Crankshaft Starter Generators Based on the Principle of Reluctance

The demand for electric power in vehicles has been steadily increasing in recent years. Limited by its belt drive, the conventional generator will no longer be able to cover this demand in the future. A crankshaft-starter-generator (CSG) will be able to meet this demand for electric energy.

Both a transverse flux reluctance machine and a switched reluctance machine are designed

Besides the supply of energy, a CSG will enable new features such as "start-stop" operation or the recovery of the braking energy in order to reduce emissions to be implemented. An electric machine based on the principle of reluctance is cheap and robust. In order to develop a CSG based on this kind of machine, two different types of reluctance machines can be considered. Both a transverse flux reluctance machine and a switched reluctance machine are designed according to the outer dimensions and the performance. Due to the short axial length of the machines, three-dimensional finite element calculations are used within the design process. This means that the flux distribution is known at each position of the rotor. A dynamic simulation is necessary to depict the behaviour of the entire system.

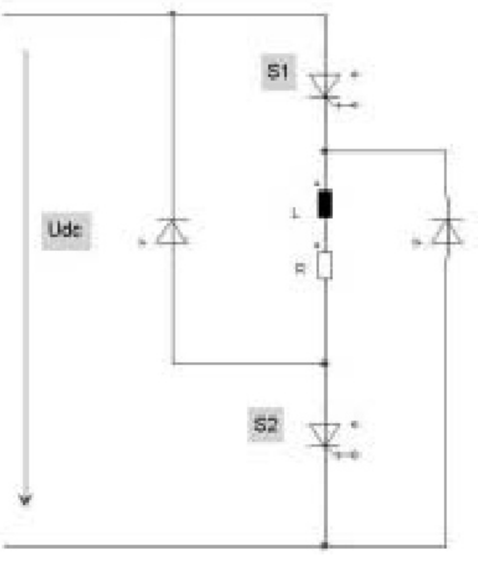

Figure 1: Asymmetrical half-bridge.

Reluctance Machines

According to the requirements of the internal combustion engine and the vehicle's electrical system, different types of electric machines may be used as a CSG. Today, the induction machine and the permanent synchronous machine are usually mentioned in this context. Both machines provide good features, but also some disadvantages.

Machines based on the principle of reluctance offer a cheap and robust alternative to conventional poly-phase machines. Reluctance machines have salient poles within the rotor and the stator. Therefore, the inductance of the direct axis differs from that of the quadrate axis. The torque is developed due to the principle of the minimization of the energy stored within the air gap. The rotor has no excitation and is magnetized by the stator. Even at high speed, the machine can be switched off electrically. High temperatures surrounding the machine have no effect. A power inverter is required to operate this kind of machine. The different phases of the machine are excited according to the position and the load. The torque depends only on the absolute value of the current and the position of the rotor. In the first prototype, the position is measured using an incremental encoder. In the next step, the encoder will be replaced using Kalman algorithms [1]. With regard to the costs, the number of semiconductor devices has been reduced. As shown in Figure 1, the inverter is in the form of an asymmetrical half-bridge.

Corresponding to Equation (1), the electrical characteristics of the machine can be calculated as follows:

$$u(t) = R \cdot i(t) + \frac{\delta \Psi(i,\vartheta)}{\delta i} \cdot \frac{\delta i}{\delta t} + \frac{\delta \Psi(i,\vartheta)}{\delta \vartheta} \cdot \frac{\delta \vartheta}{\delta t} \qquad (1)$$

Ψ = flux linkage
ϑ = angle of rotation
R = resistance of the phase

Using the flux, the torque can be calculated as follows:

$$M = \frac{\delta \int_0^i \Psi(i,\vartheta)\,\delta i}{\delta \vartheta} \qquad (2)$$

In order to determine the behaviour of the machines, the flux has to be known at all positions of the rotor and at all current densities within the coils of the stator. Due to the complex geometry, only three-dimensional field computations can be used.

Transverse Flux Reluctance Machine

Transverse flux machines are known for their development of large power densities, but they also require permanent magnets. The combination of the reluctance concept and a transverse flux path is advantageous for the application as a CSG. The stator of the transverse flux reluctance machine (TFRM) consists of a certain number of stator yokes with two teeth each. As shown in Figure 2, the stator winding is laid between the teeth. The winding is a simple ring winding running in the direction of the machine's circumference. Due to the fact that the torque generation of this machine is based on the principle of reluctance, the current in the winding is switched on in the unaligned position. The flux generated by the current pulls the rotor poles into the position of minimal reluctance. For continuous motion and the possibility to start up from every position, three phases with a displacement of 120° electrically are required. The ratio of the stator tooth width and the rotor tooth width is decisive for the development of the torque. In order to increase the torque, the cross-section of the stator teeth has to be enlarged. Limited by the straight outline, an enlargement only in the direction of the machine's circumference is possible. All stator teeth are excited by a common winding. Therefore, there is no difference in the magnetic potential of each tooth. Accordingly, the joining of the stator teeth, as shown in Figure 3, does not cause a magnetic short circuit, but increases the available cross-section. Using the ideal configuration, a starting torque of more than 250 Nm can be achieved at every position of the rotor [2].

Switched Reluctance Machine

The most commonly known and utilized reluctance machine is the switched reluctance machine (SRM), Figure 4. Because of the short axial length, the design analysis and the optimisation cannot be performed with a two-dimensional finite element model, since the influences of edge effects and the winding overhang are not negligible. The performance and the characteristic of an SRM are mainly determined by the number of stator teeth according to the number of rotor teeth. Machines with higher numbers of teeth usually provide a very smooth torque distribution. A lower number of teeth is, according to the lower inductivity, more suitable for operation at high speed.

Using 12 stator poles and 8 rotor poles (12-8 SRM) with a total axial length of 80mm, a starting torque of up to 200 Nm at every position can be achieved. Due to the distribution of the coils, a further reduction in the axial length will result in a disproportionate loss of starting torque. This machine is suitable for smaller internal combustion engines. Figure 5 shows the distribution of the magnetic flux within a 16-12 SRM. Due to the small winding overhang and the resulting copper space factor, this implementation competes favourably with short machines. The starting torque

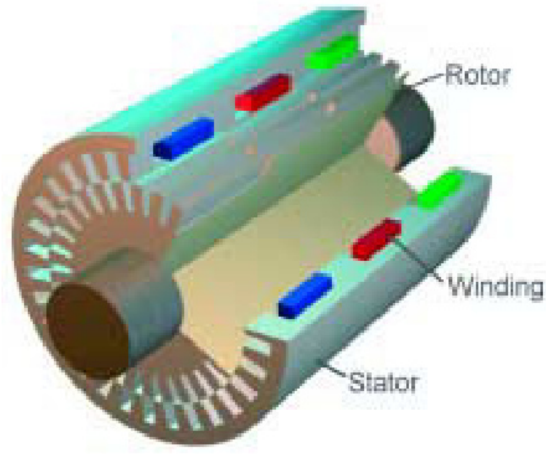

Figure 2: TFRM.

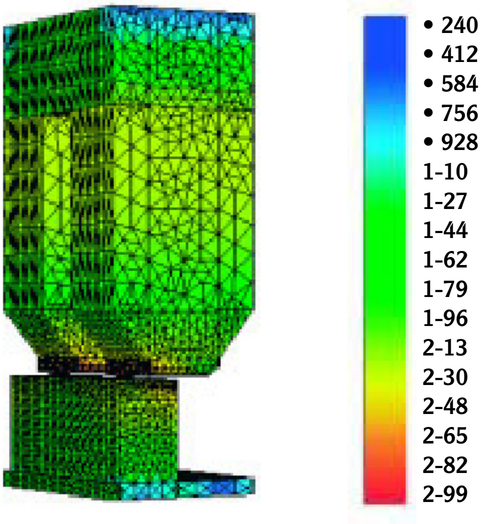

Figure 3 : Joining of the stator teeth.

The starting torque reaches up to 300 Nm

reaches up to 300 Nm. In contrast to the 12-8 SRM, the 16-12 SRM is a four phase machine. Therefore, the cost of the power inverter is slightly higher. A higher number of stator poles has also been analysed. Inferior performance in terms of starting torque and inductivity is expected compared to the 16-12 machine.

Motor Operation

The results obtained from the field calculation only characterize the static performance of the machine. Simulation software plays an important role during the design process. It helps to provide accurate and fast information about the system behaviour at an early design stage and helps to reduce experimental effort. Simplorer, with its unique system architecture and the focus on power electronics and drive technology, offers an ideal solution for the analysis of the abovementioned problem class. While block diagram-based tools such as Matlab/Simulink can only handle the control system efficiently and 'spice'-based simulators have numerical problems with power electronic circuits, Simplorer unites an extremely stable circuit simulation core designed especially for power electronic applications with block diagrams and state machines for a flexible and powerful description of any control system. Currently, VHDL-AMS is under development as an additional modelling language.

The built-in machine models cover a wide range of applications on the system design level. They are based on a power-invariant Park transformation approach and are an integral part of the software. Controls can be modelled using either Simplorer's block diagrams or the C/C++ programming interface. For several drive system designs, the use of linear model approaches alone is not sufficient. Therefore, special solutions for TRFM are necessary.

For motor operation, the reluctance machine is operated under speed control. In contrast to rotating-field machines, the torque development in reluctance machines is independent of the direction of the current within the windings. Due to the fact that the reluctance force is always an attracting force, the only decisive factors for controlling the machine are the relative position of the rotor and the amplitude of the current [3].

Using the ideal configuration of the TFRM, the number of windings has to be chosen using the dynamic simulation. As shown in Figure 6, the TFRM starts at zero speed with a load of 200 Nm. The acceleration is divided into two parts. In the first part, the set point value of 500 rpm is reached within 50 ms. After this, the load is reduced and the set point value is set to 1000 rpm. The current within the phases reaches 450 A. In order to reduce the load on the battery, a higher number of windings has to be chosen. Due to inductance, this increment lowers the maximum speed of the drive.

Using a 16-12 SRM, the start-up of the machine at a load of 200 Nm is even faster than that of the TFRM. As shown in Figure 7, a speed of 100 rpm is reached in less than 10ms and a speed of 1000 rpm after 25ms at a reduced load. The main reason for the superior performance of the 16-12 SRM compared to the TFRM is the number of phases. The 16-12 SRM has four phases, while the TFRM has only three. Therefore, start-up at the 'worst-case' position of the rotor becomes quicker due to the number of phases.

Generator Operation

The generator operation of a reluctance machine differs from the generator operation of rotating-field or DC machines. According to the position of the rotor, one phase of the reluctance machine has to be magnetized at the beginning of each electrical period. With the stator and the rotor teeth aligned to each other, the converter applies a 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 a negative dc-link voltage, and the machine works as a generator.

The performance of a reluctance machine working as a generator mainly depends on the setting of the power inverter.

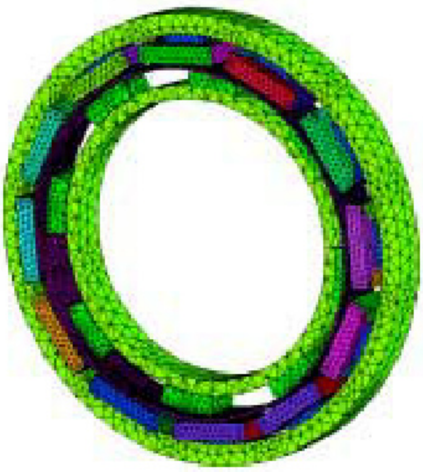

Figure 4: 12-8 SRM.

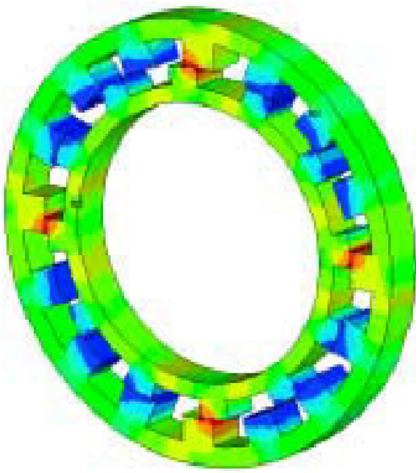

Figure 5: 16-12 SRM.

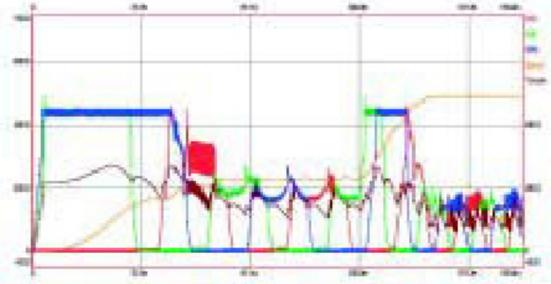

Figure 6: Start-up of the TFRM.

Parameters such as the starting and the demagnetising angle or the upper and lower limit of the tolerance band are decisive. Pure simulation gives only a forecast of the dynamic and static system behaviour by applying a fixed parameter set that is defined once, for example by an initial condition statement. Several applications however need parameter variations to achieve optimum system behaviour. Sometimes, an intuitive search is superior to methods purely based on mathematical functions.

A genetic algorithm can be used very efficiently in order to automate the search. The algorithm alters the parameter values in order to find an optimum of the quality criteria. Genetic algorithms use so-called "generations" of parameter sets. The simulation results of all parameter sets of a generation are analysed, and only the best sets (with the smallest error) are crossed to generate a new generation. This process is repeated until the results of the best members of the generations no longer improve. Since this approach tries to emulate the human way of optimisation, its success depends only on the defined boundaries of the parameter values and the available computation time. Figure 8 shows the curve of the error over an optimisation. The black and white bars indicate the generations of parameter sets. It can be seen that, for the first generations, a large spread of the overall error exists. With every new generation, the error comes closer to its final value [4].

Using the ideal parameters, the electrical power output of the reluctance machines was calculated. Figure 9 shows the output power of the 16-12 SRM at different speeds and numbers of stator windings. With lower numbers of stator windings, the maximum power output rises but also requires higher speeds. At lower speeds, this configuration provides little energy output. In contrast to this, higher numbers of stator pole windings provide good performance at low speed, but are not suitable for operation at medium or higher speed.

Prototype

Within the dynamic simulation, the 16-12 SRM competes favourably with all other reluctance machines. According to the low operating voltage, not only three-dimensional field calculations have to be mentioned. The first prototype of the machine presented above has been built at the department.

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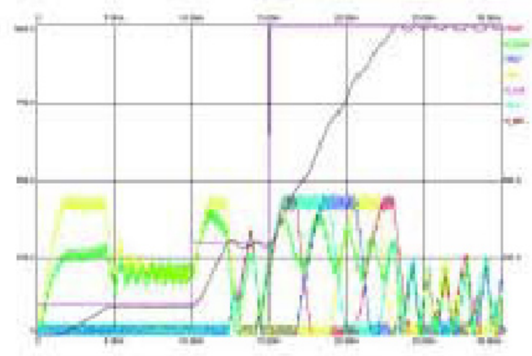

Figure 7: Start-up of the 16-12 SRM.

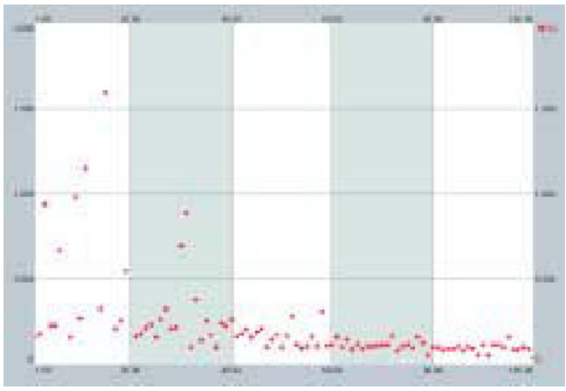

Figure 8: Generic algorithm.

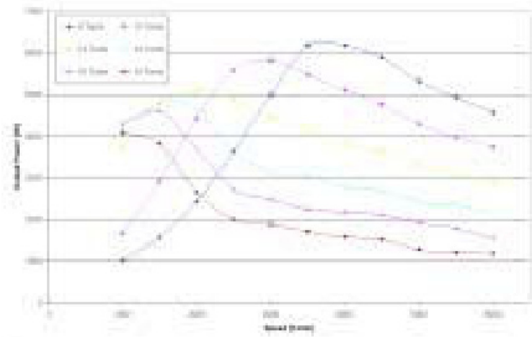

Figure 9: Generator operation of the16-12 SRM.

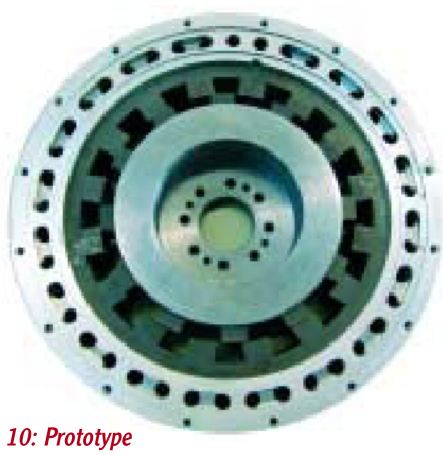

Figure 10: Prototype