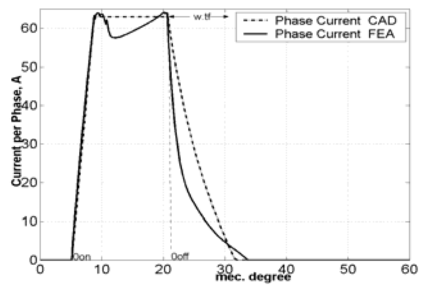

Figure 5. Evaluation of CAD and FEA phase-currents outputs for the designed

3.2 Computation of turn-off angle and currents

An approximate procedure for calculating the advanced turn-off angles and currents forms is derived from [1]. This procedure is made with the purpose of having a selection criterion for the stator and rotor pole arcs (β_s, β_r), which both depend on the desired torque vs. rotor position. Beginning from point 1) assume that the current becomes zero in (t_f) seconds before the inductance slope changes from positive to negative avoiding negative torque. 2) Increase the average torque per phase to eliminate negative torque generation by means of a dead zone ($\beta_s \leq \beta_r$). 3) Assume a turn-on angle (θ_{on}). 4) Current fall angle (θ_f) at rated speed is based on linear magnetic characteristic, *i.e*. the inductance remains constant throughout t_f and the speed is constant in the commutation time (θ_{off}-θ_{on}). Eq.(2) approximately gives the turn-off angle for a determined rated speed and maximum current per phase. The comparisons between the curves of phase current shown in Fig. 5 are moderately acceptable.

$$\theta_{off} = \frac{\pi}{N_r} + \frac{(\beta_r - \beta_s)}{2} - \omega_r t_f = \frac{\pi}{N_r} + \frac{(\beta_r - \beta_s)}{2} - \frac{\omega_r L_a}{R_s} \ln\left[1 + \frac{R_s I_{ph}}{V_{dc}}\right] \quad (2)$$

3.3 Determination of the output torque.

While a direct procedure applied to any operating condition for calculating the average torque (T_{ave}) can be simply evaluated by dividing the total coenergy by the angular displacement, this does not take into account the effect of overlapping between phases. We then calculate the instantaneous torque (T_{inst}) which allow us to find the developed torque at all rotor position (including overlapped regions). It is made when finding the incremental coenergy ΔW_c divided by the corresponding angular increment for each rotor position Eq.(3). Fig. 6 shows the corresponding instantaneous torque-rotor position (per phase), developed for the SRM CAD-design. The torque-speed and efficiency-speed characteristics of Fig. 7 indicate the expected performance fairly in accordance to design specifications for the application. Finally, table 2 gives additional comparisons between CAD and FEA for other parameters.

$$T_{ph}(\theta, I_{ph}) = \left. \frac{\partial W_c\left(\theta, I_{ph}\right)}{\partial \theta} \right|_{Iph=constant} \quad (3)$$

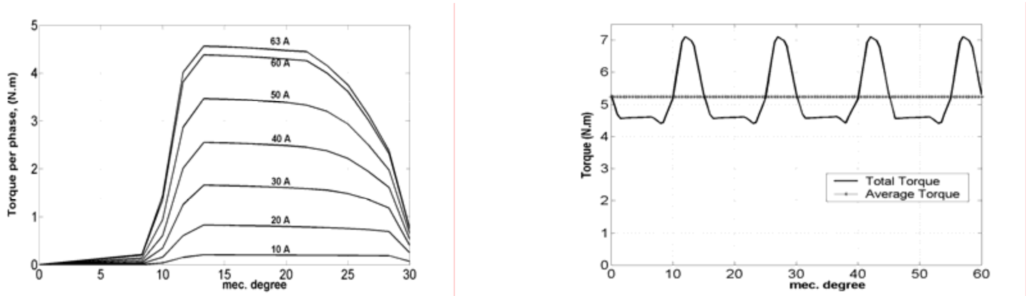

Figure 6. a) Torque vs. rotor position characteristic for SRM CAD-design. b) Total developed torque.

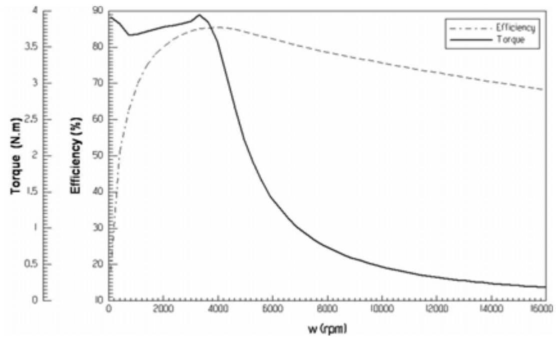

Figure 7. SRM Torque-Efficiency vs. Speed by FEA

Table 2. Comparison of supplementary electrical parameters from CAD and FEM for SRM designed

PARAMETERS	CAD	FEA
Total Cooper Loss - P_{cu} (W)	115.34	98.4
Max. Current Phase - I_{phmax} (A)	62.93	64
Coil Length per Turn - l_m (mm)	192.6	193.7
Winding Resistance Phase -Rs (Ω)	0.0277	0.02807
Unaligned Inductance - L_u (mH)	0.007109	0.007053
Alig. Ind. NotSaturated-La_{nsat}(mH)	1.5	1.4826
Alig. Ind. Saturated - La_{sat} (mH)	0.5205	0.515
Average Torque – T_{ave} (N.m)	5.25	5.41
Total Weight - W_t (kg)	5.59	5.784

4. CONCLUSIONS

A simple design methodology of a four-phase 42V SRM machine for an automotive application is presented. The design procedure is based on the combination of different approaches and has been implemented using Matlab. The model can predict detailed performance curves for the designed SRM machine, such as: inductances, flux-linkage characteristics, cooper losses, developed torque and other electrical parameters, showing an expected performance in accordance to design specifications for the application. Validation and fine-tuning of model results has been carried out by mean of FEA program.

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