EVS27
Barcelona, Spain, November 17-20, 2013

Design Aspects of Low Cost Electric Machines Used for Highly Integrated Starter-Generator Systems

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Abstract

This paper describes design aspects of low cost electrical machines used for highly integrated 48V starter-generator systems. It is shown that a belt-driven interior ferrite magnet machine with integrated power electronics and controller is a good solution for micro and mild hybridization approach. Considering the given automotive constraints and requirements, a machine design optimisation process is used that employs finite element analysis. An electric machine prototype is realized to validate the simulated design.

Keywords: HEV (hybrid electric vehicle), motor design, permanent magnet synchronous motor, ferrite magnets

1 Introduction

Due to CO_2 reduction electrification has become a major need in the automotive industry in order to deal with future legislation targets. Hybrid electric vehicles (HEV) benefit from both propulsion systems and combine the best features of the conventional internal combustion engine (ICE) and the electric machine. Depending on the varying degrees of electrification, these vehicles can be classified in micro-, mild- or full hybrids. Especially with a micro or mild hybridization a good cost/benefit ratio can be achieved. Since the dc link supply voltage exceeds the standard 12V or 24V system, the goal is to increase the power rating of the electric machine using the available voltage range up to 60V introducing a dual board net in the vehicle. The 48V starter-generator is connected via belt drive to the crankshaft of the ICE and offers different functionalities. Beside the start/stop and a better restart comfort compared to 12V systems, regenerative braking, load point shifting and electric boost are possible depending on the final application.

The presented low cost 48V belt driven starter-generator system comprises an optimised permanent magnet synchronous machine with ferrite magnets in order to avoid rare earth materials (Fig. 1).

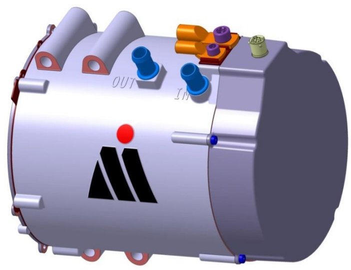

Figure 1: Starter-Generator Unit

The inverter is attached directly to the non-drive side of the electric machine to realize a combined

cooling circuit with the stator. This fully integrated solution offers package advantages and cost savings due to the avoidance of cables and connectors. It is designed for small to medium sized vehicles as an independent unit to be placed next to the combustion engine or to replace the standard 12V alternator on the accessory side depending on the power train layout (P1f or P1r-layout).
The target application for the design optimisation is a P2 power train layout [1]. This layout has a disconnect clutch between the ICE and the electric machine which eliminates the ICE drag during pure electric drive mode.
In general, the electric machine can operate as motor for a short time with a high torque capability to start the ICE. Also, the machine has to operate as a generator over a wide constant power range. The cranking performance is required at worst case condition at minimum battery voltage of 36V. Assuming the maximum belt ratio of 3:1, a torque level of about 30Nm is needed for the electric machine to cover lower end of the hybridisation range of ICEs and vehicles. Up to this point there is no differentiation to the classical starter-generator functionality. Extended functionality is the extended motor operation mode. In addition, the electric machine can provide extra torque in motor mode of operation to increase the total vehicle driveability during acceleration and pure electric drive. The maximum torque in motor operation mode is similar to the maximum braking torque.
The overall cost of the system is the underlying concern and crucial part of the design optimisation.

2 Electric Machine Design

An optimal design of an electric machine for a starter-generator application is subject to very constrained and even contrary requirements. Table 1 gives an overview of the main data. On the one hand a high starting torque in a limited core volume (for cost reduction) is needed. On the other hand a low back-e.m.f. at high speed is required to stay under the maximum battery voltage level of 60V in generator mode of operation and to minimize the risk of overvoltage in the case of a fault of the power converter [2]. The demand for high torque levels at low speed leads to high currents and consequently to a highly saturated electric machine in starter mode of operation. Therefore the magnetic saturation has to be precisely investigated in the design optimisation.

Table1: Starter-Generator Specifications

	value	unit
Maximum stator diameter	150	mm
Overall length of active parts	130	mm
Number of phases	3	
Nominal power	4.5	kW
Nominal torque	16	Nm
Maximum torque	30	Nm
Maximum power	7.5	kW
Maximum battery voltage	60	V
Nominal battery voltage	48	V
Minimum battery voltage	30	V
De-rated performance	< 36	V
Belt ratio	2.0 – 3.0	
Maximum ambient temperature	150	°C
Cooling system	water/glycol	
Maximum cooling liquid temperature	105	°C
Nominal liquid flow	6	l/min

Among many demands for developing an optimal starter-generator system especially the cost and power density are emerging as the two most important properties. With developments in power electronics and ability for high torque density and efficiency levels, the interior permanent magnet synchronous machine using field weakening control is a good candidate for the 48 V starter-generator application in HEV [3].
There are two different approaches for the design of an electric machine for this type of application.
The classical approach is to derive the electric machine design from high performance traction drives. An alternative approach can be the upgrade of 12V start/stop systems comprising axial flux design and separately excited rotors with permanent magnet support.
Following the classical but practical approach, in the last years the cost of rare earth permanent magnets has considerably increased. In order to avoid the risk related to high and mainly unstable prices of rare earth material the goal is to use an alternative and cheaper magnet material. For the introduced electric machine standard ferrite magnets have been chosen. After all, the prices of ferrite magnets are only 5–10% of the prices of rare earth magnets [4].
The need for a low back-e.m.f. and the use of ferrite magnets lead to a machine design that strongly relies on the exploitation of the reluctance torque in order to meet the requirements for ICE start.

3 Multi-objective Optimisation using Genetic Algorithm

In the past, electric machines were designed by applying a parameter sweep and calculating a maximum of several hundred designs. The calculation of a specific machine design actually means to evaluate the operational behaviour for a concrete set of parameter settings. Because of nonlinear material behaviour time intensive finite element simulations have to be applied instead of analytical calculations. To keep the duration of the overall analysis within acceptable limits a severe limitation in the number of evaluated designs has to be imposed. As such, only major design parameters that are adjusted in appropriate step sizes can be taken into consideration.
For the design of the electric machine an efficient optimisation framework is used, where a powerful applied genetic algorithm for multi-objective optimisation is exploited. One application for usage is shown in [5].
The objectives (I-IV) are dedicated parameters of the electric drive system (inverter and electric machine) for the considered P2 hybrid architecture with pure electric driving functionality:

- I. Total losses in generator operation @ 6750 rpm, 2.5kW, (Generator Losses)
- II. Total losses in motor operation @ 5175 rpm, 4.5kW, (Motor Losses)
- III. Torque ripple in motor operation @ 5175 rpm, 4.5kW, (Torque Ripple)
- IV. Total cost (Cost)

The objectives of the optimisation problem regarding current limits are aligned with the performance capabilities of the inverter [6]. The optimisation algorithm also checks additional boundary conditions:

- Phase current in generator mode @ 6750 rpm < 180Arms
- Back-e.m.f. @ -40°C: < 60V
- Air gap length: 0.4mm

The algorithm includes also the cost function for the electric machine and the inverter.

In general, to solve the optimisation problem

$$\min(f_1(\mathbf{x}), f_2(\mathbf{x}), \ldots, f_k(\mathbf{x})) \quad (1)$$

the optimisation algorithm varies the design parameters

$$\mathbf{x}^T = [x_1 \quad x_2 \quad \ldots \quad x_n] \quad (2)$$

which mainly consist of geometrical quantities within given ranges. The motor topology itself (surface mounted or interior magnets, number of pole pairs, concentrated or distributed windings, and winding schema) can be part of (2). The overall workflow is shown in Fig. 2.

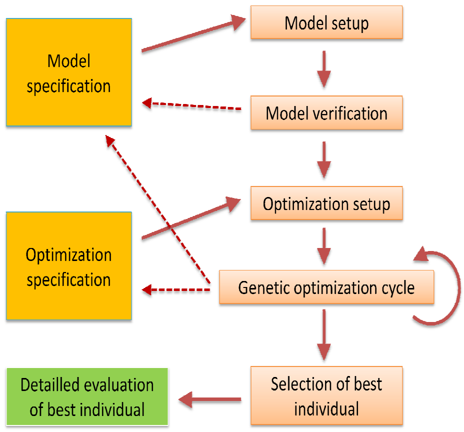

Figure 2: Schematic Optimisation Workflow

According to the optimisation algorithm described, many different electric machine designs were calculated. From over hundred designs that fulfilled the specified requirements the final machine design was chosen in a manual selection process. Minimum cost has highest priority for the selection. Fig. 3 shows the pareto fronts of objective I, II and III as a function of objective IV.

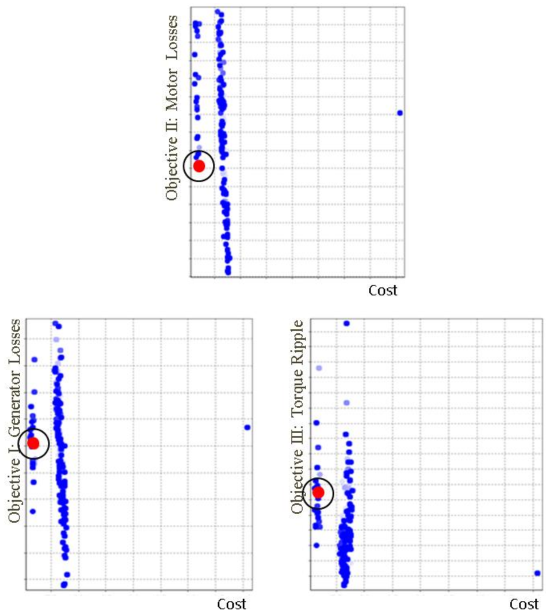

Figure 3: Optimisation results, selected machine design marked as red point

The characteristics manifests two clusters which is given by the “discrete” cost function of parallel switched MOSFETs for each phase. The absolute minimum of losses has been chosen for objective II. Optionally, for an emphasized generator application, objective I can be the choice for maximum efficiency. All other mutual relationships of objectives show no distinctive concentration of design points. Generator losses vary around 50W, motor losses have a range of 70W, torque ripple has a peak-to-peak of 0.6 Nm which means smaller than ± 2% referenced to nominal torque.

4 Finite Element Analysis

It is well known that the slot-pole combination has a significant impact on back-e.m.f., torque level, cogging toque and torque ripple characteristics [7]-[9]. In addition, the demand for a wide speed range of the electric machine reduces the feasible pole number because of the limited inverter switching frequency. The selected design has a 6-pole topology with distributed winding in 36 stator slots. Fig. 4 exemplarily shows the machine design including flux lines and flux density distribution at no-load condition.

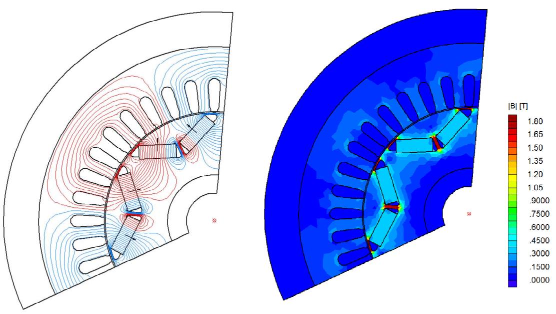

Figure 4: Machine design, flux lines (left) and field distribution (right) at no-load condition

The cogging torque and the torque ripple can cause vibrations that originate acoustic noise. The cogging torque is the oscillatory torque of zero average value caused by the tendency of the rotor to line up with the stator in a particular direction where the permeability of the magnetic circuit “seen” by the magnets is maximized [10]. Beside the slot-pole combination, the cogging can be reduced by skewing. The stator skewing is an efficient and common technique which is popular in practice due to simple realisation. A stator skew angle corresponding one slot pitch is applied to reduce the cogging torque to a negligible value (Fig. 5).

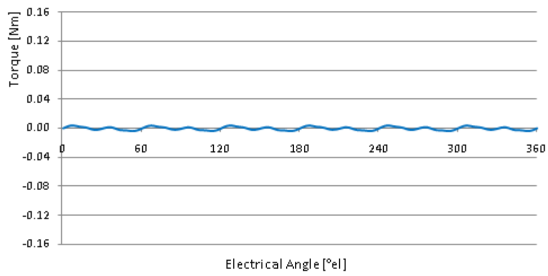

Figure 5: Cogging torque

The peak-to-peak value of the torque ripple is approx. 0.8 Nm (± 2.5% referenced to nominal torque) for the load point of objective III (Minimum Torque Ripple) (Fig. 6).

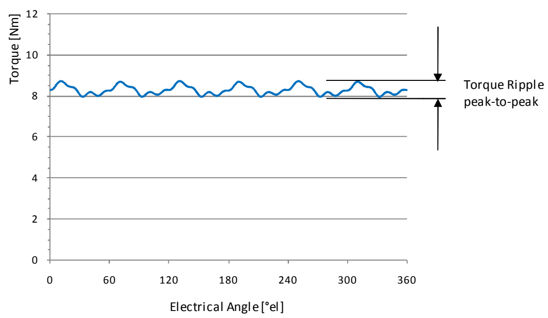

Figure 6: Torque ripple simulation of objective III

5 Experimental Validation

5.1 Prototypes

Fig. 7 shows the active parts of the 36-6 stator slot-rotor pole machine. The electric machine housing consists of the cooling jacket components and the mechanical interfaces which are compliant to the standard alternator fixtures for substitution.

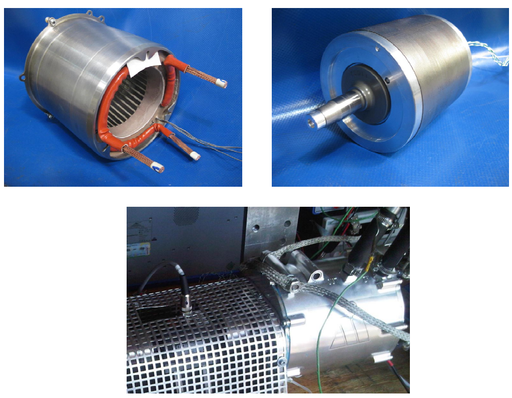

Figure 7: Stator, rotor and assembled prototype unit on the test bench

5.2 Passive Tests

Typical tests without inverter operation are the measurement of no-load back-e.m.f. and current and torque values at a symmetrical short of the three phase terminals. The measured no-load back-e.m.f. shows a good correlation with the FEM-calculation (Fig. 8). The dc-link voltage will be approx. 48V at the maximum speed in the case of a passive recuperation.

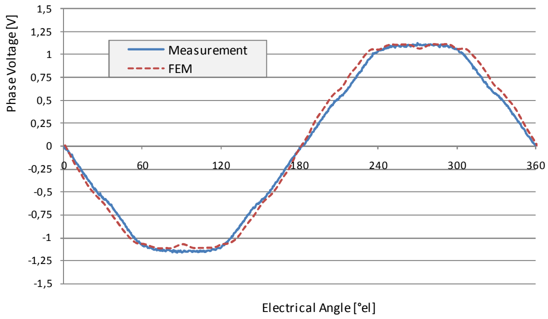

Figure 8: Back-e.m.f. comparison @ 1000 rpm

Nevertheless at lower battery voltage levels e.g. 36V passive recuperation can occur if the speed is higher than approx. 14400 rpm. In this case the triggering of a three phase short is required to avoid uncontrolled charge of the battery and to handle the transients in fault situations the transient handling via. In short circuit fault situations the higher permanent magnet flux of NdFeB magnets can cause currents higher than the nominal current and torque behaviour that can compromise the rest of the system. The short circuit torque of the ferrite machine is negligible and the short circuit current is below the nominal current (Fig. 9). In a short circuit fault situation there is no danger of thermal damage even if the fault persists for an extended period of time.

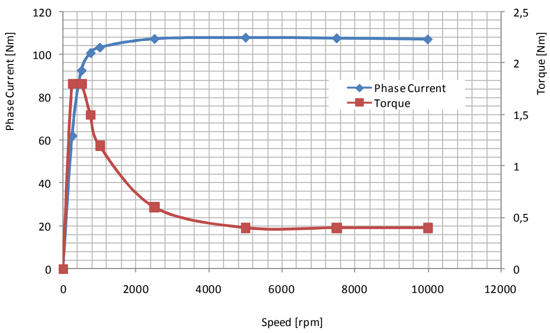

Figure 9: Measurement of phase current and torque at symmetrical three-phase short circuit

5.3 Load Tests

Fig. 10 shows the comparison between measured and simulated phase quantities of objective I and objective II operating points. Measured phase voltages are filtered with 3kHz filter, the simulated phase voltages are depicted with its fundamental for better comparison. Small deviations in waveforms are effected by slight differences of motor components temperatures set in the simulation models and actual arising temperatures in the prototype.

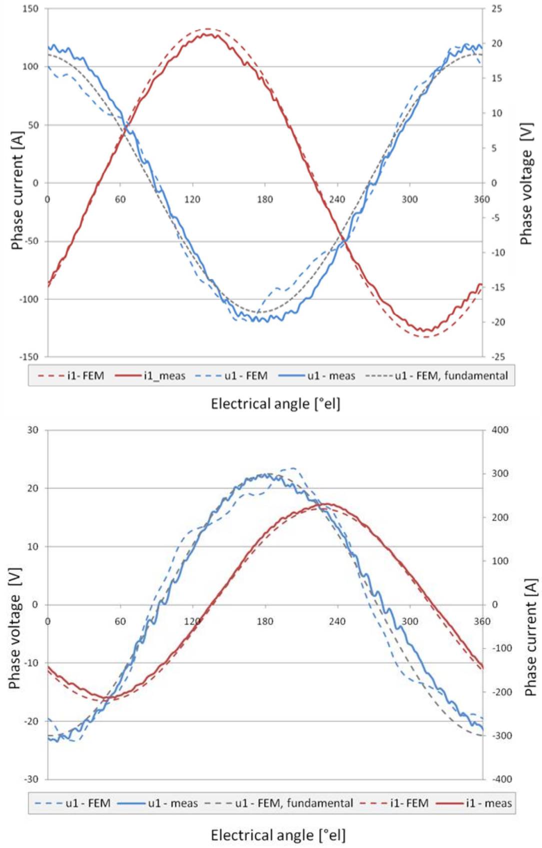

Figure 10: top graph: generator operating point @ 6750 rpm, 2.5 kW
bottom graph: motor operating point @ 5175 rpm, 4.5 kW

5.4 Thermal Validation

Small package space, high ambient and coolant temperatures require sophisticated thermal management of the motor and inverter unit. Due to the integrated design both units share an elaborate cooling system that combines a flat cooling plate for the inverter with a cylindrical cooling jacket for the electric machine. In order to avoid the hot spots in the end windings the space between the cooling jacket and the end windings is filled with a potting resin with increased thermal conductivity. Inside the electric machine prototype temperature sensors are placed in different locations to assess the thermal behaviour of the unit. Fig. 11 shows the measured temperatures in the stator at nominal load. Tests are done with a coolant temperature of 65°C and a flow rate of 6l/min. The highest end winding temperature stays below 110°C at thermal steady-state.

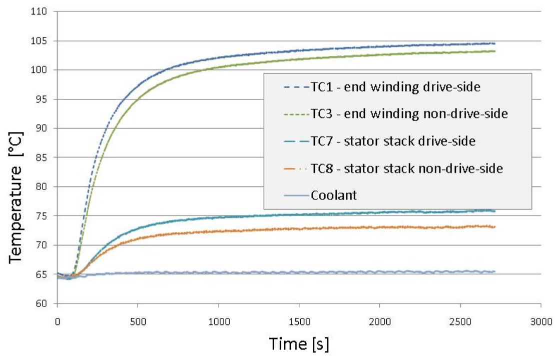

Figure 11: Temperatures for motor mode @ 4.5 kW, 2700 rpm and coolant temperature of 65 °C

For a coolant inlet temperature of 105°C a continuous operation with end winding temperature significantly below 180°C is expected. An overview of other load points in thermal steady-state condition is given in Table 2. Objective I (Generator Losses) and objective II (Motor Losses) are listed as measurements No.2 and No.5.

Due to low arising end winding temperatures and the high overload capabilities –more than 8 kW has been measured for several seconds under worst case conditions - the electric machine has the potential to meet the requirements even without potted stator.

Table 2: Measurement: Thermal steady state conditions at different load points

No.	Speed	Torque	Phase current	Flow rate	System efficiency	TC1	TC3	TC7	TC8	Coolant
-	rpm	Nm	Arms	l/min	%	°C	°C	°C	°C	°C
1	2700	-10.7	164	6.2	80.27	92.2	90.8	72.3	70.4	65.1
2	6750	-4.1	88.5	6.3	84.09	77.8	77.2	70	68.8	65
3	2700	13.1	195.7	6	82.75	104	103	75.6	73.1	65.5
4	10000	-2.5	67.4	6.5	83.93	75.8	75.2	96.6	68.5	65
5	5175	8.5	150.6	5.9	88.12	92.9	92.7	74.8	72.7	65.5

TC1 - end winding drive-side TC3 - end winding non-drive-side
TC7 - stator stack drive-side TC8 - stator stack non-drive-side

6 Conclusion

A 7.5 kW synchronous machine with embedded ferrite magnets on the rotor is presented. The design is a result of a multi-objective optimisation using a genetic algorithm. Beside material cost of electric machine the cost and losses of the integrated inverter are also considered. From the optimisation results a very conservative but practical electric machine design was chosen. The rotor comprises a standard single layer V-shape ferrite magnet arrangement and the low back-e.m.f. of the electric machine reduces safety efforts. Experimental validation on the test bench shows good agreement between simulation and measurements results. The next step will be the integration of the prototype unit into a vehicle for the specific target application described in [1]. Other alternatives to the permanent magnet synchronous machine like switched reluctance based, separated excited or axial flux machines are also being investigated. General target is the reduction, the elimination or the substitution of rare earth magnet materials. Beside cost issue such alternative machines can be more fault tolerant. The design with ferrite magnets presented in this paper belongs to the "rare earth magnet substitution" alternative with increased reluctance torque utilization.

Acknowledgments

The paper presented is grateful supported by the Austrian Research Promotion Agency (FFG) and the Styrian Business Promotion Agency (SFG). Further gratitude is to convey to the Austrian Government and Province of Styria as proprietary of the respective promotion agencies.

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