Power Electronic Supply of Automotive Starter Generator

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Abstract

The increasing consumption of electrical power in automobiles can be supplied more economically by a new 42V- than by the conventional 12V-system. This paper describes a key component of the 42V system currently being under development: The starter generator, being controlled by power electronics.

42V System with Starter Generator

The 42V system shall be used to supply loads with high power consumption such as electrical power steering, electrical valve actuators for the combustion engine or a heater for the catalysator. The higher system voltage compared to conventional 12V helps to reduce the current levels and thus to save copper for cabeling and silicon for switching. It will lead to several changes in the architecture of the electrical network in the cars [1]. A major innovation is the combination of former DC starter and former AC generator in a single AC machine, being connected to the 42V battery via a power electronic converter. It will operate as motor to start the combustion engine with high torque and relatively low speed, and as generator to supply the 42V battery and the loads connected to it over the whole speed range of the running combustion engine. Several arrangements of starter generators are possible:

- A belt driven starter generator replaces the conventional generator by an asynchronous motor complemented by a power section, while the conventional starter is omitted.

  This version may initially be of interest, because it does not require major changes in the arrangement under the hood. However its use is limited by the capabilities of the belt transmission, which does not permit to start big combustion engines with high torque and limits the electrical power to be generated.

- A synchronous or asynchronous AC machine may replace the flywheel on the crankshaft between combustion engine and clutch as shown in figure 1. Operation is basically the same as of the belt driven starter generator; however there is no limitation by a belt — any torque generated by the machine will be directly applied to the crankshaft.

  The torque required to start a cold combustion engine with high cubic capacity is considerable, which makes high demands on AC machine and current capability of power electronics.

- An approach to reduce these demands is the introduction of a second clutch between the combustion engine and the starter generator. In motor operation the latter will then accelerate a flywheel with both clutches opened; to start the combustion engine, the clutch towards its crankshaft will be closed, the applied pulse of torque setting the latter into movement.

  In a hybrid drive system, this clutch could further decouple the combustion engine from the powertrain for exclusively electric propulsion and braking, while it will remain closed in all other cases.

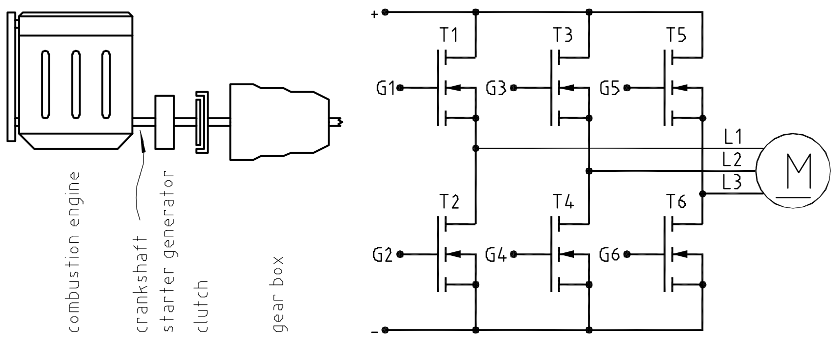

Figure 1: arrangement of and power section for starter generator

The power section for any of the aforementioned versions of starter generator typically consists of a three phase MOSFET bridge as depicted in figure 1. Several requirements can be derived for the MOSFET components:

- Blocking voltage U_{DSS} must be higher than maximum system voltage plus overvoltage peaks caused by switching of the power semiconductors. Typically $75V \leq U_{DSS} \leq 100V$ are sufficient for 42V systems.
- Current capability of the MOSFET should be sufficient for all operational points: The hightest current through the MOSFET is required for cold start at low temperature, such as $-25°C$. The current rating required to start the hot combustion engine is lower, however the current capability of the power semiconductors decreases anyway with increasing heatsink temperature, which is determined by the coolant.

  The on state resistance of trench MOSFETs is low, their current rating thus high, which makes them preferred choice.

  In general, it is advantageous to use an architecture of power section which permits to scale its current rating without major changes in the design: This kind of power section can be applied to the several versions of starter generators outlined above, and finally to a variety of combustion engines.
- Switching behaviour should be optimized for a typical frequency of several Kilohertz. To minimize overvoltage peaks caused by switching, low parasitic inductances in the commutation path from plus to minus of the DC link are desirable. An optimum can be achieved using components which integrate "upper" and "lower" switch of a phaseleg — i. e. T_1 and T_2 in figure 1.
- Power MOSFETs provide an intrinsic reverse diode which is used as free wheeling diode. A low forward voltage is advantageous with respect to efficiency in particular in generator operation. It is mandatory that the turn off behaviour of the diode is optimized to permit switching of the MOSFETs with a frequency as indicated above.
- Environmental conditions under the hood are rather harsh with respect to temperature cycles — correlating with the temperature of coolant i.e. from $-25°C$ to $100°C$ — shock etc. The components must provide a sufficient reliability under these conditions.
- Finally a contribution to reduction of system cost by good value power electronic components will be appreciated.

Power Sections

Two different ways to realize remarkably compact power sections for starter generators are proposed in figures 2 and 3: Both use components manufactured in IXYS' proprietary ISOPLUS™ technology. The components are mechanically held and pressed to a water cooled heatsink by a multiple spring clip. Their leads are soldered or welded to conductors in a PCB like plate. The basic ratings given in table 1 show, that the power sections are suitable to supply typical medium size starter generators from 42V system.

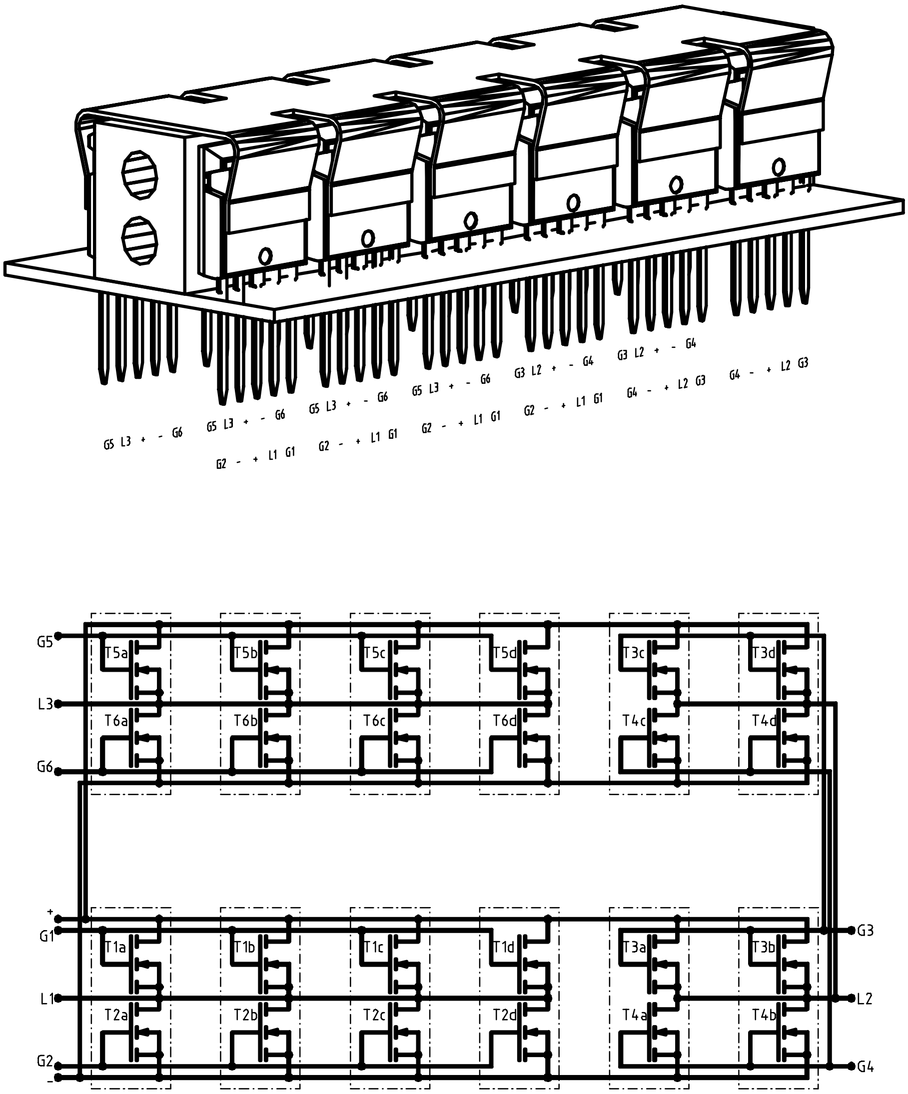

Figure 2: mechanical setup and circuit diagram of a power section with four paralleled trench MOSFET phaselegs in ISOPLUS i4™ package of FMM150-0075P type per phaseleg

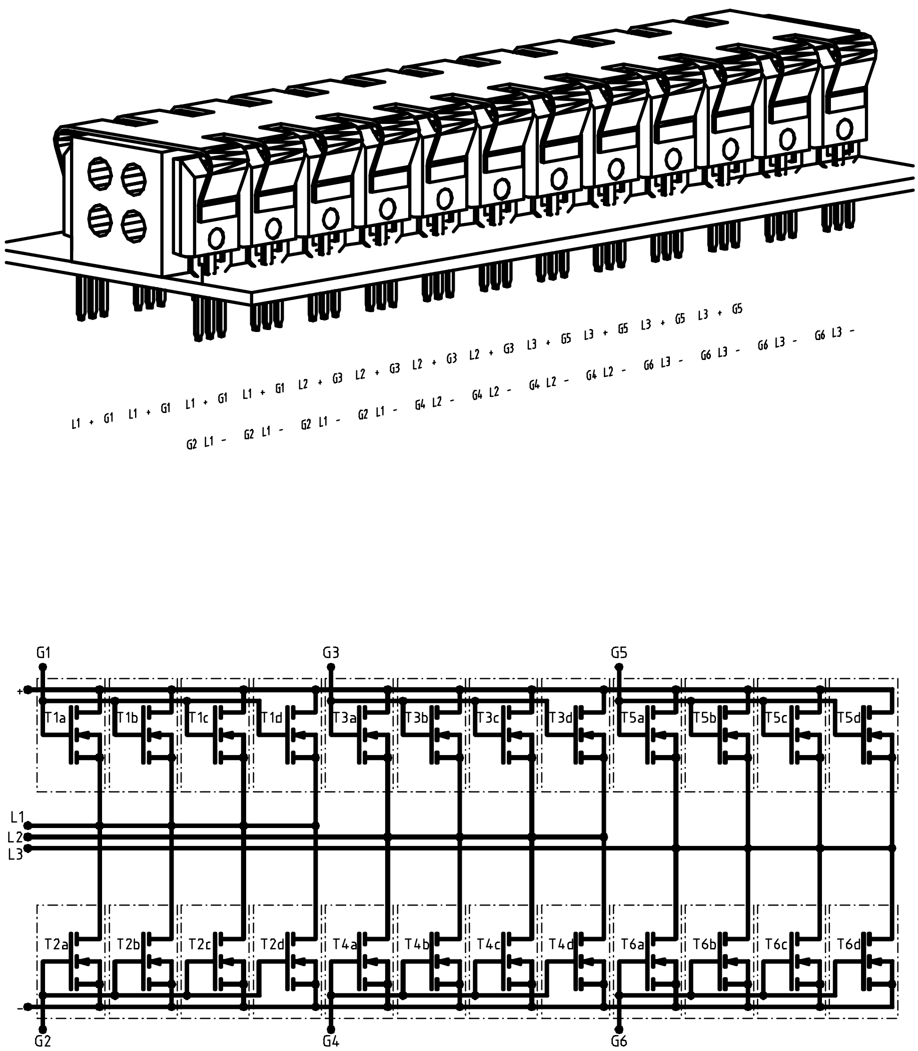

Figure 3: mechanical setup and circuit diagram of a power section with four paralleled trench MOSFET single switches in ISOPLUS 220™ package of IXUC160N075 type per switch

Table 1: configurations, ratings and characteristics of the converters for starter generators

figure	2	3
converter dimensions		
length	140mm	155mm
width	60mm	60mm
height	25mm	20mm
converter ratings		
U_{DSS}	75V	75V
I_{D25}	600A	640A
I_{D90}	480A	520A
I_{RMS}	300A	180A
trench MOSFET components		
type	FMM150-0075P	IXUC160N075
topology	phaseleg	single switch
paralleled	4 per phaseleg	4 per switch
package	ISOPLUS i4™	ISOPLUS 220™

Ratings of the trench power MOSFET components can be derived from the converter ratings: U_{DSS} is the blocking voltage and I_{D25} or I_{D90} indicate the DC current capability of each switch at a case temperature of $T_C = 25°C$ or $T_C = 90°C$ respectively. I_{RMS} expresses the steady state RMS current capability of the power semiconductor devices' leads. The fact that I_{RMS} is lower than I_{D90} is in accordance with the particular operational conditions in automotive applications, where the components are cooled by a heatsink being tempered by the coolant of the combustion engine: While thermal time constants prevent the connections of the leads — being the limiting factor — from overheating during cold start at i. e. $-25°C$, the steady state currents in power section, cooled by a heatsink at i. e. $100°C$, correspond to the I_{RMS} rating. A relatively high chip current capability as expressed by the I_{D90} value further helps to reduce chip junction temperature during operation which increases reliability, and to optimize converter efficiency which is important to avoid a too high fuel consumption of the vehicle.

Some further characteristics of both new components — currently being introduced — are indicated in table 2. Besides R_{DSon} the dynamic parameters — switching times of MOSFET t_r, t_f and intrinsic reverse diode t_{rr} — prove to be in accordance with the automotive requirements outlined above.

Table 2: typical characteristics of 75V trench MOSFET components in ISOPLUS™ packages

	FMM150-0075P	IXUC160N075
R_{DSon}	$4,7m\Omega$	$5,3m\Omega$
t_r	40ns	
t_f	55ns	
t_{rr}	120ns	
length	21mm	15,5mm
width	20mm	10,5mm
height	5mm	4,5mm

The cross section of an ISOPLUS i4™ component in figure 4 gives an insight into the novel packaging technology [2] applied: A **d**irect **c**opper **b**onded DCB ceramic substrate carries the chips, the upper side of which is connected by wire bonds to substrate or leads respectively; this subassembly is covered by molding compound. The components thus look similar to discretes, however provide significant advantages: The DCB ceramic substrate electrically isolates the terminals against heatsink, which is on ground potential — there is no need to mount additional insulator pads, coupling capacity is low. Contrary to copper used for the leadframe of conventional discrete components, DCB's thermal expansion coefficient is close to silicon's, thus guaranteeing the high temperature cycling capability of the components as required.

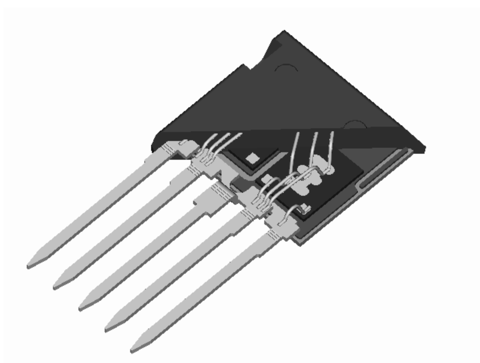

Figure 4: cross section of an ISOPLUS i4™ component

The major difference between the power sections in figures 2 and 3 is the circuit implemented in each component: The outline of three leaded ISOPLUS 220™ corresponds to

TO220 with the area around the mounting hole being additionally used for silicon; thus the IXUC160N075 components in figure 3 are single switches as shown in the schematic. They are arranged around the heatsink in a way that all "upper" switches T_1, T_3 and T_5 are on one and all "lower" switches T_2, T_4 and T_6 on the other side of the heatsink. Contrary, the larger, five leaded ISOPLUS i4™ package with dimensions corresponding to TO247 or TO264 respectively — see table 2 — permits to integrate a complete phaseleg with "upper" and "lower" switch, i. e. T_1 and T_2, which guarantees short current paths and thus advantageously low parasitic inductances; besides, mounting effort is low due to the reduced number of components and PCB layout is easier, connecting the components with their aplication friendly pinout by few wires. Figure 2 shows the geometrical arrangement of the FMM150-0075P components around the heatsink and the corresponding schematic of the connected phaselegs.

It is obvious that both versions of power section can easily be up- and downscaled without changing the architecture: A longer printed circuit board and heatsink can carry more power semiconductor devices for higher power, shorter versions are suitable for lower power.

Control circuitry — i. e. drivers and gate resistors, not shown in figures 2 and 3 — can be directly placed on the printed circuit board. Care should be taken that the current capability of the main current paths corresponds to the current ratings of the power semiconductors; this can be achieved using a relatively thick metallization or even metal sheets. The pins of the components are shown with full length in figures 2 and 3 to demonstrate, that they would be long enough for a multi level setup, for bending, clamp connection etc.

Conclusion

The described compact power sections, equipped with additional components such as capacitors in the DC link, some sensors and a controller, will be packaged and placed close to the supplied starter generator AC machine. Thus trench power MOSFET chip technology in conjunction with ISOPLUS™ packaging technology support the introduction of power electronics in automotive control units. The constraint that those have up to now been limited to lower power levels can be overcome this way as a prerequisite for the introduction of the automotive 42V system.

References

[1] A. Lindemann: Power Electronics in Automobiles; Power Electronics Europe, issue 6/2000

[2] A. Lindemann: Combining the Features of Modules and Discretes in a New Power Semiconductor Package; PCIM Conference, Nürnberg, 2000