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High voltage converter design for a belt alternator starter

***Abstract**. This paper presents high voltage power converter design, for a belt driven starter alternator. First, electrical and mechanical construction of converter is presented. Next section describes thermal simulation of converter housing to met specified temperature range. At the end control topology is presented and some cranking tests of internal combustion engine were done, to verify belt alternator system prototype functionality.*

***Streszczenie.** Artykuł przedstawia projekt wysokonapięciowego przekształtnika dla rozrusznika BAS. Mechaniczna i elektryczna konstrukcja przekształtnika została zaprezentowana, jak również opisana została symulacja cieplna obudowy przekształtnika dla otrzymania właściwego zakresu temperatury. Ostatecznie, topologia sterowania jest przedstawiona, a na wewnętrznym silniku spalinowym zostały przeprowadzone testy, weryfikujące funkcjonalność opracowanych systemów BAS. (**Projekt wysokonapięciowego przekształtnika do rozrusznika BAS**)*

Keywords: belt alternator starter, start-stop system, high voltage converter
Słowa kluczowe: BAS, system start-stop, wysokonapięciowy przekształtnik

Introduction

Environmental regulations force car manufacturers to continuously reduce cars pollution emissions, therefore this field is one of the most interesting for research in automotive industry. The simplest way of reducing emissions is to turn off the internal combustion engine (ICE) when it is not needed, e.g. when stopping on a traffic light. Such systems are called Start/Stop systems and can reduce fuel consumption and emissions by more than 5 % for in-city driving [1]. A mayor requirement of the Start/Stop system is to be able to start the ICE immediately and to be able to do much more starts as a classical starter. Up to now there are three known systems of doing warm starts of ICE. The ICE can be started using a modified classical starter [2], using combustion [3] or using a modified alternator so called belt alternator starter (BAS) [4]. Minor changes to the alternator and system layout allow the manufacturers to turn their alternators into BAS systems. This can be done by substituting the rectifier with an inverter allowing the alternator, which normally works as a generator, to be used in motoring mode and cranking the ICE. Such a BAS system can also additionally reduce emissions and increase car performance by “smart” charging the battery when the BAS is coupled to a battery management system e.g. not charging when accelerating, heavy charging when breaking or ICE shut-off.

In this article High Voltage BAS topology and converter design will be presented. In the converter design process of the mentioned system several aspects were considered, as automotive standards, thermal optimization and mechanical design of converter housing and at the end suitable control algorithm in motoring and generating region.

BAS construction

High voltage topologies of hybrid electric vehicles are based on high voltage DC bus and high voltage battery. Such topologies are usually used in mild or full-hybrid designs. In some designs claw-pole machine (alternator) is replaced with induction or synchronous reluctance machine to help at accelerating. In this article described converter is used with alternator.

Figure 1 shows parts of the described converter, while figure 2 shows assembled converter prototype. The converter is designed to meet all the requirements for in passenger car under hood mounting. Because of the high voltage architecture of BAS, galvanic isolation is used between the high and low voltage circuitry. No metal busses are used for carrying currents due to high voltage. Therefore power cables are connected directly on printed circuit board (PCB) of power board. Converter uses only standard electronic components PCB materials. Also no special technologies like bonding or gluing are used. In this way assembly process of converter is easy and cheap.

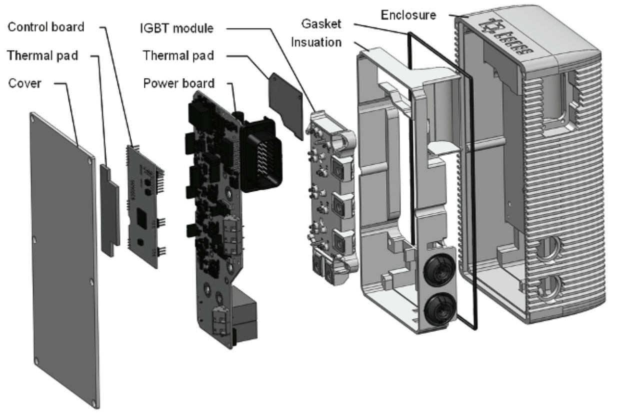

Fig. 1. Exploded view of virtual prototype

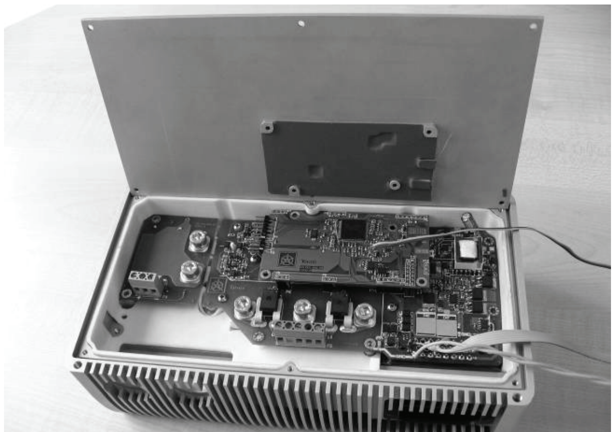

Fig. 2. Converter prototype

The converter consists of four major parts. High voltage inverter which is build with an IGBT module, two foil DC-Link capacitors and three half bridge drivers. To enable magnetization of alternator, low voltage buck stage is used, which is build with PCB mounted MOSFET’s, high-low side driver and two 150 °C aluminum electrolytic capacitors. On control board, control and communication circuitry is implemented which is build on a 32bit digital signal processor (DSP) and isolated CAN interface. For DSP programming JTAG interface is implemented and also serial communication for automated testing of converter. Power supply circuitry is the fourth part which is build of passive and active voltage clamping circuits. A flyback converter and linear voltage regulators are used to generate stable voltages and grant isolation.

Total output power of converter is 10 kW which can be achieved at temperature range from -55 °C to 110 °C (survival temperature range: from -55 °C to 150 °C) with case thermal performance of 0,3 K/W at passive convection.

Mechanical and thermal design

A mechanical and thermal design optimization process of electronics enclosure was performed with CFD software ANSYS V.11, whereby a complex CAD geometry model of the device was generated with SolidWorks interface.

The heat source, where the SEMiX IGBT module represents an energy source with 100 W of thermal losses, is mounted on the base plate, made of Al6063 aluminium with thermal conductivity of 240 $Wm^{-1}K^{-1}$. According to the results of preliminary simulations an optimal heat distribution is achieved with custom fit 12 mm thick base plate of enclosure, wherefore the base plate is completely designed and adapted to the installed electronics, as it can be seen on figure 3. Furthermore the SEMiX IGBT module is rigidly mounted on a mentioned base plate, whereby the connection of an IGBT module with the power board is provided by integrated springs, which accommodates thermal deformations and mechanical vibrations during usage of such a device while driving a vehicle.

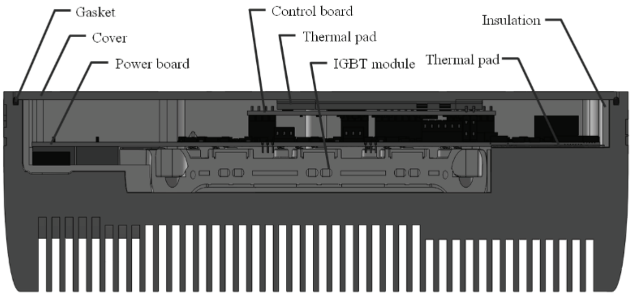

Fig. 3. Cross sectional view of a virtual prototype

To accomplish required mechanical and thermal specifications, the enclosure of a device further comprise the insulation which is installed in interior of enclosure and therefore the insulation prevents the heat to dissipate into the inner side of the housing. Furthermore the insulation acts as an electrical insulator between electronics and enclosure to provide a secure operational mode of such a converter.

As the size of the electronics was minimized, the size of the enclosure has been reduced to its minimum size as possible, while the thermal analysis of device was performed in combination with mechanical design optimization. Hence, the device was designed for low-cost mass production whereby the usage of exotic synthetic liquids for advanced heat transfer techniques, allowing even smaller systems to be designed, was omitted. Therefore the number, length, width and thickness of integrated fins was optimized using advanced computational fluid dynamics simulations, where physical parameters mentioned before were optimized to reach the low-cost enclosure with its high energy dissipation efficiency. There are also some other minor heat sources, generated by diodes, linear voltage regulators and microprocessor on control board, where the heat is dissipated via thermal pad in connection with cover of enclosure, whereby electric insulation is provided also by the thermal gap-pad filler.

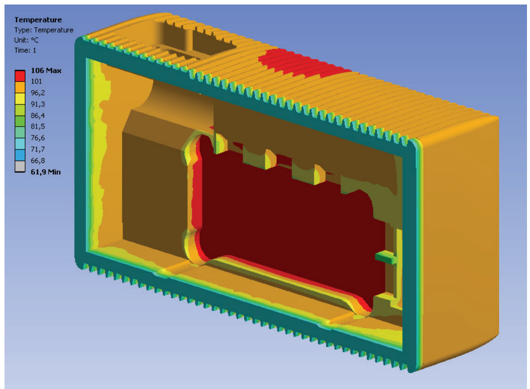

Fig. 4. Steady-State Thermal condition of the device, where the cover of the enclosure is not shown for clarity of figure.

According to the design specifications regarding thermal conditions with maximum ambient temperature of 60 °C, the maximum temperature of an enclosure was limited up to 95 °C. After the goal driven optimization process with multi-objective optimization technique within ANSYS V.11 Design Explorer software, the enclosure of a device with thermal performance of 0.3 °C/W was reached with passive convection, as it can be seen on figure 4. It is essential to notice that there still exists some potential for further optimization process of mechanical design, where an under hood airflow should not be omitted nor neglected. Namely, according to some other preliminary studies, the size of the enclosure for this converter could be reduced down to 70 % of momentary volume size, where the power density with 13 kW/dm^3 should be accomplished.

Control algorithm

Figure 5 shows control algorithm implemented on a TMS320f2809 digital signal processor. It is devided in two parts: motoring region part for starting ICE and generating region part where alternator operates as generator. In generating region it is possible to control high voltage U_{dc} or current I_{dc}. The output of the control loop is duty ratio of half bridge buck stage where on its input 12 V low voltage battery is connected and on the output of buck stage alternator magnetizing winding is connected.

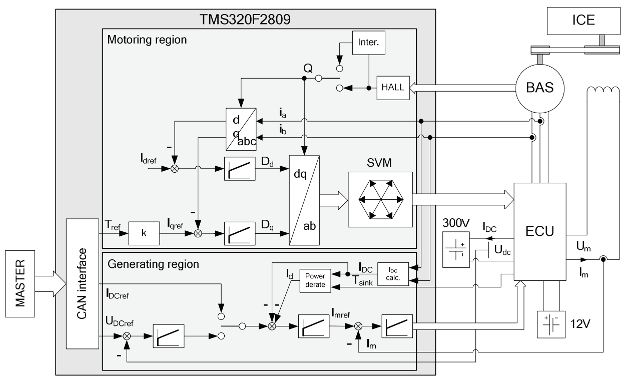

Fig. 5. Control algorithm

In motoring region classical field orientred control is used with two PI controllers where in q axis desired torque can be commanded from master through CAN interface. Rotor position information is obtained from three hall sensors mounted on alternator. Therefore rotor position information is taken at 60 electrical degrees period. At start-up rotor position information is taken directly from hall sensors, when rotor speed becomes higer, rotor position information is obtained with the help of linear interpolation which reduces torque shocks and current transients.

Figure 6 shows phase current measurement of alternator in motoring region where current scale is 20 A/div and converter DC-link voltage meausrement which was set to 330 V. The current reference in *q* axis was set to 60 A. At start-up we can see transients in phase currents bacause rotor positon information which is needed for *dq*-αβ transformation changes each 60 degrees. Afther that rotor position angle is calculated using linear interpolation and currents become more likely sinusoidal. Control algorithm also has protection, which limits phase currents and electrical torque when current controllers are close to saturation. This can be seen on figure 6, where at higher speed phase currents reduces.

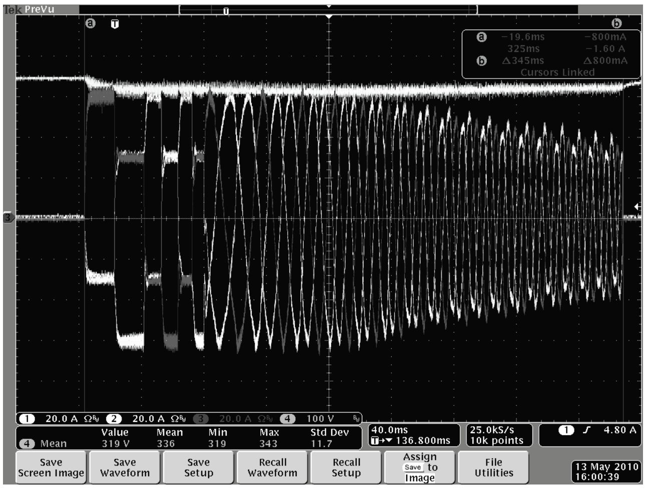

Fig. 6. Start-up test measurements in motoring region

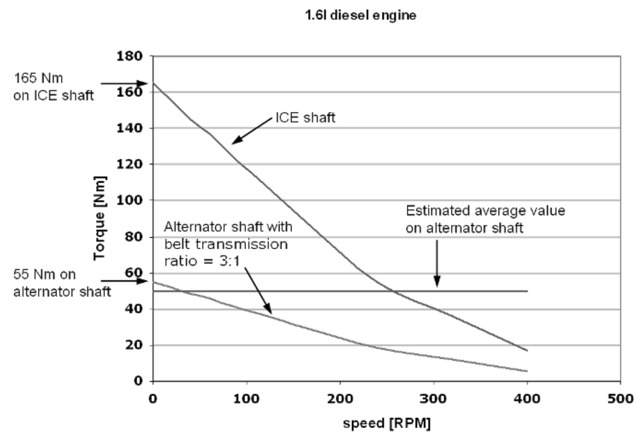

Fig. 7. ICE torque measurement

To be able to crank ICE, BAS system should produce enough torque on ICE shaft when speed is zero. Afterwards when ICE starts turning the torque on their shaft falls rapidly. Figure 7 shows, torque needed for starting diesel engine and torque on alternator shaft when belt with transmission ratio 3:1 (ICE : alternator) is used. From figure 6 average value of torque on alternator shaft can be estimated. For the start-up test shown on figure 6 modified alternator Iskra AAN 230V with twelve integrated permanent magnets was used, asynchronous motor for simulation of ICE and belt with transmission ratio 3:1. The estimated moment of inertia of drive was around 0.14 kgm^2 and speed at the end was 1000 RPM. Measured start-up time between cursors is 345 ms. Using equation 1, average value of torque on alternator shaft can be estimated:

$$(1)\qquad T_e = J\frac{\Delta\omega}{\Delta t} + T_b = 0.14\frac{1000\cdot\pi}{30\cdot 0.345} + 7.5 = 49.9Nm$$

where: T_e – electrical torque, J – moment of inertia, $\Delta\omega$ – mechanical speed, Δt – start-up time.

From figure 7 it can be figured out, that average value of alternator torque with belt transmission ratio 3:1 which represents actual torque at cranking time is lower than estimated average value of calculated torque. Therefore, at point when speed is zero, actual torque of start-up test torque was consecutively higher than 55 Nm. This demonstrates that there will be more than enough of torque on ICE shaft, to overcome the 165 Nm when using appropriate belt transmission ratio.

ICE cranking measurements

To verify prototype BAS system starting ability, cranking tests on real ICE were done. Figure 8 shows test bench with an old 1.3l Lada Samara gasoline engine. The same alternator Iskra AAN 230V was used and belt wilt transmission ratio 2.7:1 (ICE : alternator). Converter DC-link voltage was set to 300V. Because start-up time of ICE differs from time to time due to ICE pistons position and temperature conditions of environment, converter software calculates alternator speed where a certain speed limit is indication when ICE has started. For a given ICE, alternator had to accelerate up to 1700 RPM which was figured out after some tests. Before testing begun, ICE was warmed up a bit.

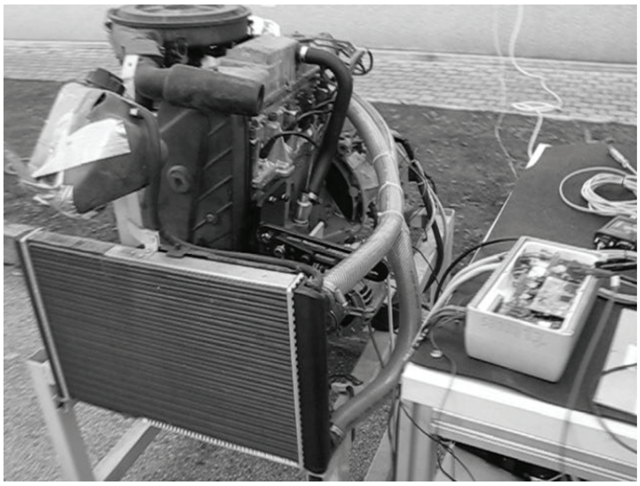

Fig. 8. BAS system test bench

Figure 9 shows measurements of successful ICE cranking. The current reference in *q* axis was set to 30 A. Usually cranking time of ICE using BAS is around 500 ms [4]. In this case ICE cranking time was around 200 ms which can be figured out from time duration of alternator phase current. This actually means acceleration time until ICE shaft made more than a turn, what is enough for a given ICE to start running. Figure 10 shows measurements when current reference in *q* axis was set to 50 A. ICE cranking time was shorter, around 180 ms, but converter input current was about twice as higher than in previous case. Consequently, input power was also twice as higher. This test shows that a lot of power was converted in to losses, because ICE cranking time doesn't differ very much from previous case. Therefore, there is no sense to increase starting current for a given ICE. From figure 9 and 10, can also be figured out that ICE was accelerated, as long its shaft made a whole turn. Number of periods for phase current on images shown below, is around 18. Taking in to account alternator six pole pairs, than alternator made three turns. From ICE point of view, its shaft therefore made more than a turn, considering belt transmission ratio 2.7:1.

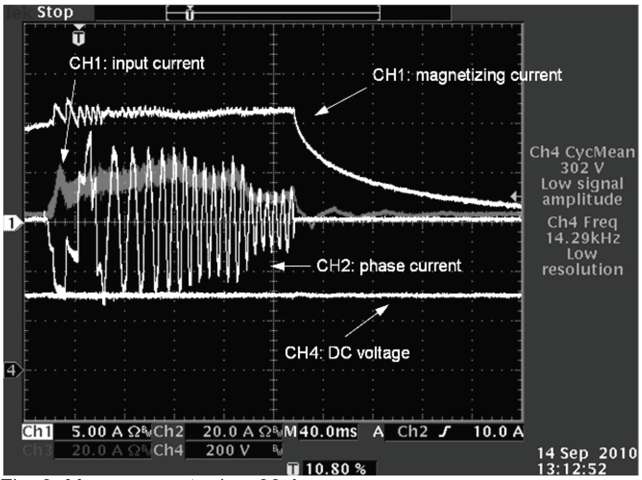

Fig. 9. Measurements, i_{gref}=30 A

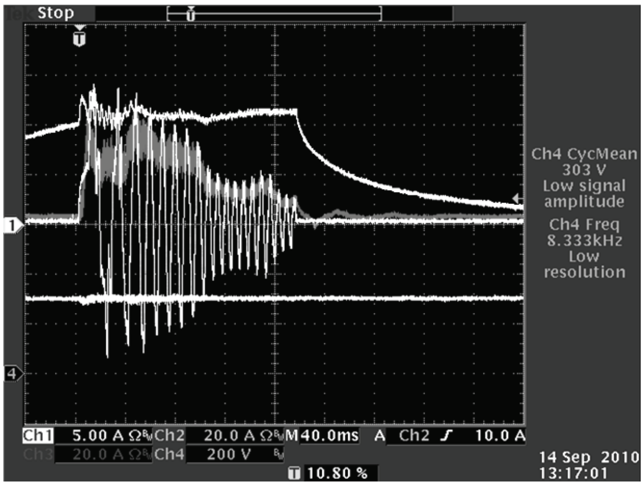

Fig. 10. Measurements, i_{gref}=50 A

Conclusion

In this paper low cost high voltage converter design for BAS system was presented. Trough optimization technique converter enclosure was designed so that temperature stays under 100 °C where passive convection was considered. Thus there is still room for enclosure improvement where also under hood air flow should be considered. In laboratory start-up test was done, to obtain estimated value of ICE torque at zero speed. At the end, experimental tests of ICE cranking, approved in laboratory torque estimation at zero speed time. Tests showed that there was more than enough starting torque for a given or any other ICE used in up to C segment medium car.

REFERENCES

[1] Fayazi, S.A., Farhangi, S., Asaei, B., "Fuel consumption and emission reduction of a mild hybrid vehicle", Industrial Electronics, 2008. IECON 2008. 34th Annual Conference of IEEE, 216 – 221
[2] http://csr.bosch.com/content/language2/html/3177_ENU_XHTML.aspx
[3] http://www.mazda.com/mazdaspirit/env/engine/siss2.html
[4] Richard D., Dubel Y., "Valeo StARS Technology: A Competitive Solution for Hybridization", Power Conversion Conference - Nagoya, 2007, 1601-1605

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