INTEGRATED STARTER-GENERATORS FOR AUTOMOTIVE APPLICATIONS

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Abstract – **The integrated starter-generator (ISG) replaces both the conventional starter and alternator (generator) of an automobile in a single electric device. It allows greater electrical generation capacity and the fuel economy and emissions benefits of hybrid electric automotive propulsion. The ISG requires contrary specifications, i.e. a high starting torque and a field-weakening capability in a wide speed range, therefore its design is a challenging job. In this paper the basic characteristics and some of the ISG variants will be discussed. Also a switched reluctance machine (SRM) based ISG prototype will be presented in detail.**

1. Introduction

In the last decades the automotive industry has been investigating alternatives to conventional internal combustion engine powered vehicles in order to improve their fuel efficiency and to reduce their greenhouse gas emissions. In 2002 automotive manufacturers have announced plans to improve passenger vehicle fuel economy with 25% or more by year 2005. Fuel economy improvement levels beyond current mandates are likely to be legislated during the next five years in North America. In Europe and Asia the mandates for reduced CO_2 emissions are already coming into effect.

This challenge of fuel economy standards is promoting optimised and sometimes novel vehicle powertrain architectures, that combine the traditional internal combustion engine (ICE) with various forms of electric drives. The different types of the hybrid electric vehicles (HEV) are real competitors of the classical ICE driven cars. Today hybridised power trains are already commercially available. In such type of cars hybrid spin-off applications, such as the integrated starter-generator (ISG) are emerging with benefits to hybrid electric vehicles, but with little or no cost/performance penalties.

The ISG replaces the conventional starter motor and the alternator (generator). It provides, beside its two basic functions (starter and alternator), an auxiliary one, as a convenient automatic vehicle start-stop system for further improved fuel efficiency. The electronic control system switches off the ICE at zero load (such as when standing at a traffic light) and automatically restarts it using the ISG very rapidly when the gas pedal is pressed. The IEC is accelerated to the required cranking speed (idle speed) and only then the combustion process for instant ignition is initiated. During braking the ISG can convert the vehicle's kinetic energy into electrical energy, and then feed this power back into the electrical system.

As it fully supports the stop-and-start operation, electric drive-off and acceleration and recycling of braking energy the ISG helps to reduce both fuel consumption and emissions.

This paper presents different constructing variants, the advantages and benefits of the ISG. A part of the paper deals with the comparison of different electrical machine types that could be used for ISG applications, mentioning also some typical commercial available units. In the final part of the paper a switched reluctance machine (SRM) for ISG application will be presented, which was designed, built up and tested at RTWH Aachen (Germany).

2. The hybrid electric vehicle

One of the aims of the automotive industry is a more efficient use of energy in a vehicle. HEVs are potential candidates to reduce both consumption and emissions.

Hybrid powertrains use a conventional ICE in combination with an electric motor, a battery, and an electronic controller.

HEVs have two basic configurations: series and parallel hybrids (see Fig. 1).

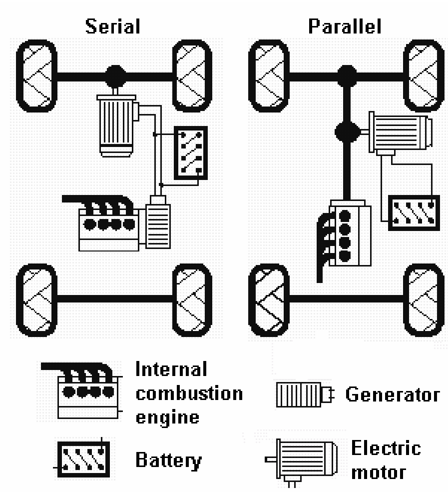

Fig . 1. The basic configurations of HEVs

In the series variant, the ICE is used to drive an alternator to generate electricity, which is then stored in a battery system or sent directly to the electric motor, which powers the wheels. The engine is not supplying power directly to the wheels. The efficiency of the engine is maximised because it operates within a narrow range of speeds.

The parallel hybrid has two power paths, so that either the IEC or the electric motor (or both) can be used to power the wheels directly. Like the series configuration it can operate in zero-emission mode (power supplied solely via the electric motor). At cruising speeds the IEC is usually the sole power source, but under high loads (during acceleration and hill climbing) both the ICE and electric motor will operate together, with the electric motor boosting the low-speed torque of the ICE helping to save 10 to 15% in fuel costs [1]. While the parallel configuration may not match the efficiency of a series hybrid system, its generally higher power output is better matched to the practical demands of everyday motoring [2].

As the electric motor and the battery provide additional power to the ICE, the fuel consumption is reduced without affecting power output. To further save fuel, the engine automatically stops when the vehicle comes to a stop, and starts again automatically when the accelerator is depressed. The battery is recharged using the energy captured during regenerative braking, relieving the IEC of doing all that work, and saving more fuel. A hybrid powertrain is completely self-sufficient, it doesn't need to be plugged in and charged up overnight.

The first mass-produced hybrid passenger vehicle in the world, the Toyota Prius, is running on the roads since 1998. Its advanced new powertrain system achieves nearly twice the fuel efficiency of conventional gasoline engines [3].

Another, simplified version of the hybrid powertrains is the so-called "mild hybrid", which has an ISG instead of an electric propulsion motor. The ISG cannot actually move the car, but it can assist its propulsion and recover energy through regenerative braking. This HEV variant is also capable of efficient heavy-duty towing.

The mild hybrid cars are basically operated in a same manner as the full hybrids.

Unlike a full hybrid, a mild hybrid has a much smaller battery than a full hybrid and cannot run on battery power alone.

A typical mild hybrid vehicle system's configuration is given in Fig. 2.

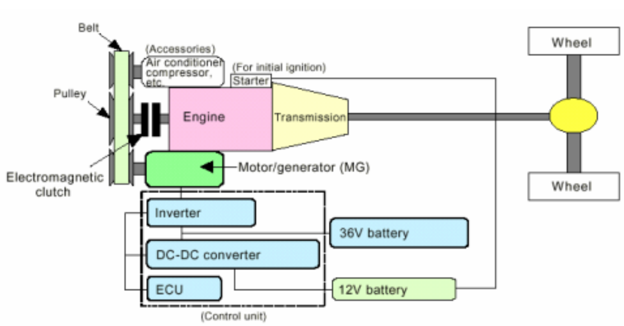

Fig . 2. Mild hybrid vehicle system

One of the most notable advantages of the mild HEV system is its relatively low cost compared to the full HEV system. Clearly, a less expensive hybrid system is more likely to appeal to a greater number of mainstream consumers than would more robust and more expensive hybrid systems, at least in the initial phases of market development. As consumers gain a greater understanding of the differences in hybrid technologies, they will be better able to match their need for increased fuel mileage with the most cost-effective system [4].

3. The integrated starter-generator

The electronically controlled integrated starter-generator (ISG), as its name implies, replaces both the conventional starter and alternator (generator) in a single electric device.

The reasons to combine starter and alternator in a single machine of increased power rating are:

- A desire to eliminate the starter which is only a passive component during engine operation.
- A need to replace the present belt and pulley coupling between the alternator and the crankshaft.
- A need to provide fast control of generator voltage during load dumps in order to improve the distributed power quality.
- A desire to eliminate the slip rings and the brushes in some present wound rotor alternators.

The ISG acts as a bi-directional power converter, changing mechanical energy into electrical energy and vice versa. Functioning as an electric motor, it starts the ICE almost soundlessly and considerably faster than any conventional starter. As a generator, it produces power for the lights, the air-conditioning system, the radio and all other electrical consumers in the car, but with higher efficiency than previous systems.

In several other cases the ISG is sandwiched between the engine and transmission (see Fig. 3).

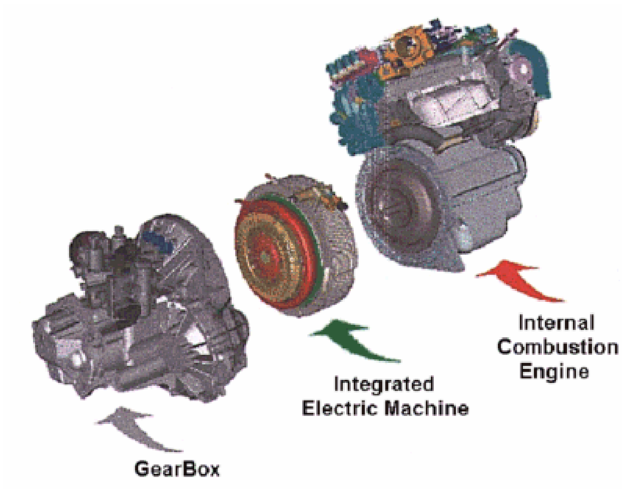

Fig . 3. A possible place of the ISG in a HEV powertrian

The ISG has three important functions: start-stop, electricity generation and power assistance.

The ISG allows the ICE to turn off and conserve energy (and to save fuel) at stops and instantly restart upon pressing of the gas pedal. Thus instead of continuing to use fuel at idling speed, for instance when waiting at a traffic light, the engine of a car with ISG switches off completely when the car is no longer in motion. When the traffic light turns green and the driver presses the accelerator to move off, the ISG car starts up almost instantly.

In this "engine cranking" mode the ISG can provide sufficient rotation using battery power to drive the ICE to the maximum starting speed. Once that speed is exceeded, the ISG drive power is turned off. The vehicle driver, however, will not notice any difference because the ISG system will restart the ICE independently.

The ISG can generate electric energy to be stored in the battery taking mechanical energy from the spinning crankshaft of the vehicle (running power generation mode).

In addition the ISG can also act as a retarding force for the crankshaft and to regenerate and feed back into the battery free electric energy when braking the car (recuperative braking), both when releasing the accelerator and when pressing the brake pedal (braking power generation mode).

In the boost-mode the ISG can be used to support the ICE by supplying additional power for fast acceleration. ISG remains active throughout the driving process, for example during overtaking or at other times when extra power is needed.

The ISG has a lot of advantages [5]:

- As the ICE is combined with an electric motor system and the ISG system augment power of existing engines by providing electric "motor assist", or enabling a "start-stop" feature a smaller ICE can be used without reducing performance.
- Its start-stop and the recuperative braking capability, respectively its higher voltage and increased size makes the ISG more efficient than a conventional generator, resulting in up to 20% reduced overall fuel consumption.
- Because using ISG no fuel enrichment is necessary to start the ICE lower start emissions can be achieved, especially during the cold start period.
- With the ISG the engine shuts off instead of idling. For the user who drives a lot in urban traffic, there is clear evidence this environmental benefit. The ICE simply is not used when the car is not moving.
- It can achieve noise and vibration reduced operation improving comfort.
- The components of the ISG system are not subject to wear and tear and are maintenance-free because of the system’s brushless design.
- The ISG has the ability to perform torque smoothing of the driveline. By applying an adequate damping control algorithm also powertrain oscillations and noises can be neutralised.
- ISG can be integrated with most of actual car models, therefore is no need to develop a new car model or significantly modify an existing car. Thus it is very cost-efficient system.
- As the cold starting requirements have a great influence on the design of any ISG it can start the ICE also under extremely low temperature conditions.

The main breakpoint of the ISGs is that they require specialised power systems.

The design of an ISG is a great challenge for professionals because the ISG drive's requirements are quite severe:

- High starting torque at most unfavourable operating conditions.
- Wide speed range in generator mode.
- High efficiency in wide speed range (600÷8000 rpm).
- Vibrations of up to 20 g in crankshaft mounted systems.
- Cycle life over 250 000 stop/start cycles in 10 years.
- Temperature: -30°C to 115°C ambient, +180°C under the hood.
- Good serviceability, high reliability, acceptable cost, etc.

Two types of ISG are currently being used: the belt driven (Fig. 2) and that directly connected to the crankshaft between the engine and the gearbox (Fig. 3). The two ISG types compared with the classical separate starter and generator solution are given in Fig. 4. As it can be seen the crankshaft ISG is mounted behind the engine, where the clutch or torque converter previously sat alone. This avoids the cost and complexity of the belt driven construction, but needs considerable additional weight of copper and iron of the crankshaft ISG.

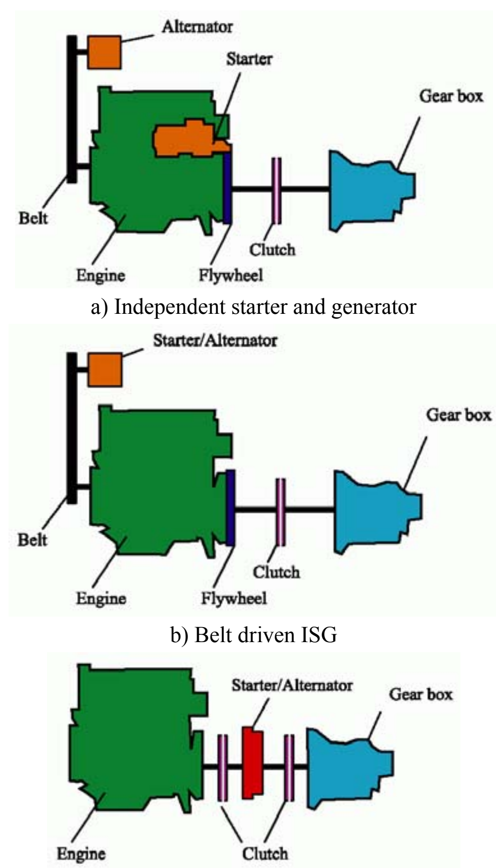

Fig . 4. Starter and generator constructions

4. ISG variants

According to the requirements of the ICE and the vehicle's electrical system different types of electrical machines may come into operation as an ISG: induction (IM), permanent magnet synchronous (PMSM), brushless dc (BDCM), and variable reluctance (VRM) machines [6, 7, 8].
The IM and the PMSM are between the main competitors at this time, but other special electrical machines must also to be considered in the future.
The IM is a robust machine of low costs. On the other hand it has several drawbacks as cooling problems, limited efficiency, small air-gap, expensive stator windings, complex control system, etc.
One of the most representative ISG products based on IM is the Integrated Starter Alternator Damper (ISAD) system of Continental Automotive Systems. Beside the general ISG features this product in addition can neutralise powertrain oscillations and noise, enhancing this way riding comfort.
The PMSM has compact construction and can be designed with a larger air-gap than machines with no excitation within the rotor, which is quite important in the case of crankshaft mounted ISG. In addition good efficiency at generator operation can be obtained. The main negative aspects are due to the costly permanent magnets and to the stator winding. According to the position directly at the ICE the magnets are exposed to high temperatures. With the engine running this kind of ISG cannot be switched off electrically and even at low speed field weakening has to be realised [9].
The Sachs' DynaStart crankshaft ISG is based on a special external rotor PMSM delivering enlarged tangential force on the surface and accordingly producing enlarged torque. Its design features include a large air gap of 1 to 1.5 mm, field excitation by NdFeB magnets, a high number of pole pairs, and a simple single-tooth winding. This ISG meets all the specific requirements including good field-weakening range up to ≈ 1:40, low battery current of 100÷300 A for starting, efficiency of over 85%, and small electronic control unit with 300÷600 A phase currents.
The brushless dc machine has constant torque and constant power operation with field weakening up to high speeds due to reluctance torque. It has larger torque for the same peak current and voltage as its competitors. Low inertia, no maintenance, and no heat producing components on the rotor are also attractive benefits when used for ISG. The main drawbacks are due to the PM: high costs, magnet corrosion and demagnetisation. This type of motor needs to be rated for higher power than IM for the same speed range and higher stator current over the field weakening region. Honda uses such machines in its advanced integrated motor assist (IMA) systems installed in small passenger cars.
Machines based on the principle of variable reluctance offer a cheap and robust alternative to conventional polyphase machines. Reluctance machines have salient poles within the rotor and the stator. Therefore the inductance of the direct axis differs from that of the quadrature axis. The torque is developed due to the principle of the minimisation of the energy stored within the air-gap. The rotor has no excitation and is magnetised by the stator. Even at high speed the machine can be switched off electrically. High temperatures surrounding the machine have less or no effect [10].
An ISG developed using a SRM will be discussed in the next section.
The use of transverse flux machines (TFM) for ISG are now also under investigations by our research team due to their high torque and power density (of 20÷60 Nm/kg, respectively 0.5÷1.3 kW/kg) compared with that of the other machines in discussion (4÷5 Nm/kg, respectively 0.1÷1.5 kW/kg) [11].

5. An ISG prototype

A switched reluctance machine (SRM) for ISG application was designed, built up and tested at RTWH Aachen (Germany) [12].
The SRM was designed according to the imposed outer dimensions and the performance. Due to its short axial length three-dimensional (3D) finite element (FEM) computations were performed. The flux distribution was computed at each position of the rotor. Using the Maxwell stress tensor method the torque was predicted. Upon the static investigation it was concluded that a higher number of stator teeth increases the available starting torque, but nevertheless increases the inductance of the phases of the machine, too. Dynamic simulations were necessary to depict the behaviour of the entire system and to choose the optimal motor structure to build up. The best results were obtained for a 16/12 poles SRM [12].
Next some of the results obtained for the SRM based ISG will be presented.
The motor's structure can be seen from its 3D FEM model shown in Fig. 5.

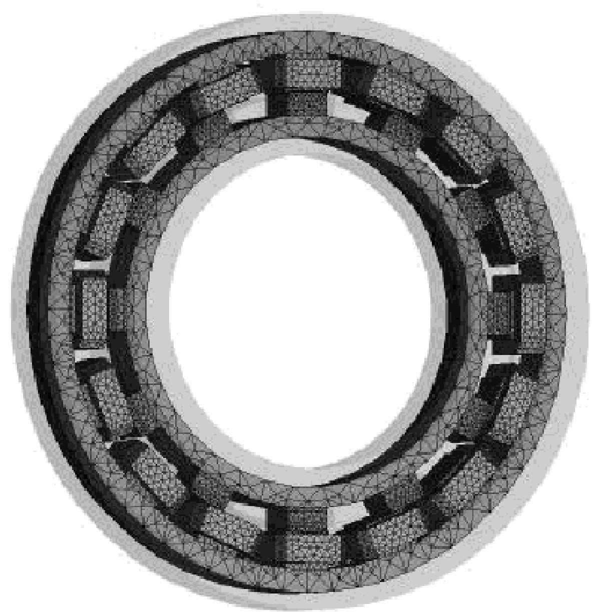

Fig . 5. The structure of the 16/12 SRM

Due to the small winding overhang and the resulting copper space factor this implementation competes favourable for short machines. The starting torque reaches up to 300 Nm.

The picture of the ISG prototype's stator is given in Fig. 6.

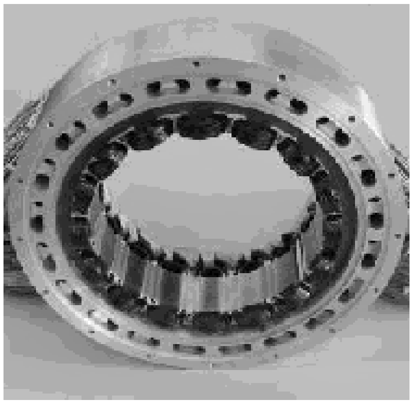

Fig . 6. The prototype's stator [13]

As the control of the designed ISG concerns the power converter of such type of machine requires a single rectifier for each phase. To be able to realise both the functions of a starter and alternator the converter has to be able to provide full operation within all the four quadrants by controlling each phase independently.

Hence the machine is fed with only unidirectional currents a reduced structure of the well-known full H-bridge converter can be applied, the asymmetrical halfbridge converter shown in Fig 7.

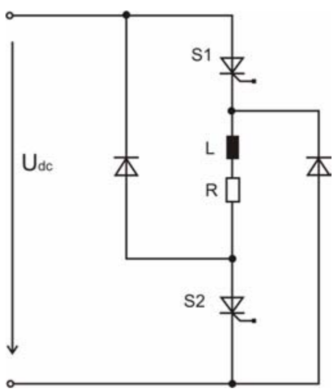

Fig . 7. A phase of the converter

All the phases of the machine are connected parallel to the same DC-link. The DC-link is fed, according to the new 42 V standardisation by a 36 V onboard battery. The phases of the machine are excited according to the position and the load. The torque only depends on the absolute value of the current and the position of the rotor. In regard to the costs: the number of semiconductor devices is reduced by half, but being a four-phase machine the costs of its power inverter is slightly higher than of those used for three-phase machines.

For motor operation the SRM has a speed control system. In contrast to rotating-field machines, torque development in reluctance machines is independent of the direction of the currents through the windings. Due to the fact that the reluctance force is always an attracting force, the only decisive factors to control the machine are the relative position of the rotor and the amplitude of the current.

The maximum achievable speed depends on the number of stator pole windings (Fig. 8). A higher number of stator pole turns reduces the absolute value of the current, but also lowers the achievable speed. A lower number of turns reduces the inductance of the phase and therefore increases the maximum speed. Thereby the absolute value of the current is increased.

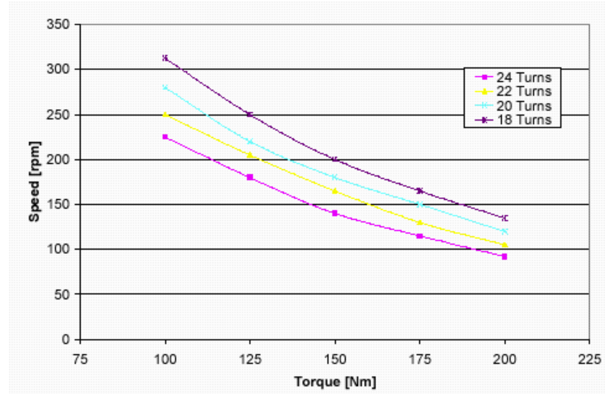

Fig . 8. The motor operation of the 16/12 SRM

Generator operation of a reluctance machine differs from generator operation of rotating-field or DC machines. According to the position of the rotor one phase of the reluctance machine has to be magnetised at the beginning of each electrical period. With the stator and the rotor teeth aligned to each other the converter applies positive dc-link voltage to the phase. The current within the phase rises until it reaches the upper level of the tolerance band. At this point a further increment of the current is limited by negative dc-link voltage; the machine works as a generator. The current is reduced until it reaches the lower limit of the tolerance band. Zero voltage is applied to the phase and due to the declining inductance of the phase the current rises again. At the end of the electrical period the phase is de-magnetised using negative dc-link voltage.

Using the ideal parameters of the power inverter, obtained via a genetic algorithm, the electrical power output of the SRM has been calculated. Fig. 9 displays the output power of the 16/12 SRM at different speeds and numbers of stator windings.

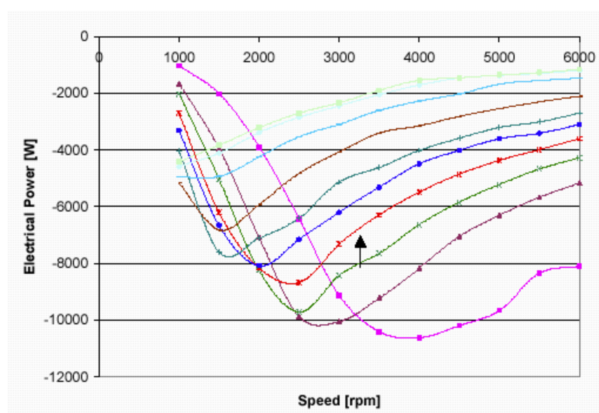

Fig . 9. The generator operation of the 16/12 SRM

With lower numbers of turns per phase of the stator winding the maximum power output raises but also tenders to higher speeds. At lower speeds this configuration provides little energy output. In contrast higher number of turns of stator pole winding provide good performance at low speed, but are not suitable for operation at medium or higher speed. The best choice is marked with an arrow. This configuration combines

high power output at medium speed and also good performance at low and high speed [10].
The prototype of the 16/12 SRM based ISG was tested on a special test bench built up for this purpose at RTWH Aachen. From the numerous experimental results here only two figures will be presented [13]. First the four phase currents and the speed are given in Fig. 10.

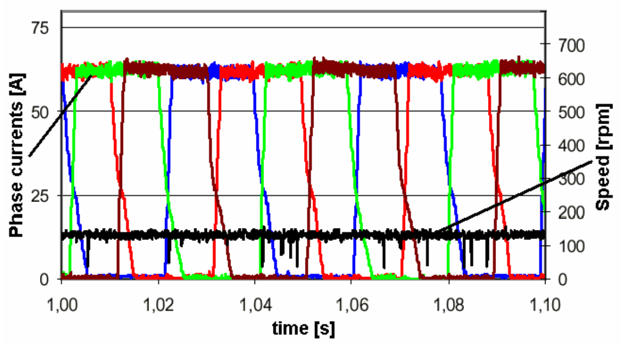

Fig . 10. The currents and speed during the motor operation

The generated currents and voltages are given in Fig. 11.

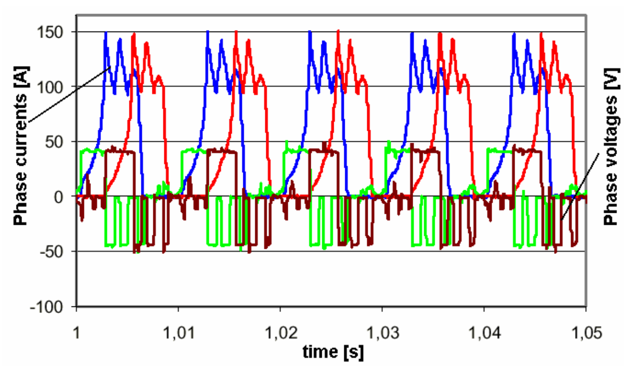

Fig . 11. The currents and speed during the generator operation

6. Conclusions

Hybrid vehicles are coming on the transportation scene as a means to meet the increasing challenges of fuel economy and low emission of greenhouse gases. Technical and business considerations based on market demands are driving hybrid vehicle architectures to be improved day by day.
Hence several specialists consider, that HEVs present economically viable solutions for the manufacture of low-consumption, low-exhaust vehicles in large production volumes.
Mild hybrids realisable with ISG systems are capable of providing engine cranking, energy recuperation and acceleration assistance having several benefits, as improved fuel economy, reduced exhaust emissions and improved power performance.
As the obtained results show the proposed, designed, built up and tested 16/12 SRM meets all the requirements for ISG mentioned in Section 3. Therefore it can be used favourably as a crankshaft ISG.

Acknowledgements

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