

A Simple Knowledge Base Software Architecture for Industrial Electrical Machine Design: Application to Electric Vehicle's In-Wheel Motor

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Abstract The paper presents the application of a knowledge based software architecture (KBSA) scheme which has been developed and implemented in order to be used as a tool in the electrical machines design industrial process. The proposed scheme's layers are introduced, considering several impact factors from many points of view (i.e. technical, material, algorithmic, economic etc), as well as their interference. It is evident that the specific engineering design problem poses inherent demand for a knowledge representation framework that could support the entire life cycle: requirements, specification, coding, as well as the software process itself. In this context, the work continues by presenting design results of the implemented KBSA for a certain type of permanent magnet motor currently under research in electric vehicle industry, for an in-wheel electric vehicle (EV) application. The KBSA employs evolutionary algorithms for the systematic optimization and the results reveal the effectiveness of the aforementioned procedure followed.

Keywords Knowledge bases systems · Electrical machine design · Genetic algorithms · Electric vehicle in-wheel motor

1 Introduction

By definition, a knowledge-based system (KBS) is a computer program that reasons and uses a knowledge base to solve complex problems. The term is broad and is used to refer to many different kinds of systems. The one common theme that unites all KBSs is an attempt to represent knowledge explicitly via tools such as *ontologies* and *rules* rather than implicitly via code the way a conventional computer program does [1, 2]. Also, in a typical artificial intelligence (AI) structure as

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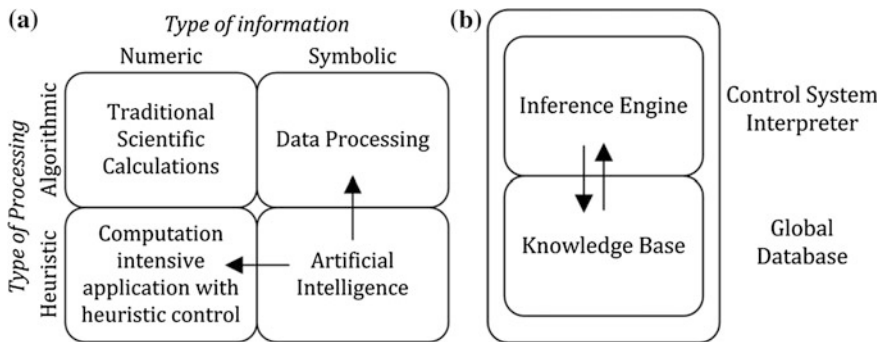


Fig. 1 Main structures **a** computing areas, **b** knowledge based system architecture

in Fig. 1a, the goal is to construct a computer program that performs at high levels of competence in cognitive tasks. At the same time, a KBS has two types of sub-systems: a knowledge base and an inference engine (Fig. 1b). The knowledge base represents facts about the world, often in some form of subsumption ontology. The inference engine represents logical assertions and conditions about the world, usually represented via *if-then* rules [3, 4]. KBSs have been successfully utilized for solving real world electrical engineering problems. In [5] a KBS for supervision and control of power systems was applied, while in [6] autonomous agents were utilized for control and diagnosis in electric power industry. Results of [7, 8] are also indicative examples of KBS applications in robotics. To the authors' knowledge extend though, there is no KBS implementation yet in literature to the engineering area of *electrical machine design*. In this context, the paper's effort is to provide an alternative engineering method that represents a merging of object oriented programming (OOP), AI techniques and computer-aided design technologies, giving benefit to customized or variant electrical machine design solutions. The work is organized as follows: In Sect. 2 a brief problem statement is given. In Sect. 3 the developed KBS is described, while Sect. 4 shows the detailed problem demands and some case results. Section 5 concludes the work.

2 Aspects of Electrical Machine Design Problem

The design of electrical machines is known as an inverse problem, i.e.: From the characteristic values given by the schedule of conditions (for example a motor's torque), obtain the structure, the dimensions, the thermal behavior and the material compositions of the machine constitutive parts, [9, 10]. One is usually interested in performing an optimal design where a given criterion is optimized (e.g. the volume of the magnet is minimized). The interest of the electrical machine design combining optimization algorithms and analytical models has in fact already been widely shown in the literature i.e. [11–14]. Nevertheless, a designer is generally

confronted with a number of sub-problems for which there may not be one solution, but many solutions. An “ideal” design should ensure that the product perform in accordance with the requirements at higher efficiency, lower weight of material for the desired output, lower temperature rise and lower cost. Also, it has to be reliable and durable. A practical designer must effect the design so that the stock (standard frames, punching etc.) is adaptable to the requirements of the specification. He must also affect some sort of compromise between the ideal design and a design which comply with manufacturing conditions, material availability, country regulations, competitive market etc.

3 Proposed Knowledge Based System Structure

The developed KBSA consists of a number of knowledge sources (KSs) that are organized into several layers (or levels) as shown in Fig. 2. Also, there are some reasoning modules (RM) employed. Their incorporation is explained briefly in this Section. *Data-level* determine the appropriate domain-independent KS, based on the information provided for the hard and soft magnetic material properties (i.e. iron, steel types, permanent magnet types), for the conductor material properties (conductivities, predefined wire diameters etc), and insulation material properties (dielectric strength, sheet widths etc). This level is actually used to “control” various tasks, such as the activation of other KSs, in other levels. *Technical-level* KSs combines user-input information for the electric machine’s specifications as well as

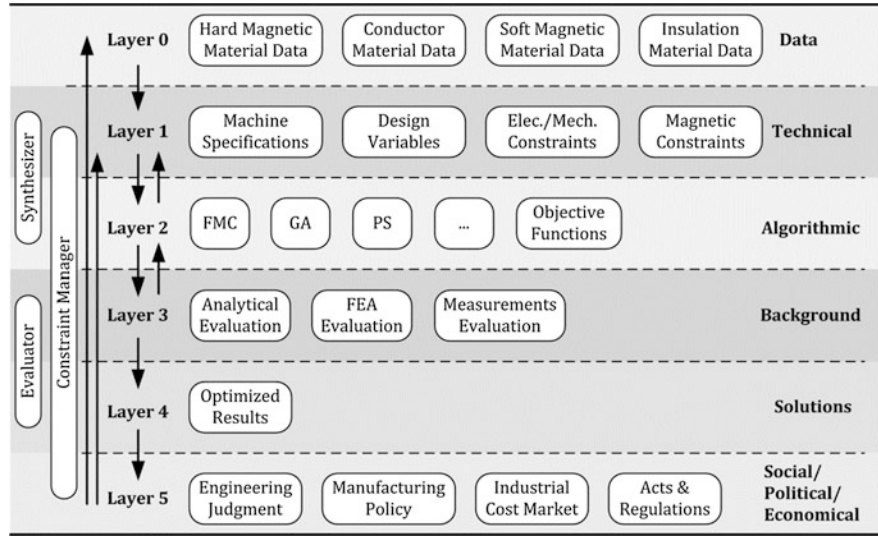


Fig. 2 Structure of the developed knowledge based system software developed (main knowledge sources representation and modules shown)

the desired design variable which have to be determined. This level's KSs can be “fired” also from the data-level KSs regarding electromechanical and magnetic constraints which—some of them—are directly depend on the materials used. The *Algorithmic*-level comes next. Here, the KSs are comprised of the mixed coding of optimization methods (i.e. GA) along with appropriate engineering expert *if-then* rules. An important issue in this level arises from the justification of the appropriate objective functions chosen. The first RM called the *synthesizer* takes a set of specifications and constraints and generates one or more conceptual designs. *Background*-level follows, which is also a mixed-coded layer and evolves the evaluation of the conceptual designs. The second RM called the *evaluator* actually performs a preliminary evaluation of all the feasible alternative solutions that are generated by the synthesizer. It acts on a network of object templates; this network exists in all the domain KS levels. Moreover, we employ a finite element analysis (FEA) geometric reasoner KS which is an intelligent computer-aided design (CAD) graphics system that performs the following tasks when fully fed: (1) understands engineering sketches and drawings, (2) generates geometric models and reasons about these models, and (3) performs interference checking between design objects. Furthermore, some tests (which are not even feasible in laboratory setup), can be virtually performed by FEA method. The *Economical*-level completes the

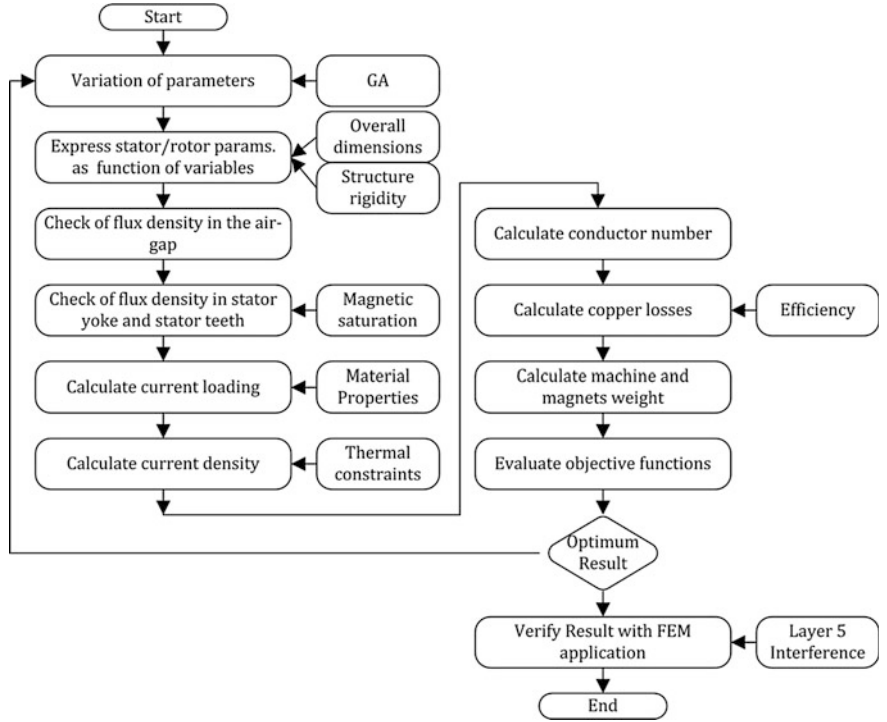


Fig. 3 Main procedure of solving electrical machine design problem adopted here using a GA

proposed structure by incorporating all the necessary KS in regard to manufacturing, economical and market information. The last RM, the *constraint manager*, performs the evaluation and consistency maintenance of constraints arising in the solution designs. Figure 3 depicts the employed rule strategy (in flowchart mode). It should be noted however that despite the simple structure provided, the proposed KBSA fulfill three necessary building conditions: (a) the reasoning mechanism is stable, (b) the knowledge base is able to grow and change, as knowledge is added and (c) this arrangement enables the system to be built from, or converted to, a *shell*.

4 Application: In-Wheel Motor Concept Design

In-wheel motors are traction motors which actually change rotary motion to linear motion. Their attachment to the wheel is not implemented through gearing; instead they are part of the wheel itself [15]. This fact limits these direct-drive motors to a size that will fit inside the wheel, while at the same time performance requirements should be preserved (Fig. 4a). At the same time, permanent magnet synchronous

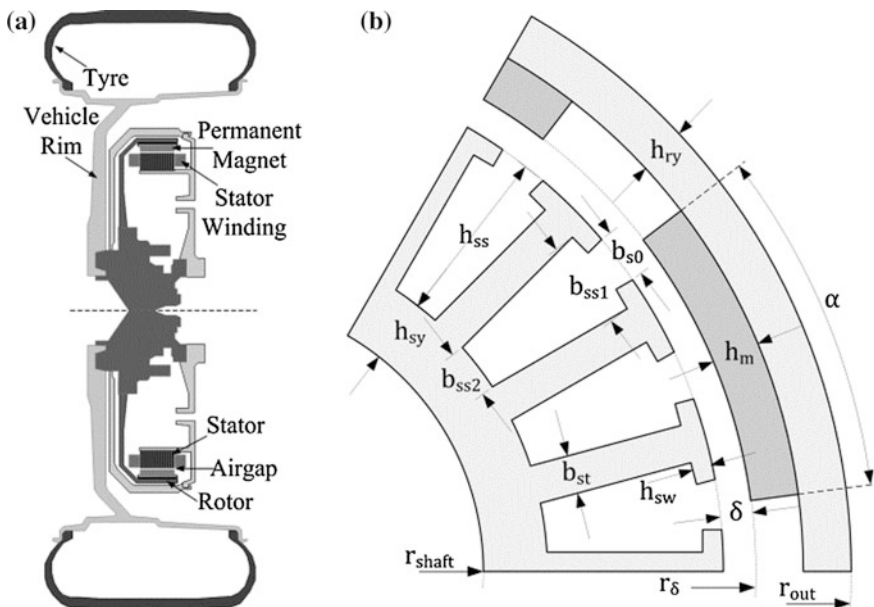


Fig. 4 Schematic representations of the problem: **a** cross-section of an in-wheel motor assembly and, **b** generic geometry topology of an outer-rotor PMSM

machines (PMSM) exhibit high torque-to-inertia ratios as well as efficiency thus are suitable candidates for this kind of EV traction. From an industrial perspective, considerable research effort has been put into studying the behavior of appropriate PMSMs i.e. [15–19]. Most of these research efforts though, were performed w.r.t. inner-rotor topologies mainly, so outer-rotor ones have to be studied more. In this context, two outer-rotor machines are investigated here and also are going to be the “test-bed” for the developed KBSA. Figure 4b shows the relevant topology, where the parameters shown have to be optimized while satisfying certain constraints. It can be seen that there is a simple geometrical representation between these variable as described by,

$$\begin{aligned} r_s &= r_{out} - h_m - h_{ry} - \delta & h_{sy} &= (r_\delta - r_{shaft} - \delta - h_{ss}) \\ b_{ss1} &= \pi \frac{r_s - h_{sw}}{Q_s} - b_{st} & h_{ry} &= (r_{out} - r_\delta - h_m) \\ b_{ss2} &= \pi \frac{r_s - h_{ss}}{Q_s} - b_{ts} & k_{open} &= \frac{b_{s0}}{b_{ss1}} \end{aligned} \quad (1)$$

As aforementioned, apart from the geometrical information, there is a lot of information to be fed to the KBSA pertaining: (a) the electrical properties, (b) the magnetic properties, (c) the thermal properties, (d) the material properties, (e) the mechanical properties and (f) the economical and viability properties of the motor design. The reader can refer to the literature (i.e. [11, 14]) for further details on the above topics. Finally, for the sake of space, all the variable names are summarized in Tables given next. Table 1 shows the specific application requirements, Table 2 the problem constraints, while Table 3 some materials’ data (which have been finally chosen).

Table 1 EV in-wheel motor requirements

Quantity	Symbol	Value	Unit
Output power	P_{out}	15300	W
Output torque	T_{out}	170	Nm
Efficiency	η	≥ 90	%
Number of poles	p	$2 \leq p \leq 80$	–
Synchronous speed	n_s	850	rpm
DC link voltage	V_{dc}	820	V
Inverter modulation ratio	m_a	0.8	–
Slots per pole/phase	q	$0.1 \leq q < 1$	–
Number of turns/slot	n_c	$1 \leq n_c \leq 100$	–
Active length	L	≈ 30	mm
Outer radius	r_{out}	216	mm

Table 2 Main design problem constraints

Description	Symbol	Constraint	Unit
Stator yoke flux density	B_{sy}	≤ 1.6	T
Stator teeth flux density	B_{st}	≤ 1.6	T
Rotor yoke flux density	B_{ry}	≤ 1.6	T
Airgap flux density	B_{δ}	≤ 1.1	T
Airgap length	δ	$1 \leq \delta \leq 3$	mm
Stator yoke height	h_{sy}	$\geq h_{ss}/3$	mm
Rotor yoke height	h_{ry}	≥ 8	mm
Slot base width	b_{ss2}	$0.15h_{ss} \leq b_{ss2} \leq 0.5h_{ss}$	mm
Stator teeth width	b_{s0}	≥ 2.0	mm
Stator teeth width	b_{st}	≥ 2.5	mm
Magnet height	h_m	$2.5 \leq h_m \leq 10$	mm
Copper losses	P_{Cu}	≤ 1500	W
Magnet weight	M_m	≤ 1.0	kg
Machine weight	M_w	≤ 25	kg

Table 3 Motor’s material data used

	Constant	Symbol	Value
Magnet (NdFe35)	Remanent flux density	B_r	1.23 T
	Relative permeability	μ_r	1.09
	Magnet density	ρ_m	7400 kg/m ³
M19_24G	Bulk conductivity	σ_s	1.96×10^7 S/m
	Steel density	ρ_s	7650 kg/m ³
Winding	Relative permeability	μ_r	9.99×10^{-1}
	Bulk conductivity	σ_{Cu}	5.8×10^7 S/m
	Copper density	ρ_{Cu}	8900 kg/m ³

4.1 Case Studies and Optimization Results

In order to validate the performance of the developed KBSA, two case studies were examined: (a) an in-wheel motor which has to be extremely light (the main consideration here is total motor weight) and (b) an in-wheel motor which has to present the lower power losses (main consideration here is efficiency). However, both cases have to satisfy all the other relative constraints. Let us denote “Motor1” and “Motor2” the final solution topologies which refer to these cases respectively. With respect to Fig. 4 and Tables 2, 4 show the overall results of the aforementioned cases though the KBSA. Figure 5 depicts the exact design solution provided

Table 4 Design variables^a results

Quantity	Symbol	“Motor1”	“Motor2”
No. of poles	N_m	66	28
No. of slots	Q_s	54	24
Motor shaft radius	r_{shaft}	164	119.61
Motor outer radius	r_{out}	216	216
Air gap radius	r_δ	205.47	182.14
Air gap length	δ	1.322	1.0
Slot opening width	b_{s0}	2.9	11.9
Slot top width	b_{ss1}	11.4	20.0
Slot base width	b_{ss2}	11.4	20.0
Stator teeth width	b_{st}	12.21	27.38
Stator tooth tip height	h_{sw}	1.3	0.2
Stator slot height	h_{ss}	25.05	44.2
Stator yoke height	h_{sy}	15.09	17.32
Rotor yoke height	h_{ry}	8.025	31.36
Magnet height	h_m	2.5	2.5
Pole arc/pole pitch ratio	α	0.37	0.48
Slot fill factor	s_f	0.56	0.57
No. of conductors/slot	n_c	26	48
No. of wires/conductor	n_w	4	6
Wire diameter	d_w	1.15	1.29

^aall dimensions in mm

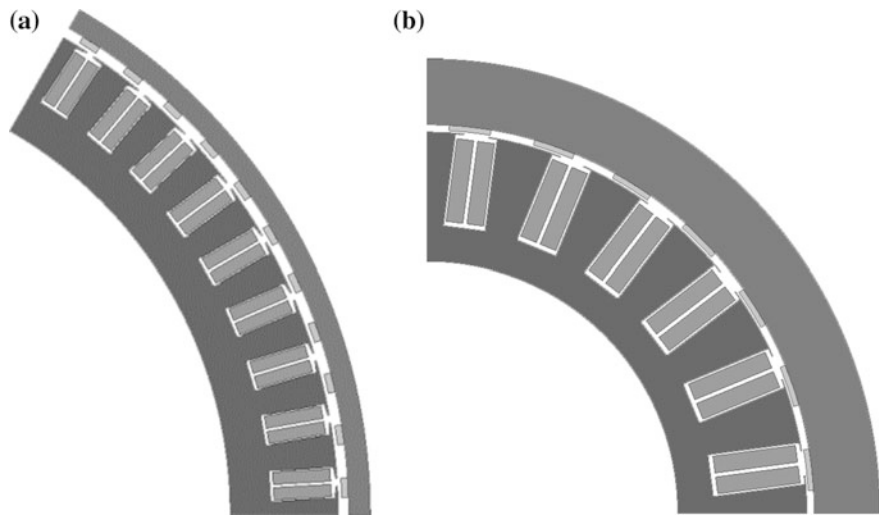


Fig. 5 Cross-sectional geometric views of the two motors designed through the developed KBSA. **a** weight is of primary concern (Motor1), **b** efficiency is of primary concern (Motor2)

Table 5 Electromechanical quantities results

Quantity	Symbol	“Motor1”	“Motor2”	Unit
Efficiency	η	91.83	94.57	%
Line current	I	60.28	62.70	A
Armature current density	J_c	14.51	7.98	A/mm ²
Copper losses	P_{Cu}	1326.76	842.67	W
Core losses	P_{Core}	33.44	35.59	W
Magnet weight	M_m	266.72	306.94	gr
Machine weight	M_w	12.03	22.391	kg
Cogging torque	T_{cog}	0.24	1.17	Nm
Torque ripple	T_{rip}	7.87	4.65	%
Torque angle	T_{ang}	56.10	50.82	deg
Fund. induced voltage	emf	213.9	220.817	V
Nom. frequency	f	467.5	198.33	Hz

for the two motors. Moreover, w.r.t. Tables 1, 2 and 5 show the electromechanical and performance quantities results. It can be easily seen that the KBS succeeded in satisfying all the constraints and to provide feasible solutions for the electric vehicle in-wheel motor design application. Specifically, in Case (a), the final solution presents a very low weight of 12 kg (with a constraint of 25 kg), while pertaining the desired power output, high efficiency (91.83 %) and mechanical rigidity. The same are valid in Case (b), where the solution provided by the KBSA present very low power losses of 842.27 W (with a constraint of 1500 W), very high efficiency (94.57 %) and quite low current density (7.98 A/mm²). Mechanical rigidity and magnetic saturation are also found within acceptable limits. Finally, for demonstration purposes, the magnetic flux distribution when the motors are in running condition is shown in Fig. 6.

5 Conclusions

As knowledge-based systems becomes more complex the techniques used to represent the knowledge base becomes more sophisticated. Rather than representing facts as assertions about data, the knowledge-base becomes more structured, representing information using similar techniques to object-oriented programming such as hierarchies of classes and subclasses, relations between classes, and behavior of objects. The paper dealt with a complex problem in electrical engineering design area; the electrical in-wheel motor design. A KBSA based on the above principle was developed and applied successfully. It was observed that,

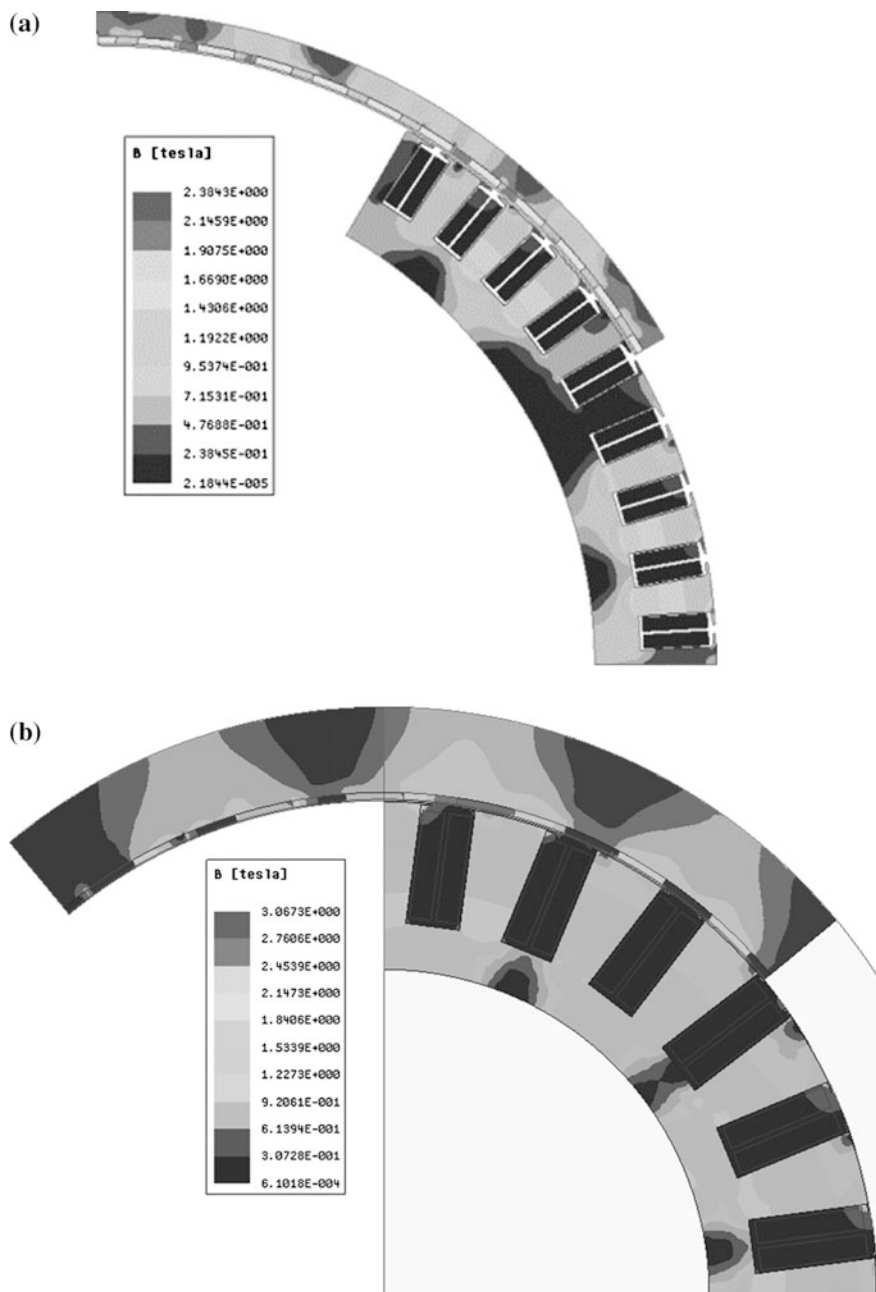


Fig. 6 Magnetic flux density distributions (in motor running condition) of the two motors designed through the developed KBSA. **a** Motor1 (low weight), **b** Motor2 (high efficiency)

despite the complexity, the correct rules and interactions within the knowledge base, satisfactory results can be withdrawn. Also, it seems that there is a great potential for the electric vehicle industrial sector in using such architectures. Future work might include the incorporation of this KBS though Internet so to expand it to a Semantic Web application.

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