Design comparison of two rotating electrical machines for 42V electric power steering

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Abstract - The proposed paper presents two design procedures of rotating electrical machines for 42V embedded application. Particularly, for an electrical power steering, a three-phase interior permanent magnet synchronous machine (PMSM) fed by a switch redundant power converter and a six-phase induction machine (IM6) fed by a new type of six switches converter are designed for future 42V DC system. For the PMSM, the magnetic circuit has been fully designed using the optimization from analytic and finite-element based software. For the IM6, a classical magnetic circuit coming from a traditional three-phase squirrel-cage low power induction machine has been used. The final design results are compared on the basis of the power-to-weight ratio.

***Keywords*: Permanent magnet synchronous machine - Induction machine - Fault tolerant design - Electrical power steering**

I. Introduction

The automotive industry today is faced with ever-increasing electrical power demands that are stretching the capabilities of present on-board power supplies. The use of electrical and electronic features to enhance customer comfort, convenience and safety, such as electronic automatic climate control, entertainment systems, antilock brakes (ABS) and traction control (TC) systems, contribute to exponential growth in power demand and also to size and complexity of the wiring harnesses as well [1]. Today's typical luxury class vehicle draws 1,200W to 1,500W of steady state power from the electrical system and has about 2.5km of wire in the harness with some 350 connectors and nearly 1500 cut leads [2]. The steady state electrical power needed in the years to come is estimated to be in the range of 3,000W to 7,000W [3].

Standardization of the electrical system is critical, especially when contemplating a system voltage increase. When the industry changed from 6V to 12V batteries in 1955, the change-over was accomplished within essentially two years [4]. Few major subsystems were impacted then, namely, generator, battery, ignition, lighting, horn, clock and cranking motor. Today, the number of affected subsystems is enormous by comparison. Changing the electrical system today will impact nearly all components, subsystems and systems. This is why automotive OEM's in North America, Europe and Asia are participating in the development of global standards for the next generation electrical system. The Consortium for Advanced Automotive Electrical/Electronic Components and Systems, organized and coordinated by MIT, now comprises some 39 companies with the goal of establishing the 42V PowerNet specification as the new voltage standard [1].

Even if this will make a revolution in embedded electrical machines technology, new types of actuators will be introduced in the near future. In this way, all-electric new systems eliminate the traditional pumps, hoses, hydraulic fluid, drive belt and pulley on the engine to significantly improve fuel economy. An example of these new systems is the electric power steering (EPS). It is mechanically simpler than a hydraulic system, meaning that it should be more reliable. One of the significant constraints of EPS system is the reliability. Indeed, it is not conceivable to imagine that the function provided by this device stops in the event of faults. The function must be maintained, even in a degraded way, in order to authorize the vehicle driver to confront this situation.

One of the most important originality of this paper is to set the problem of design for an EPS taking into account the fault tolerance. For PMSM, the fault tolerance will be concentrated on the power electronic converter. For the IM6, the focus will be more oriented towards the stator windings and the number of phases without increasing the complexity of the power electronic converter.

II. Design Specifications

The principal EPS systems proposed by industry for small and middle size vehicles are mounted on the pinion steering gear, eliminating parasitic losses normally associated with hydraulic power steering systems. Analyzing electrical actuators currently in existence, it can be found that for small and middle size vehicles, the maximum torque/speed characteristic for moto-reductor associated to the steering column corresponds with characteristic of figure 1.

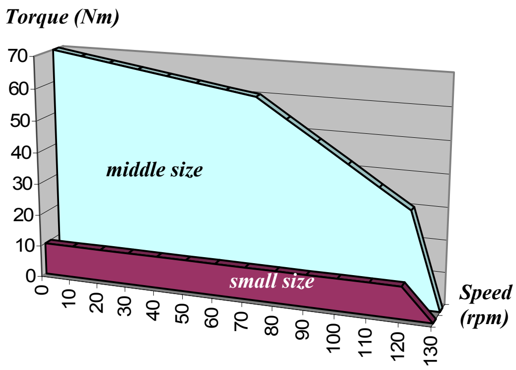


Fig.1. Proposed assistance torque/speed characteristic

Adopting a high-speed actuator to keep a low volume and simplicity for the windings even for 6-phase machine, its speed can be fixed at 3000rpm. PMSM is a 4 poles machine with a 100 Hz rated frequency and IM6 is a 2 poles machine with a 50 Hz rated frequency. The rated torque chosen is 0.3Nm to fit to small vehicles requirement with a reduction gear equal to 25. Of course, as it is an embedded vehicle system, a voltage source inverter (VSI) interfaces the different actuators with the 42V DC bus. Then, in order to perform a fault tolerant system, two AC machines have been proposed:

- a three-phase interior PMSM fed by a switch redundant VSI
- a IM6 fed by an original six switches VSI

The common design parameters are:

- Rated power : 90W
- Rated torque : 0.3Nm
- Rated speed : 3000rpm
- DC battery supply voltage : 42V

III. Three-Phase Interior Permanent Magnet Synchronous Machine (PMSM) Design

A. Inverter for PMSM

For this actuator, a possible converter topology is shown in the figure 2. In the case of destruction of a component, only the phase corresponding to the defect is disconnected [5]. So a faulty mode is possible with two active phases.

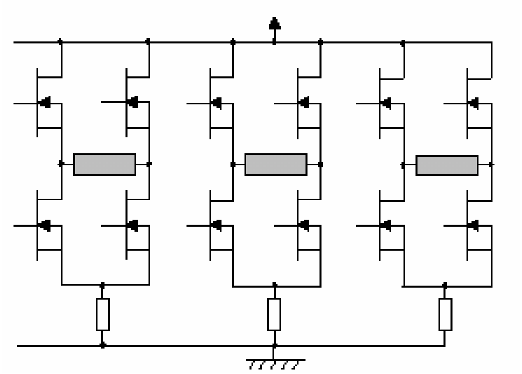


Fig.2. Three-phase VSI with redundant switches

B. Rotor structure

In this design, the objectives to be reached are the reduction of the volume and total weight as well as the reduction of the size of the magnets to decrease the cost [6]. An easiness of the manufacturing process must be kept in mind for a future industrial application. Other objectives as the dynamic behavior and the torque ripple will be examined in the fiture with the power electronic and control interactions.

Major investigations are realized in rotor structure so at this time the stator is a conventional one with distributed windings. Possibilities of stator improvement will be studied latter with solutions like fractional slotting for example.

There are many possibilities to install the magnets on the rotor [7], [8], which can be divided in two categories: the surface-magnet rotors (Fig.3.a and b) and the interior-magnet rotors (Fig.3.c and d). These last can be used easily for high speeds without additional can ring.

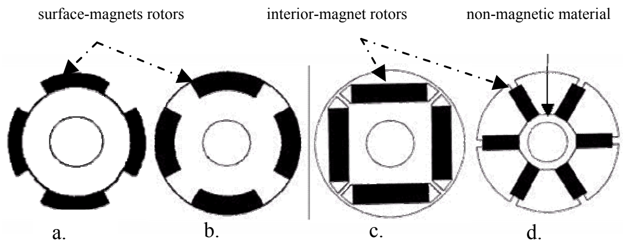


Fig.3. Different magnet layouts for PMSM

The structure shown in figure 3.c is the chosen one, it is particularly interesting because it has a good power-to-weight ratio as demanded in automotive applications [9]. This structure is also interesting for its capability to generate a quasi-sinusoidal back *emf*. On the contrary, the surface mounted magnets rotors are usually used to generate trapezoidal back *emf* for DC brushless motors. Figure 4 shows back *emf* shapes with associated sinusoidal and square-wave currents. AC brushless motor with sinusoidal back *emf* is more suitable to produce a smooth torque than a trapezoidal one [10].

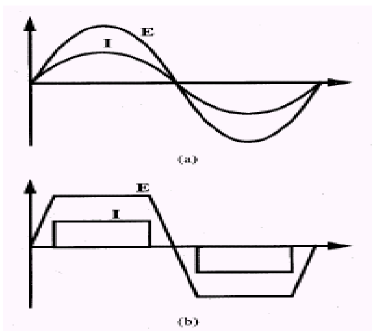


Fig.4. Back *emf* and current for AC (a) and DC (b) brushless

This structure can be improved to optimize the dimensions of magnetic circuit in order to create flux barriers, to avoid magnetic short-circuits and to draw the quadrature flux in the best way as shown figure 5.

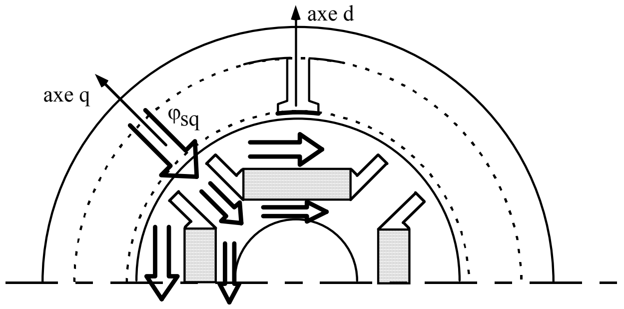


Fig.5. Rotor magnetic circuit improvement

C. Design procedure

Taking into account the important number of design variables, an optimization under constraints is chosen. Variables are classified into discrete and continuous one. If discrete variables are fixed (number of stator slots for example), a non-linear mathematic algorithm can be used to optimize the machine structure with geometrical constraints. A number of n optimization variables noted X are selected in order to find optimal values noted X* as shown below.

• **X*** minimizes an objective function f:

$$f(\mathbf{X}^*) = \mathrm{Min}_{\mathbf{X}} f(\mathbf{X})$$

•**X*** verifies the feasibility domain under constraints:

$$* \ h_i(\mathbf{X}^*) = 0$$
$$* \ g_j(\mathbf{X}^*) \geq 0$$
$$* \ Xl_i \leq X^*_i \leq Xu_i$$

X* must permit to reach the desired goal with the minimization criterion. It must also verify the equality and inequality constraints while keeping in the range of allowed values.

For example, if the magnet thickness has to be limited, it is necessary to choose:

$$\bullet\ \mathbf{X} : \begin{cases} \mathbf{X}g = \text{geometrical parameters} \\ \mathbf{X}f = \text{functional parameters} \end{cases}$$

• f(**X**) = magnet thickness
• g_1 (**X**) = external diameter ≤ D_max
• ...
• g_i(**X**) = desired torque ≥ T_{min}

The method is based on an analysis module and an optimization module. The analysis module uses the parametric model with the variables X to calculate the energetic values of the machine according to design specifications. The analysis module treats three domains (Fig.6).

The magnetic domain is the first and the central one because it is coupled with the two others. It allows the evaluation of inductance, *emf*. This brings to electromechanical performances. The thermal domain gives temperature of magnets and copper to estimate flux density and resistances. The electrical domain gives the relationship between the current reference and the real current according to the voltage limit.

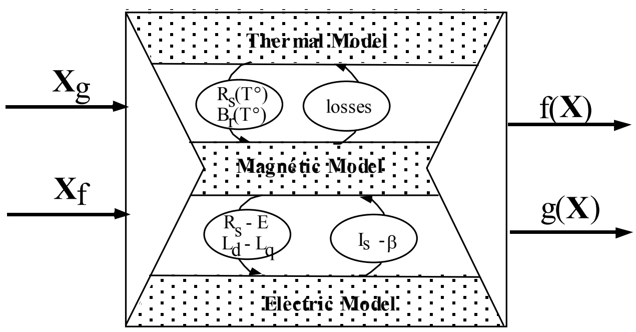


Fig.6. Coupled model

The optimization module manages the variables X on the basis of f(X) and g(X) information given by the analysis module. Figure 7 shows a quarter of the final machine design with all geometrical data obtained by the previous method.

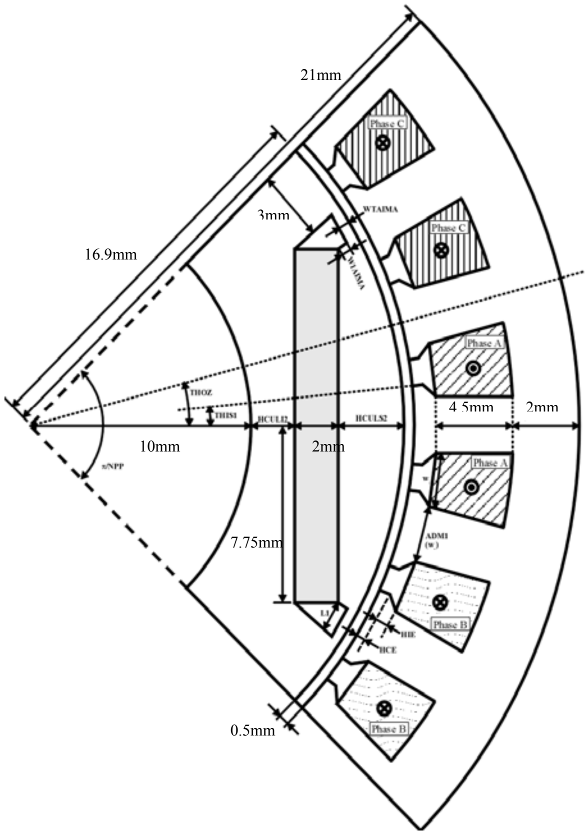


Fig.7. A quarter of PMSM final design

IV. SIX-PHASE INDUCTION MACHINE (IM6) DESIGN

Specific induction machines can be built with any number of phases on the stator. With more than three phases, they can be called high phase order machines. Among the advantages are lower current per phase for a given voltage rating, lower amplitude of torque pulsations and lower rotor I^2R loss for the harmonics when a voltage source inverter (VSI) is used and the ability of the motor to start and run with one phase open or more [11], [12].

The fundamental idea is to design an induction machine easy to build and very reliable for any EPS application. It is well known that this machine has to be fed by a voltage static inverter (VSI). Thus, it is necessary to minimize the number of the stator and the rotor slots, the number of power switches of the VSI and the number of stator phases of the machine. A traditional induction machine having three stator phases and six controlled switches is not suitable for the proposed application. Welchko and Lipo [13] published a new three-phase induction motor drive system using only three controlled switches. In fact, a structure of three phases and three controlled switches can satisfy the operating of a three-phase induction machine fed by a VSI (Fig.8). Despite of the unidirectional current, the stator neutral point permits the phase current to circulate and to generate an appropriate rotating air-gap flux.

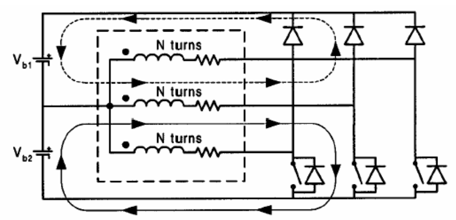


Fig.8. Three-phase VSI with minimum number of switches

The main drawback present in this structure resides on the fact that in case of opening one stator phase, the machine could not operate correctly. This fact penalizes a lot the application in term of reliability. On the other hand, this ideal implementation cannot be used with a passive DC link. A visual inspection of this circuit reveals that the upper DC link supply Vb1 does not have a discharge path. For all of the possible switching states, it is either inactive or absorbing energy from the motor. To solve this problem, the idea is to increase the number of phases of the machine in order to use a DC bus with a middle point

The proposed converter topology (Fig.9) allows the IM6 to be fed by unidirectional stator currents and sequenced such that a rotating air-gap flux is induced in order to perform a smooth machine operation.

Using a simple IM6, the drive system requires a symmetrically wound induction machine and a DC bus with a middle point. In particular, if one of the motor phases is lost, the IM6 allows the operation with an asymmetrical winding structure. For this machine, the minimum number of stator slots is 12 for 2 poles. This fact can make easy the IM6 design using a simple magnetic circuit already existing for low power 2-pole three-phase squirrel-cage induction machines.

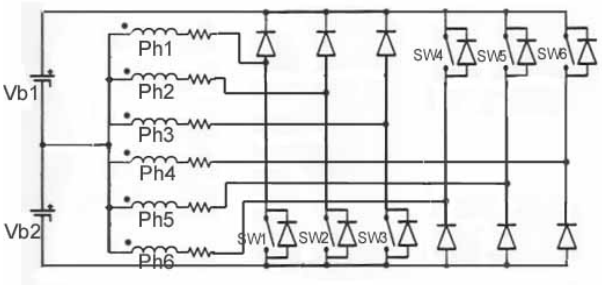
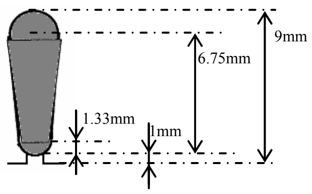


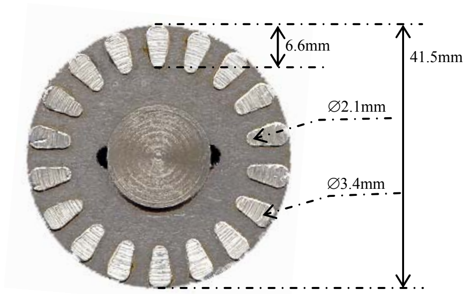
Fig.9. Six-phase VSI with minimum number of switches

A. Structure of IM6

A magnetic structure used before for a 90W-3000rpm three-phase squirrel-cage induction machine is adapted to the embedded application. The geometric characteristics for the stator and rotor magnetic circuit turn around 24 slots for the stator side and 18 slots for the rotor side (Fig.10). The stator internal diameter is 41.9mm, the rotor diameter is 41.5mm and the core length is 45.7mm. The air-gap of this machine is 0.2mm.



a.



b.

Fig.10. IM6 magnetic circuit design
a) Stator slot – b) Rotor slot

B. Design procedure

Then, the task for designing this machine is principally the scheme of the six-phase stator winding. Designing AC windings means assigning coils in the slots to various phases, establishing the direction of currents in coil sides and coil connections per phase and between phases, computing the number of turns for various coils and the sizing the conductor diameter.

The number of phases for a machine is assumed to be the same as the number of stator terminals excluding the neutral. However, giving number of phases is not always an adequate description. This is the case because for a given number of phases on a machine, two versions are possible based on the two possible values of the phase belt angle [11]. For example, almost all three-phase motors have 60° phase belts but three-phase motors are occasionally wound with 120° phase belts and they have some characteristics which are different from the 60° version.

Dealing with the phase angle, it is convenient to specify the number of phase belts per pole. The symbol q' will be used for this number and it is given by:

$$q' = \frac{180}{\beta} \quad (1)$$

where β is the phase belt in electrical degrees.

To design a six-phase machine, the phase belt angle β is 60°, the number of phase belts per pole q' is 3 and the minimum number of stator terminals is 6. Figure 11 shows the schematic diagram for a star-connected six-phase induction machine.

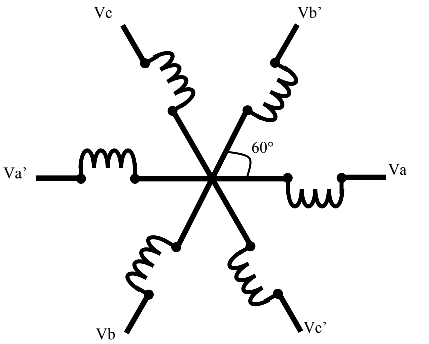


Fig.11. Schematic diagram of stator connections for an IM6

Using an original winding connection (Fig.12), it is possible to ensure a quasi-constant steady-state electromagnetic torque with a VSI and a DC bus voltage of 42V. For the proposed IM6 design, the phase belt angle β is 60°, the number of phase belts per pole q' is 3 and the number of stator terminals is 12.

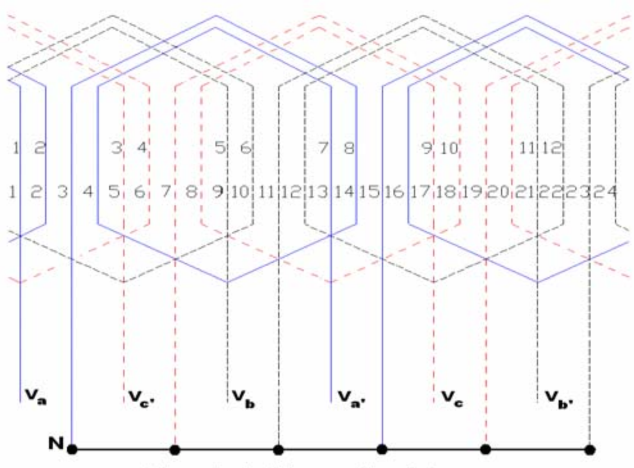


Fig.12. IM6 stator windings

In this stator winding, each phase is made of a single coil. The six phase are space shifted by 60° and the phase-shift is 60° between phase axes. For the 24 stator slots, 12 coils are present and that is two coils per phase to produce 2 poles. The phase a winding starts in slot 1 and continues in slots 17, 2 and 16. For the phases c', b, a', c and b', they are placed in different slots by moving 4/3 of a pole (4 slots pitches). All coils/phases are connected in series to form one current path.

Starting from these parameters, the total flux, the number of conductors per slot as well as the section of the wire can be computed using simple analytical formula [14].

The number of turns of each phases, the number of turns for various coils and the conductor sizing can be computed respectively by the expressions (2), (3) and (4). The total flux ϕ_t is computed using the characteristics of the three-phase induction machine.

$$N = \frac{0.97E}{n\phi_t k_d k_p f_d f_p} \quad (2)$$

$$a_s = \frac{P}{Em\eta\lambda q J_s} \quad (3)$$

$$N_c = \frac{2Nqm}{Nes} \quad (4)$$

$$B_g = \frac{\phi_t 10^6}{D_s l_c} \quad (5)$$

with:

N	number of turns in series of each phases
N_c	number of turns for the different coils
N_{es}	number of stator slots
a_s	conductor sizing (mm²)
P	rated power (W)
E	line voltage (V)
n	synchronous speed (rad/s)
B_g	magnetic field (T)
ϕ_t	total flux (mWb)
J_s	current density (A/mm²)
η	efficiency
m	number of phases
λ	power factor
q	number of slots per pole per phase
k_d	winding distribution factor
k_p	pitch factor
f_d	flux distribution factor
f_p	flux form factor
D_s	internal stator diameter (mm)
l_c	core length (mm)

The proposed design allows the IM6 a number of conductors per slot of 30 (60 per phase) for a single-layer winding and the section of the wire of 0.65mm². The efficiency η of this IM6 is 75% in theory for a current density J_s of 4A/mm² and 83% in simulation without taking into account the core losses.

V. Design comparison

The design parameters have permitted to reach the final performances for the two actuators with the same specifications. High torque to weight and torque to volume ratio are two interesting features which can be evaluated from the design procedure. They are very important in automotive applications where a saving of place and weight are always requested. The first criterion of comparison is the volume of the rotor. In fact, the outside dimensions for the two stators will be related to the condition of cooling as in most of the embedded electrical machines.

Table I

Design Comparison Of The Rotor Parameters

	Three-phase PMSM	**IM6**
External rotor diameter	33.9mm	41.5mm
Core length	40mm	47mm
Rotor volume	36.1cm^3	63.5cm^3

In table I, the main rotor dimensions are compared for the designed machines. The power-to-weight ratio can be deduced from Table I because the two machines have the same speed and magnetic material without significant weight density differences. It is clearly higher for the synchronous machine due to the presence of the high flux density magnets (NdFeB).

VI. Conclusion

Two different embedded AC actuators have been designed for a 42V DC bus application with the same torque and speed specifications. The results obtained in term of volume and power-to-weight ratio show an advantage for the PMSM compared to the IM6.

Nevertheless, other criteria like efficiency, cost of the sensors, power electronics and control circuits have to be compared. Indeed, in order to reach good performances in term of dynamic response the IM6 will use vector-control scheme and the PMSM will be associated with self-control technique. Then, the torque ripple should be less for the IM6 and the fault tolerance has to be carefully studied. These last criteria will be evaluated in the near future for these proposed embedded actuators applied to EPS.

VII. Acknowledgement

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