HYBRID ELECTRIC VEHICLES BASED ON SWITCHED RELUCTANCE MOTOR DRIVES

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Abstract: The necessity to improve the fuel economy of the cars and to decrease their emissions requires important changes in the conventional vehicle structure and philosophy. One of the most valuable solutions is the hybrid electric vehicle (HEV), which usually combines the internal combustion engine (ICE) of a conventional vehicle with the battery and electric motor of an electric car. In this paper, after a brief discussion of the basic structures and topologies of HEVs, two solutions for the vehicles' electric drive are presented: a vehicle with ICE and integrated starter/generator (ISG) and a "mild" HEV, both based on switched reluctance motor (SRM) electric drive. A section of the paper is dedicated to the SRM's design via 2D FEM magnetic field analysis.

1. INTORDUCTION

HEVs combine the ICE of a conventional vehicle with the battery and electric motor of an electric vehicle. This combination offers the extended speed range and rapid refuelling that consumers expect from a conventional vehicle, with a significant portion of the energy and environmental benefits of an electric vehicle. The practical benefits of HEVs include improved fuel economy and lower emissions, compared to conventional vehicles. The inherent flexibility of HEVs will allow them to be used in a wide range of applications from personal and public transportation to commercial hauling.

Many configurations are possible for HEVs. Essentially, a HEV combines an energy storage system, a power unit, an electric motor and a vehicle propulsion system. The primary options for energy storage are batteries, but also other possibilities are being studied. HEV power units are typically ICEs similar to those employed in conventional vehicles. Other "power plant" options for hybrids include gas turbines and fuel cells [1].

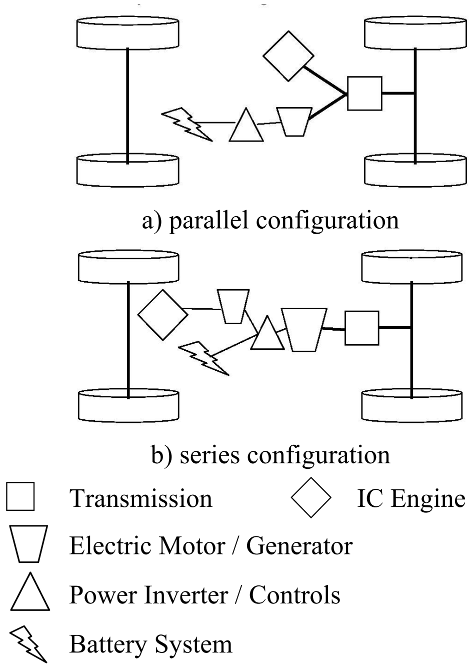


Fig. 1. HEV configurations

There are two main system types of propulsion, which define the two main branches of hybrid-electric technology:

i) The parallel configuration, in which the role of the engine is to provide direct mechanical input to drive the vehicle in parallel with the electric motor, and also to charge the battery, Fig. 1a.
ii) The series configuration, in which the propulsion comes solely from an electric motor. In this case the engine is used to continually repower the battery, Fig. 1b.

As shown in Fig. 1a, an HEV with a parallel configuration has a direct mechanical connection between the ICE and the wheels through a transmission, as in a conventional vehicle. The parallel concept uses an electric motor to drive the transmission as an alternative to the ICE.

As illustrated in Fig. 1b, an HEV with a series configuration uses the ICE as a source of power to a generator, which in turn, supplies electricity for the battery pack.

Series HEVs have no mechanical connection between the ICE and the wheels; therefore, all the energy is transferred directly to the electric motors that drive the wheels.

There are really four main categories of HEVs:

i) 42V ISG systems with engine stop/start and regenerative breaking which doesn't look as a true HEV;
ii) "Mild" HEVs that in addition include the ability for the electric motor/generator to truly act as a traction motor in parallel hybrid mode, but that do not allow for all electric operation;
iii) "Full" HEVs that also include the capability for electric launch and may include some zero emission vehicle (ZEV) range;
iv) True HEVs that like battery electric vehicles (EVs) and fuel cells vehicles (FCVs) have a full-sized electric motor and only use the ICE to recharge the battery pack.

The 42 V ISG systems have relatively little in common with FCV systems due to their relatively low voltage and the fact that the motors and motor controllers used for these small low voltage systems are rather different than the higher-voltage systems for HEVs with larger traction motors.

Regenerative braking systems may be the main connection between these vehicles and FCVs. The relatively "mild" hybrids will tend to use similar motor/controller systems as will the FCVs.

Next, the "full" HEVs with larger motors and full electric launch capability have electric-drive systems that are even closer to those likely to be used in FCVs, again due to the larger electric drive system and the higher system voltages that are likely to be used [2].

At present, there are three primary choices of motor technology for use in EV drivetrains: alternating current (AC) induction, brushless permanent magnet (BPM) and switched reluctance motors, which is a third, but much less used option. All these options offer significant advantages over conventional direct-current (DC) brush motors.

These include lighter motor weights, higher efficiencies, and lower service requirements. In general, AC induction motors provide high efficiencies over a wide range of operation, while BPM motors provide higher peak efficiencies. BPM motors also tend to be lighter, but they use rare earth magnets that are somewhat costly at present [3].

Both AC motors, induction and BPM, require quite complicated supply and control system that allows them to operate from a DC source, which is the battery or the fuel cell (FC).

The SRM, even if has not so good performances as the others motors, is cheaper and requires an uncomplicated supply and control system. It operates as well as generator and therefore constitutes a valid alternative for the HEVs' drivetrains.

In the paper, after a brief presentation of the SRM, the motor that was chosen, first an ISG system with SRM will be presented.

Finally the solution with a SRM will be developed for a "mild" HEV.

In the latest case a test bench model is under developing, some data and design details of the SRM being given, too.

2. THE SWITCHED RELUCTANCE MOTOR DRIVE

The switched reluctance machine is a double salient machine with a passive rotor. In the switched reluctance motor (SRM), the torque is produced by the tendency of its rotor to reach a position where the inductance and the flux produced by the energized stator winding are maximized. SRM's rotor and stator both have salient poles. The stator winding consists of coils placed on the stator poles, usually one coil on each pole. An excitation phase comprises two poles' coils connected in series, usually two opposite poles, but other connections are also possible. Each phase is independent and the excitation represents a sequence of voltage/current pulses applied to each phase in turn.

The SRM is among the simplest rotating electric machines and, due to the latest improvements of the motor design and control; it is a very valuable option for variable speed drives. The SRM has several attractive features, such as high output power, high starting torque, wide speed range, and rugged and robust construction and low manufacturing costs. The SRM has some notable weaknesses too, such as variation of the phase induction with rotor position, torque ripples and the need of accurate rotor position detection [4].

The SRM construction is simple, particularly the rotor. Fig. 2 shows a basic view of a SRM: the stator and rotor iron cores and one phase winding consisting of two coils placed on the opposite poles [5].

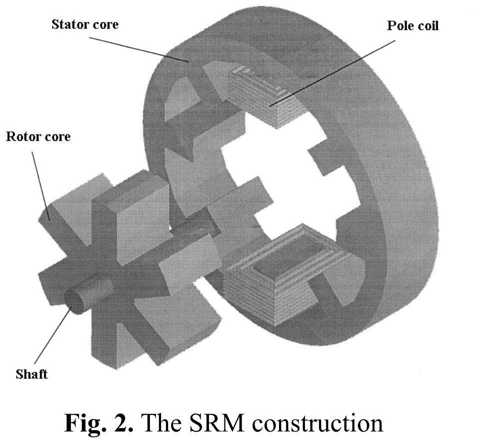


Fig. 2. The SRM construction

The torque developed by a phase in which current flows tends to move the rotor in such a direction as to increase the phase inductance, towards the nearest aligned position. This means that the motoring torque can be produced only in the direction of the rising inductance. The motor and generator operating mode period of the SRM, function of the rotor position, and also the phase inductance variation, are shown in Fig 3.

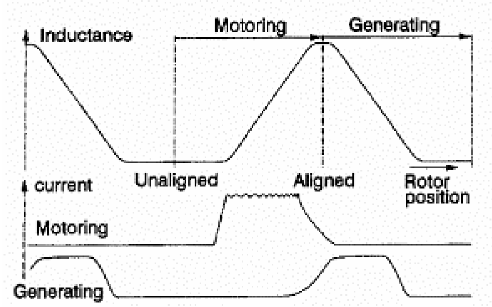


Fig. 3. Motor and generator operating mode period of SRM

The SRM uses a rotor position sensor to provide precise knowledge of the rotor position. The supply device is usually a classical 3-phase single-rail circuit with two transistors per phase, suitable for use with a 6- or 12-pole stator.

A variant of the supply circuit for a three phase SR starter/generator is given in Fig 4.

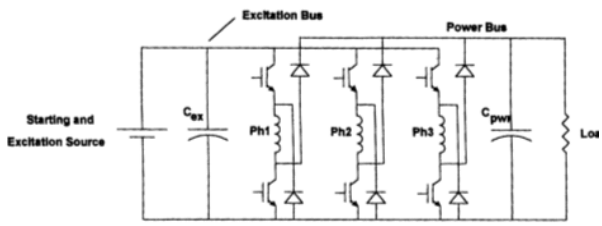


Fig. 4. SR starter/generator's power electronic converter

Due to the fact that the SRM's supply electronic converter is specific and quite simple, it can be built easier with more than three phases. Therefore, in order to use the well-known advantages of increased phase and consequently pole number, many SRMs with more than three phases were developed and used in different applications.

The SRM motoring and generating operation mode can be explained better by using computer simulation characteristics, Fig. 5.

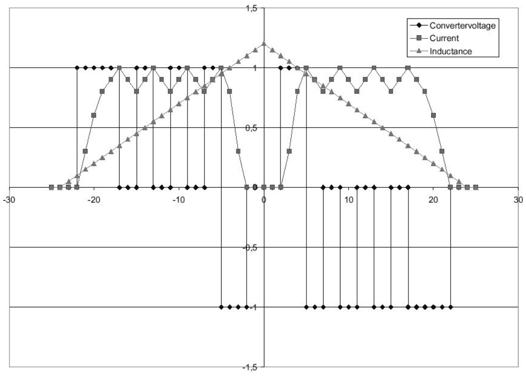


Fig. 5. SRM phase operating period

Since in the case of SRM the phase can be considered decoupled and only one phase and its asymmetrical half-bridge converter is considered. As seen from Fig. 5 in the first part of the considered period, the inductance value increases and the machine provides positive torque operating as motor. When the inductance decreases, in the second part of the phase electrical period the machine works as a generator. At the beginning of the generator-operating mode the SRM phase has to be magnetised by using the source energy, Figs. 4. and 5. The control of the converter is different for generator and for motor operating mode.

3. SWITCHED RELUCTANCE (SR) STARTER/GENERATOR

As shown above the SR machine can be a starter/generator having quite good performances. Such a task was proposed and fulfilled by building a four phase 16/12 poles SRM, Fig. 6 [6].

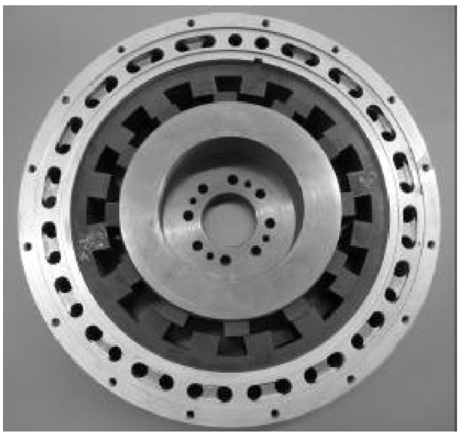
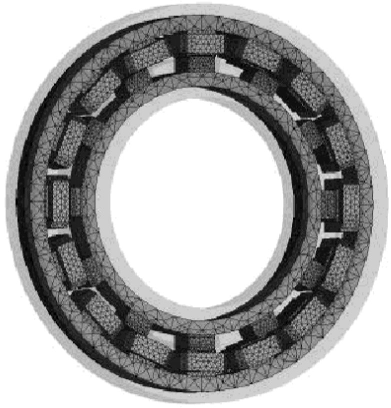


Fig. 6. The 16/12 SR starter/generator

Many solutions were analyzed, considering variants of SRMs with different number of poles and the best performance, in the imposed frame and operating conditions. The best solution was found to be the 16/12 poles variant. In the design stage a 3D-FEM analysis was carried out. The machine structure, respectively the torque variation function of rotor angular position are given in Fig. 7a and respectively Fig. 7b.



a) SRM structure with 3D mesh

b) Torque versus rotor angular position

Fig. 7. SRM with 16/12 poles

As it can be seen the minimum torque is 250 Nm and the average torque is about 320 Nm, values that fully cover the drive system's requirements [7].

The laboratory prototype four-phase asymmetrical converter is presented in Fig. 8.

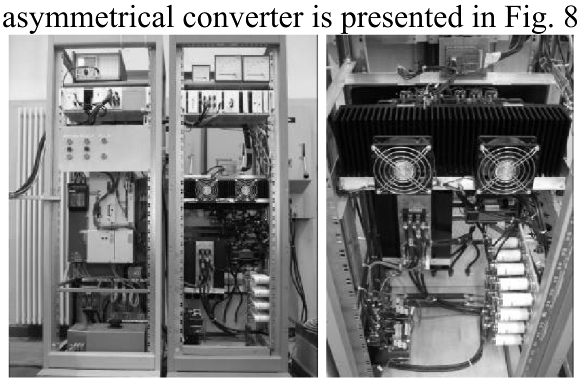


Fig. 8. General view and a detail of the prototype converter

The results obtained on the test bench and with the car engine equipped with this crankshaft starter-alternator were very promising.

4. MILD HEV VARIANT WITH SRM

Mild HEV have significant regenerative braking and the electric motor may assist the vehicle's launch, but does not allow all electric operation. The peak power of the electrical system is typically less than 23 percent of the total ICE power. The fuel economy archived for such a system, compared with a conventional ICE vehicle, is up to 15 percent. It means that such a system has more performance than a simply ISG system. It has quite the same structure, but the electric machine power is a bit larger and the control is different.

The SRM is a possible variant for the electric motor/generator of a mild HEV due to its advantages. A very important one, which was not evinced above, is the fact that SRM is a very good fault tolerant device, besides that it has a large starting torque. Since it is impossible, for the moment, to build up a mild HEV with the proposed SRM drive, it is intended to test the solution on a test bench, which will model the system. The SRM to be used in this model is obtained from an induction motor, 5.5 kW, p=2. The stator and rotor sheets have no slots and teeth but poles, 6 on the stator and 4 on the rotor. Since the stator and rotor yoke remains unchanged the stator pole width was quite imposed, as was the stack length. The structure of the 6/4 poles SRM is given in Fig. 9, with two poles in aligned position.

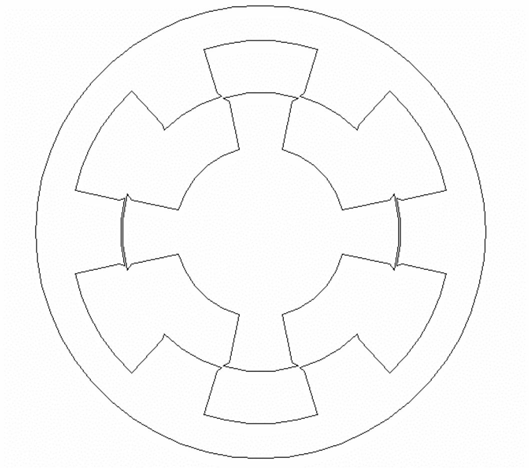


Fig. 9. SRM's cross section

In order to calculate the excitation MMF and to have the data for the asymmetric bridge supply converter, a 2D-FEM analysis was carried out for different values of the phase ampere-turns. A zoom of the built up mesh for 2D-FEM analysis is shown in Fig. 10. The field lines with the rotor pole-axis in the stator d-axis (aligned position) respectively q-axis are presented in Fig. 11.

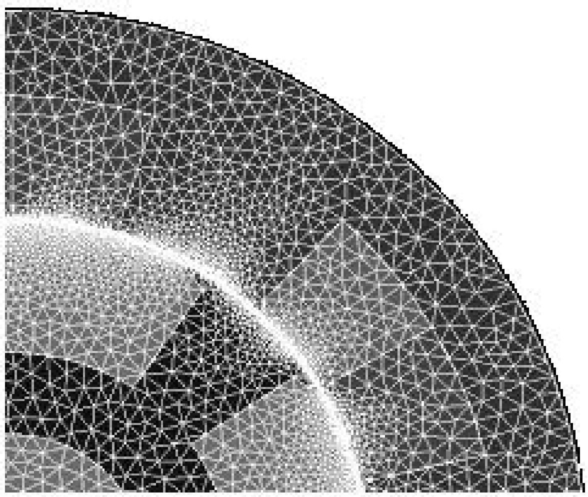
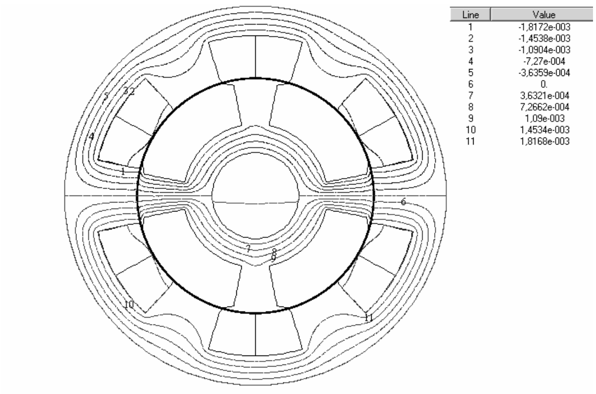
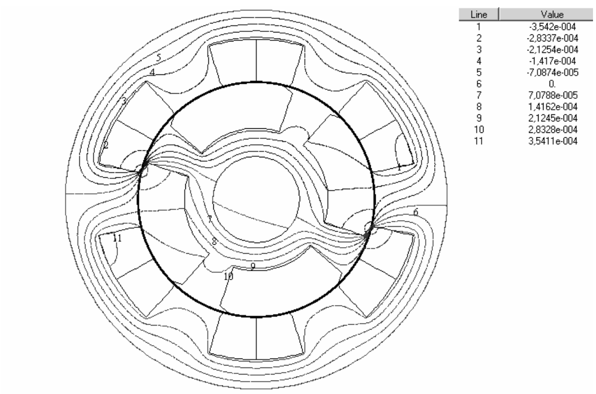


Fig. 10. A zoom of the 2D-FEM mesh



a) Aligned position



b) Rotor pole axis in the stator q-axis

Fig. 11. Field lines

The air gap flux density variation over a stator pole pitch is given in Fig. 12 for the unaligned (Fig.11b), respectively aligned position (Fig.11a). In Fig. 13 the torque variation function of rotor position is shown. The maximum torque is about 10 Nm for the considered excitation MMF value that is 40A.

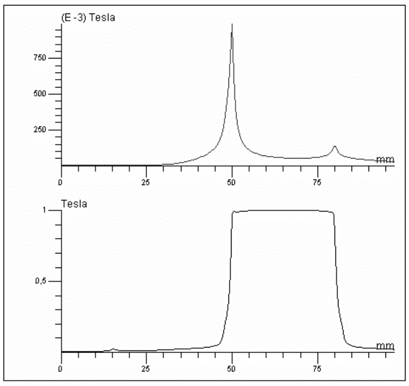


Fig. 12. Air gap flux density versus rotor position

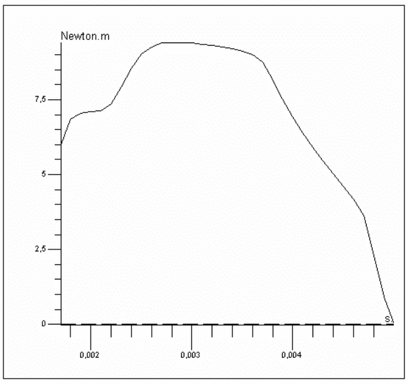


Fig. 13. Torque versus rotor position

All these results are promising and encourage the researchers to continue their work in this field.

5. CONCLUSIONS

The different types of the hybrid electric vehicles are real competitors of the classical ICE driven cars. Therefore researches done in this field may be of real interest for the huge number of scientists working in this interdisciplinary field.

Switched reluctance machines can be successfully used in such types of cars.

Two examples were illustrated in this paper.

A 16/12 poles SRM to be used as integrated starter/generator and another, of 6/4 poles type, for the electric motor/generator of a mild HEV.

As all the obtained results show the analysed SRMs meets all the requirements for the proposed application.

6. ACKNOWLEDGEMENTS

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