New Power Electronic Components for Materials Handling Drive Systems

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There is a variety of drives in lift trucks and other materials handling equipment: They supply the mechanical energy to move the materials — such as the motors for hydraulic pump or propulsion of a fork lift truck — and are further used as auxiliary actuators — e. g. for steering. If the operating energy is stored on board in a battery, those drives consist of electric machines, being fed by a converter. The following considerations deal with a new series of power semiconductor components designed for use in this kind of converters. Their basic characteristics are discussed with special regard to the requirements in materials handling equipment, additionally some setups of drive inverters are proposed.

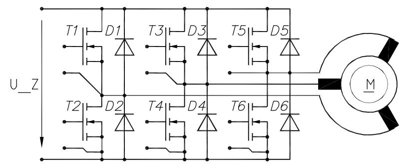

Figure 1: AC drive with MOSFET power section

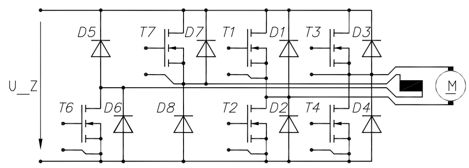

Figure 2: DC drive with power section consisting of MOSFETs and Schottky diodes

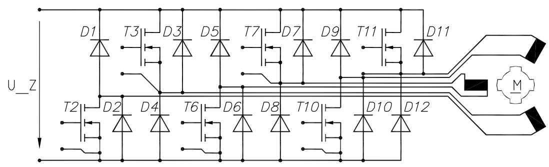

Figure 3: switched reluctance drive with power section consisting of MOSFETs and Schottky diodes

Types of Drives

The majority of the electric drives under consideration makes use of AC or DC motors, additional types such as switched reluctance machines are presently gaining importance. Figures 1, 2 and 3 show schematics with a symbol of the respective machine, connected to an appropriate power section. DC link voltage U_Z of the latter originates from a battery.
The DC machine in figure 2 is fed by a dual converter: The armature winding is connected to a H bridge, symbolised by transistors T_1 to T_4 and diodes D_1 to D_4. This topology permits to apply both polarities of voltage and current to the winding; thus operation in all four quadrants can be controlled. The excitation wind-

ing is connected to a reduced H bridge with only two controllable switches T_6 and T_7, complemented by two free wheeling diodes D_5 and D_8. This topology permits the controller to apply both polarities of voltage to increase and decrease the unidirectional current flow in the excitation winding. Of course, this topology is not mandatory for any DC drive in an industrial vehicle: If appropriate from the point of view of control, a full H bridge could be used for the supply of the excitation winding instead of the armature winding, which permits to save some power semiconductors because of the different current levels, maintaining the four quadrant operability. If the latter is not required — for example a hydraulic pump of a fork lift truck is only used in motor operation with one direction of rotation — the circuits can be further simplified.

DC machines have been used for a long time due to the simplicity of torque and speed control. However today the same controllability can be achieved by field oriented control of AC machines. A power section to generate the appropriate AC system is shown in figure 1. The three phase full bridge is suitable to supply asynchronous and synchronous motors. An excitation winding of a synchronous machine would be additionally fed as described with respect to the excitation winding of a DC machine in figure 2.

While AC machines require bidirectional current flow through the windings, unidirectional current flow is sufficient for the control of a switched reluctance motor. This means, that each winding can be supplied by a reduced H bridge as already discussed and as shown for a three phase switched reluctance drive in figure 3.

Power Semiconductors

It is obvious that the power sections in figures 1, 2 and 3 are similar — several topologies repeat:

- Phaselegs consist of two series connected MOSFETs. Power MOSFETs are able to conduct a reverse current; this is used to carry the current driven by the inductance of the machine while the respective transistor has been turned off. Thus there usually is no need for separate free wheeling diodes. The symbol D_1 represents this intrinsic reverse conduction capability of MOSFET T_1 in figure 2, D_2 correspondingly T_2's. It however is important, that this reverse conduction capability comprises a reasonable — in particular sufficiently fast — switching behaviour.

  Two phaselegs constitute a H bridge — see T_1 to T_4/D_1 to D_4 in figure 2 —, three a three phase full bridge — see T_1 to T_6/D_1 to D_6 in figure 1.
- Boost and buck choppers consist of one MOSFET and one separate free wheeling diode — see T_5/D_6 and T_7/D_8 in figure 2. Current flow in the choppers is unidirectional; this is the reason why the intrinsic reverse diodes D_6 and D_7 of the MOSFETs won't conduct.

Blocking voltage of the MOSFETs and possibly the diodes depends on battery voltage U_Z in the intermediate circuit; there are several dominating levels: Automotive or truck like lead acid batteries are 12V or 24V versions, which is intended to be complemented by 42V in future. Besides, higher battery voltages up to some 100V are frequently used in industrial vehicles. The required rated blocking voltage is determined by the sum of battery voltage U_Z and possible overvoltages. To minimise the latters within power section in switching operation, it is advantageous if phaseleg or chopper circuits are integrated in a single component with an internal low inductive current path. Besides, avalanche rated MOSFETs are able to dissipate some amount of energy, stored in the inevitable parasitic inductance of commutation path.

Semiconductors' required current ratings are determined by the power rating of the drive at nominal and overload. Each switch should be capable to conduct and control the required current at defined ambient conditions, the most important of which is temperature: In particular conduction and switching of the power semiconductor chips lead to power losses. The heat to dissipate is transferred from the component via the heatsink to ambient. This may not lead to a chip junction temperature exceeding the rating of the component. These considerations make trench MOSFETs a preferred choice for battery supplied industrial vehicles: This technology reduces the length of the current path in vertical power MOSFET chips and thus leads to a low on state resistance R_{DSon} [1], while a sufficient switching speed for the typical frequencies of several kilohertz is maintained; it is particularly suitable for blocking voltages of up to some 100V...200V. In chopper circuits trench MOSFETs may advantageously be complemented by Schottky diodes with low forward voltage and fast switching capability. To optimise efficiency of the drive, which is an important feature of industrial vehicles influencing the operation time, it may be favourable to make a low on state resistance R_{DSon} or high current rating respectively reduce conduction losses.

The required current capability may be achieved, using one single or several paralleled components with suitable ratings. This directly leads to the subject of packaging technology: The package protects the incorporated chips against environmental influence, it provides terminals for the electrical connections and a thermal interface towards a heatsink. This mounting tab of all components proposed in this paper is isolated from the electrical circuit by a **d**irect **c**opper **b**onded DCB ceramic substrate. Thus assembly effort is low, because there is no need to place insulator pads externally. Further, DCB based components provide superior reliability due to the matched thermal expansion coefficients of silicon chips and the DCB substrate, the formers are soldered onto. This reduces mechanical stress during load or temperature cycling respectively, which periodically occurs during operation of the equipment. The DCB based components thus contribute to the overall reliability of the industrial material handling equipment, which is claimed to be high.

There are two basic constructional approaches for those DCB based power semiconductor components — modules [2] and discretes [3][4]. Modules in general are larger which means that they either integrate switches with a higher current capability or a more complex circuit. In comparison, isolated discretes permit the setup of power sections with low or easily scalable high current ratings, varying the number of paralleled components.

Examples

Ratings, characteristics and topologies of several isolated components with trench power MOSFETs suitable for drive applications in battery supplied materials handling equipment and industrial vehicles respectively are listed in table 1 — dealing with discrete ISOPLUS™ components, see also figures 4 and 5 — or table 2 — dealing with a module type, see also figure 6:

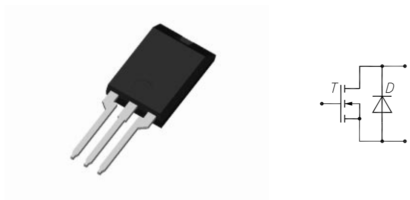

Figure 4: isolated ISOPLUS220™ package $10,5mm \cdot 15,5mm \cdot 4,5mm$, single switch topology

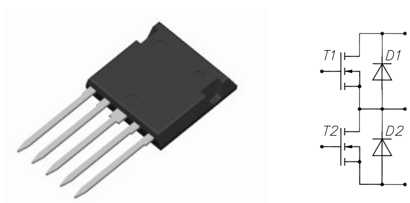

Figure 5: isolated ISOPLUS i4™ package $21mm \cdot 20mm \cdot 5mm$, phaseleg topology

Table 1: basic ratings and characteristics of components with trench MOSFETs in ISOPLUS™ discrete packages

	IXUC100N055	IXUC200N055	FMM150-0075P	IXUC160N075	IXUC60N10	IXUC120N10
U_{DSS}	55V	55V	75V	75V	100V	100V
I_{D90}	80A	160A	120A	130A	45A	90A
I_{RMS}	45A	45A	75A	45A	45A	45A
R_{DSon}	$6,1m\Omega$	$4,0m\Omega$	$4,7m\Omega$	$5,3m\Omega$	$12,8m\Omega$	$7,3m\Omega$
t_{rr}	80ns	80ns	120ns	120ns	80ns	80ns
circuit	single switch	single switch	phaseleg	single switch	single switch	single switch
package	ISOPLUS220™	ISOPLUS220™	ISOPLUS i4™	ISOPLUS220™	ISOPLUS220™	ISOPLUS220™
see figure	4	4	5	4	4	4

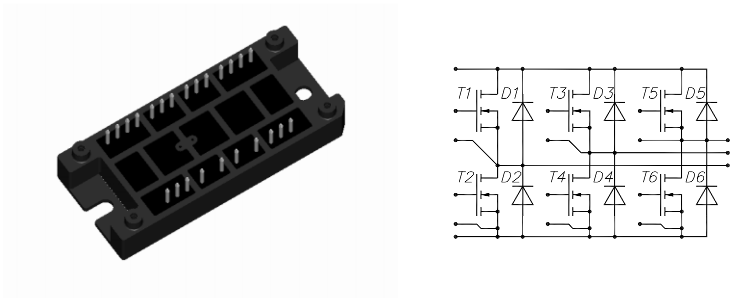

Figure 6: isolated module package $40,4mm \cdot 93mm \cdot 17mm$, three phase full bridge — sixpack — topology

Table 2: basic ratings and characteristics of a module with trench MOSFETs

	VWM350-0075P
U_{DSS}	75V
I_{D80}	250A
I_{RMS}	200A
R_{DSon}	$2,3m\Omega$
t_{rr}	120ns
circuit	sixpack
package	module
see figure	6

U_{DSS} is the blocking voltage and I_{D80} or I_{D90} indicate the DC current capability of each MOSFET switch at a case temperature of $T_C = 80°C$ or $T_C = 90°C$ respectively. I_{RMS} expresses the steady state RMS current capability of the power semiconductor components' terminals. Although the current capability of several types of packages already has been optimised, it happens that I_{RMS} is lower than I_{D80} or I_{D90}. This restriction to a lower current level is however — as mentioned above — in accordance with the approach to make the power MOSFET chips run cooler, which has a strong impact on operating on state resistance R_{DSon}: The latter will increase with junction temperature T_J; lower drain current I_D leading to lower junction temperature T_J thus helps to reduce on state losses and thus to optimise the efficiency of the converter. Further, a lower range of operating temperatures contributes to higher load or temperature cycling reliability. The noticeably low typical values of MOSFETs' on state resistance R_{DSon} at a junction temperature of $T_J = 25°C$ are listed in the tables, further the reverse recovery time of their intrinsic reverse diodes, proving that those are suitable for use as free wheeling diodes in phaseleg topology.

Besides the products as above, a variety of additional chips with different ratings and characteristics or further packages incorporating various circuits can be combined to achieve an optimum match of the components to the requirements of the drive. As an example, figure 7 depicts a larger module housing with screw terminals; its suitability for use in industrial vehicles has been proven. Several topologies, using trench MOSFETs and the aforementioned Schottky diodes, can be integrated.

Application

The drives under question cover a rather broad range of power ratings: Small materials handling equipment or auxiliary drives in fork lift trucks — such as for electric steering — need relatively low power of several hundreds of watts, while nominal power of drives for hydraulic pumps and propulsion of large fork lift trucks may reach some tens of kilowatts. Exemplarily some setups of power sections shall be suggested, making use of components as described above, for supply of AC drives with medium power and energy storage in a 36/42V battery. Three phase full bridges are required, the switches providing a blocking voltage of $U_{DSS} = 75V$. It is assumed that some coolant is available for heat exchange; otherwise, a geometry of power section, leading the heat directly to the case of the motor controller, being itself cooled by air flow or attachment to the car body, would be more recommendable.

Different ways to realize remarkably compact power sections are proposed in figure 8 — showing a sixpack module being screwed to heatsink — or in figures 9 and 10 — both depicting ISOPLUS™ components, which are mechanically held and pressed to heatsink by a multiple spring clip. The respective terminals are soldered or welded to conductors in a PCB like plate, which also carries control circuitry — i. e. drivers and gate resistors, not shown in the figures. Anyway, care should be taken that the current capability of the main current paths corresponds to the ratings of the power sections; this can be achieved using a relatively thick metallization or even metal sheets.

Table 3 indicates the configuration of trench power MOSFET components to set up the suggested converters, their resulting basic ratings and their mechanical dimensions, being mainly determined by the shape of heatsink. The examples would represent typical ways to set up power sections in industrial vehicles:

- The module solution in figure 8 requires only minimum mounting effort — the whole power circuit is integrated in a single component. Parasitic inductance within the module is low, operational behaviour thus favourable. Additionally, measures have been taken to optimise thermal resistance.
- The five leaded ISOPLUS i4™ components integrate a complete phaseleg. Their pinout is user friendly — the conductor pattern, needed to connect the devices arranged on two sides of the heatsink as depicted in figure 9, is still rather simple. Further, current paths remain short, disturbing parasitics thus small. Mounting effort however is higher compared to a module due to the increased part count; this may be compensated by the useful feature, that the suggested power section may easily be scaled, varying the number of components.
- Finally the setup in figure 10 comes closest to what is known from state of the art, paralleling TO220. In comparison to those traditional devices however, ISOPLUS220™ components contain more chip area, increasing power density or reducing on state resistance R_{DSon}, and don't need an external isolator. The power section, again with an arrangement of the components on two sides of the heatsink as depicted, remains scalable. However mounting effort is some higher and PCB layout more complex, compared to the approach with ISOPLUS i4™ phaselegs.

Conclusion

It can be concluded that a series of new isolated power semiconductor components has been developed, which well meet the requirements

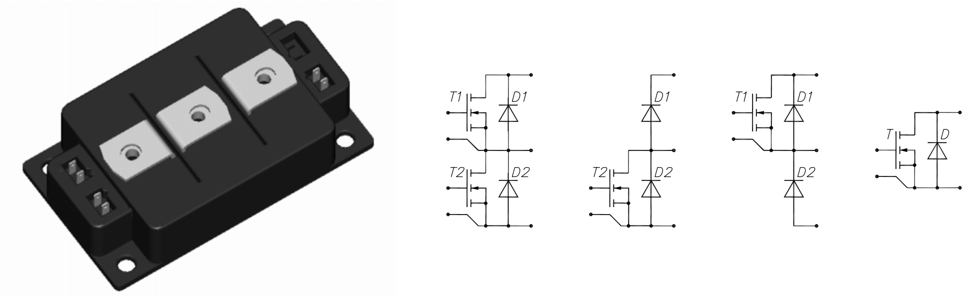

Figure 7: isolated module $62mm \cdot 110mm \cdot 30mm$, phaseleg, chopper and single switch topologies

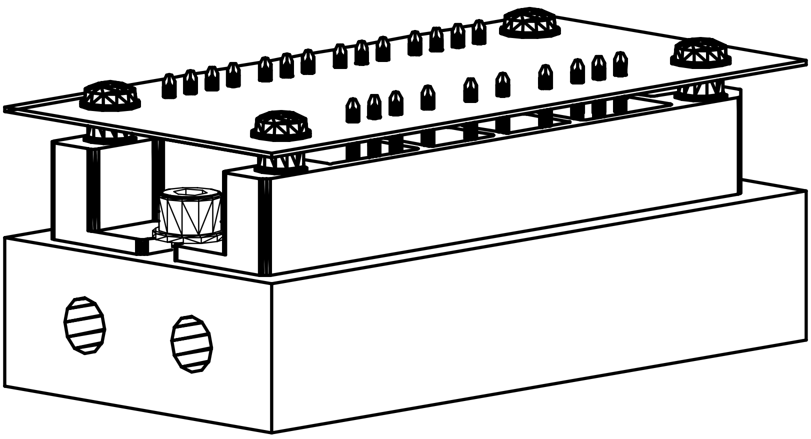

Figure 8: power section for a three phase AC drive with one trench MOSFET sixpack module of VWM350-0075P type

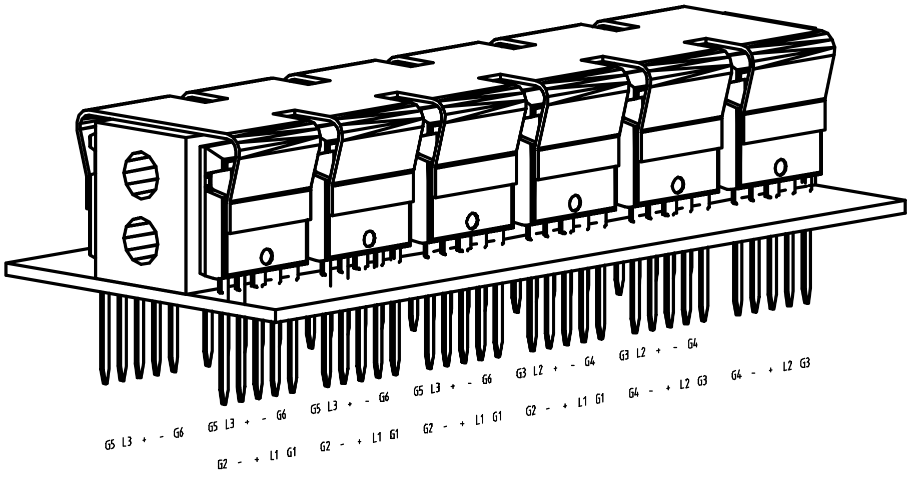

Figure 9: power section for a three phase AC drive with four paralleled trench MOSFET phaselegs in ISOPLUS i4™ package of FMM150-0075P type per phaseleg

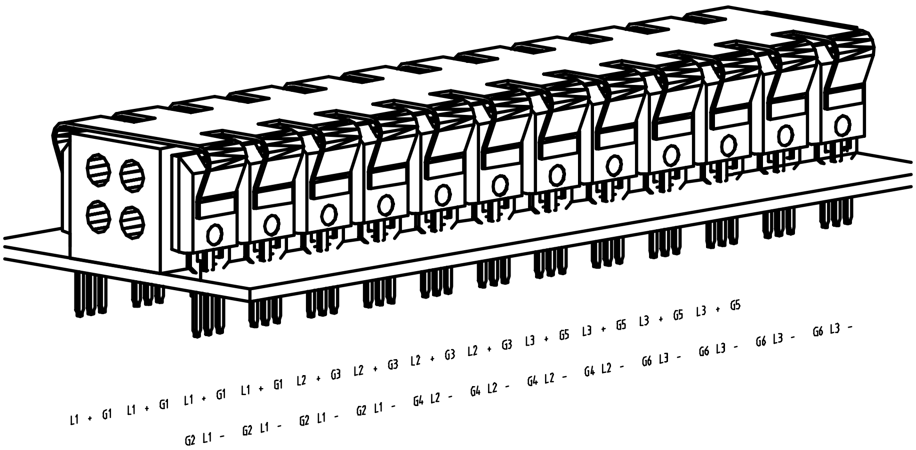

Figure 10: power section for a three phase AC drive with four paralleled trench MOSFET single switches in ISOPLUS220™ package of IXUC160N075 type per switch

Table 3: configurations, electrical ratings and mechanical characteristics of converters for drives in industrial vehicles

figure	8	9	10
configuration of trench MOSFET components			
type	VWM350-0075P	FMM150-0075P	IXUC160N075
topology	sixpack	phaseleg	single switch
paralleled	1	4 per phaseleg	4 per switch
package	module	ISOPLUS i4^{TM}	ISOPLUS220^{TM}
electrical ratings of the converter			
U_{DSS}	75V	75V	75V
I_{D90}	250A	480A	520A
I_{RMS}	200A	300A	180A
converter dimensions			
length	100mm	140mm	155mm
width	50mm	60mm	60mm
height	36mm	25mm	20mm

of materials handling equipment or industrial vehicles respectively. The devices can be used to design power sections in different ways with ratings matched to the various drives. The decision for a particular solution out of several equally good approaches will need to take into account special application related requirements, preferences for certain assembly methods etc. Sometimes, forming of an opinion may finally be a question of philosophy.

References

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[2] A. Neidig: Neue Montagetechnik für Leistungsmodule; Mikroelektronik, Vol. 5, Issue 2, Fachbeilage Mikroperipherik, 1991

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