Development of a Modular Power Converter

A. Stepanov, L. Biesenieks, A. Sokolovs, I. Galkin
Riga Technical University/Institute of Electrical Engineering and Industrial Electronics, Riga, Latvia
gia@avene.eef.rtu, astepanov@eef.rtu.lv, bisenieks@eef.rtu.lv, alvis.sokolovs@rtu.lv

Abstract - **This report describes the most important details of elaboration of a versatile power module that can be utilized as a part of various converters. Two or more modules connected together can form a frequency converter or multilevel converter or 3-phase inverter/rectifier etc. Initially the module was developed for fast prototyping of uninterruptible power supplies and energy systems with alternative energy sources. The module can be used also as a basis for laboratory equipment of the power electronics course.**

I.   INTRODUCTION

Laboratory training is the significant part of study process in the field of electrical engineering. Power semiconductor converters are often investigated in such works. These converters are different, but they contain multiple blocks composed of two connected in series transistors with two free-wheeling diodes (fig.1). Industrial converters, of course, consist of the same blocks. This gives an opportunity of modular approach in the development of the power converters. This means that they are made of few similar power modules that are connected in different ways. For example, the 3-phase inverter (fig.1) can be made of 3 such phase-leg modules.
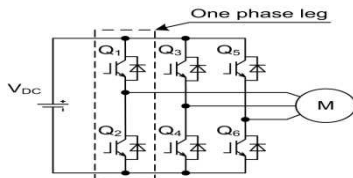

Fig. 1. Three phase inverter

It was decided to develop the module which has all the necessary parts to operate as a single unit or as a part of more complex converter like of 1/3 phase half/full bridge rectifier/inverter, PFC (power factor corrector) circuits, charge/discharge leg, multilevel converters etc. This also regards combinations of converters: DC-link one/three phase frequency converter, uninterruptible power supply, active filter etc.

Such modules should be safe, easy repairable and reconfigurable. Elaboration of such modules includes the following tasks: 1) choice of the conductor's system that is electromagnetically friendly as well as fits the above requirements; 2) development of the local protection system; 3) forming of the robust cooling system that also satisfy the above requirements. Beside that a number of voltage and

current sensors must be installed in the module to provide a feedback for its control system.

II.   POWER BOARD

The described module was designed, produced and tested. Its power board contains 2 transistors, 2 DC-bus capacitors, 3 dividers for voltage measurements, hall sensor for current measurements as well as connectors for driver and measurement boards (fig.2). The power board is based on the bus bar approach that minimizes current paths and their stray inductances thus leading to lower overvoltages across the transistors and less EM noise. Other boards are connected to the power board directly through machined contacts that minimizes parasitic parameters of low current circuits too as well as insures reparability.
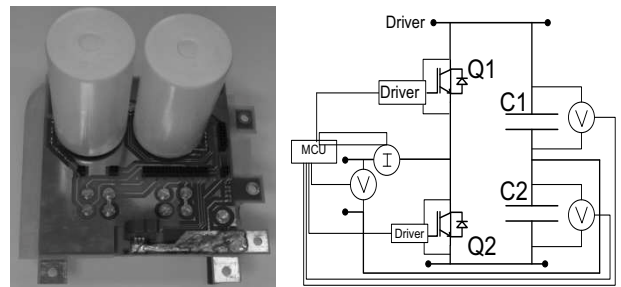

Fig. 2. Power board of module

III.   DRIVER BOARD

The driver board includes drivers, devices that control the drivers, as well as power supplies for them.

Power transistors are driven by 2SD106A-17_E (SCALE) drivers manufactured by „CT Concept". These devices ensure not only correct switching, but also protection against overloads and short circuits. The drivers require very few additional components the parameters of which are easy to calculate. Some additional logic IC protects the power transistors also in case of incorrect control signal (when both channels are set to high level).

Control signals for the drivers, as well as backward status signals are provided through optical fibers and optical transmitters/receivers. Optical interface are necessary to protect control device from high voltage in the case of accident as well improve noise immunity of the control signal.

The drivers are supplied with +15V by a DC/DC converter that has on its input 100…850V from the DC-bus. One more

SCIENTIFIC PROCEEDINGS OF RIGA TECHNICAL UNIVERSITY
THE 50TH INTERNATIONAL SCIENTIFIC CONFERENCE „POWER AND ELECTRICAL ENGINEERING," OCTOBER 2009

Power Electronic Converters / Energoelektronikas Pārveidotāji

DC/DC converter generates 5V for the optical receivers, transmitters and logic IC, as well as for measurement board.
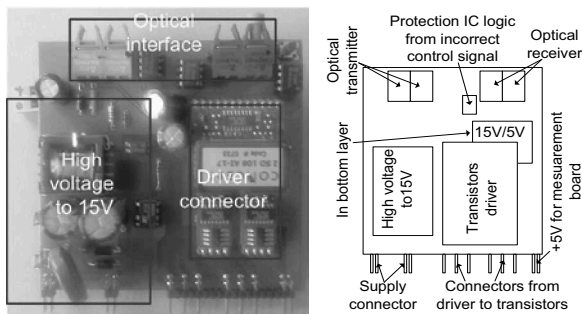

Fig.3. Driver board

IV. MEASUREMENT BOARD

Measurement board is necessary for feedback for control system and galvanic isolation of measured signals.
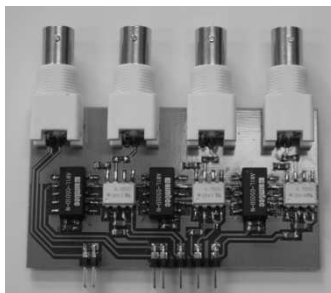

Fig.4. Measurement board

Voltages are measured on the both DC-bus capacitors and in the midpoint of the transistors leg. Voltages are divided by resistive divider by 2000. The divided voltages are measured and amplified by 4 by isolation amplifiers HCPL7400. This element also adds 2.5V offset. Therefore the output voltage of the board may be expressed with the equation:

$$U_{out}=2,5 + U_{in}*0.002 \qquad (1)$$

It means that 400V input voltage produces output voltage of the board of 400*0.002+2.5=3.3V. In case of -400V the output voltage is 1.7V. Zero voltage then produces 2.5V at the output. As a current is measured by hall-sensor this signal doesn't need any additional galvanic isolation. It is measured by the control system directly. The rated current of the hall-sensors is ±45A that assumes output signal (U_{out}) of:

$$U_{out}=2.5 \pm 0.04167 \cdot I_P \qquad (2)$$

V. OPTIONAL LOCAL CONTROL BOARD

Each module may have its own control board based on MSP430 series microcontroller. Two optical receivers and two transmitters are placed on the control board to send control signals to the transistor drivers and receive signals about their status. Since the microcontroller cannot ensure

sufficient current for transmitters an additional logic element LA18 is added for its signal amplification. The control board receives measured signals trough BNC connectors, but voltage dividers with potentiometers allow adjust signal levels for the microcontroller. Such modular control is inconvenient for complex converter control since there is a need of data exchange among modules, but is useful for training purposes when power converters are made of one module. Sometimes also modules of a complex unit like UPS (fig.5), may be controlled as separate converters too. For example the rectifier of such UPS ensures 400V across both DC link capacitors and sinusoidal input current. The second module charge/discharge energy storages and performs buck converter function with current control to charge them or boost converter function to keep DC link voltage at 800V. The last module generates sinusoidal output voltage.

If the measured signals are input/ output current (depends on usage), input/output voltage and upper and lower capacitor voltages then the modules may operate as separate units. Depending on module usage each signal can be used for main control loop or for protection purposes.

VI. COOLING SYSTEM

To make the modular converter more versatile each module has its own heatsink. It was decided to use water cooling that allows free placement and connection of these heatsinks. The heatsinks (fig.5) are made to fit power package SOT227. Practical sizes of heatsink were calculated based on heat transfer theory [1-5]. The heatsinks are connected in series.
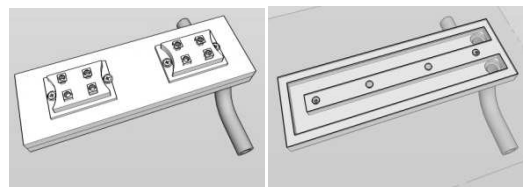

Fig. 5. Heatsink for liquid cooling

VII. AN EXAMPLE OF THE MODULAR APPROACH

At the testing stage it was decided to form and debug a modular uninterruptible power supply (UPS) with 2 different energy storage devices: battery and supercapacitor (SC). Such UPS contains 4 converters: rectifier, inverter, two buck converter with different control algorithms and two boost converters with different control algorithms (fig.6).
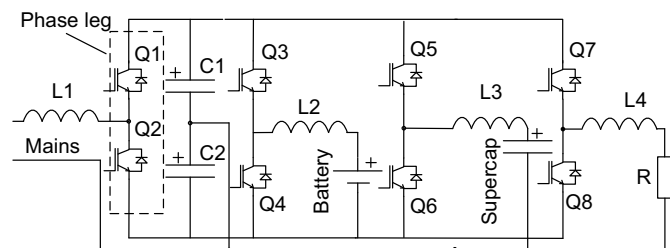

Fig.6 UPS with two energy storages: battery and supercapacitor

SCIENTIFIC PROCEEDINGS OF RIGA TECHNICAL UNIVERSITY
THE 50TH INTERNATIONAL SCIENTIFIC CONFERENCE „POWER AND ELECTRICAL ENGINEERING," OCTOBER 2009

Power Electronic Converters / Energoelektronikas Pārveidotāji

One module (phase leg) is used for input rectifier Q1, Q2, one is used to make boost and buck converter for battery charging and discharging (Q3, Q4), as a UPS has a supercapacitor as a energy storage another converters are necessary to charge/discharge the supercapacitor, and one phase-leg is used as an inverter (Q7, Q8).

The following parameters of the UPS were chosen:

TABLE I:

UPS PARAMETERS

Output parameters	P_{out}=4kW,U_{out}=230V,I_{out}=21.7A(cos(f)=0.8)
Input parameters	U_{in}=180-260V
Battery parameters	V_{bat}=96V(8x12V), C_{bat}=17A*h
Supercapacitor parameters	Backup time - 1min. charging time - 15min

It is obvious that the rectifier module has higher power ratings than the other modules because it controls not only output power, but also supplies chargers. The most significant parameters of the modules are calculated below.

Taking into account that the backup time supported by supercapacitor is 1 minute it must store energy of

$$E = (P_{inv} + P_{inv\_los} + P_{SC\_los})*t = 253kJ \qquad (3)$$

where P_{inv} - inverter power (4kW), P_{inv_los} - inverter power losses that are shown below. P_{SC_los} – supercapacitor discharger losses that are shown below.

Since the operation of the boost converter is less effective at very low duty cycles the minimum voltage of the supercapacitor was defined as 1/10 of DC-bus voltage (80V). One 125V/63F supercapacitor manufactured by "Maxwell technologies" was chosen. Altogether it can store 492kJ. If it is discharged to 80V it stores 202kJ. The difference of 290kJ is enough for the described application.

The maximum current of the supercapacitor is

$$I_{bt\_max} = (P_{bt} + P_{inv\_los} + P_{SC\_los})/U_{sc\_min} = 52.75A \qquad (4)$$

where P_{bt} – the power of the boost converter (the same as of the output inverter), U_{sc_min} – minimal voltage on SC.

To charge the supercapacitor in 15 minutes its current must be

$$I_{sc\_charge} = CV/t = 63*125/15*60 = 8.75A \qquad (5)$$

This gives maximum power of buck converter for SC of

$$P_{sc\_max}=8.75*125=1094W \qquad (6)$$

Battery also must supply inverter with full power (4kW) that (if its voltage is 10.5Vx8=84V in the worst case) requires battery discharge current of

$$I_{bt\_max} = (P_{bt} + P_{inv\_los} + P_{b\_los})/U_{sc\_min} = 50.6A \qquad (7)$$

where P_{B_los} – battery discharger losses

Charge current of lead-acid batteries usually is 0.25*C or, in the given case, 4,25A. Then the power of the charger (at the worst voltage of 14Vx8=112V) is:

$$P_{b\_max}=112*4.25=476W \qquad (8)$$

Total power of rectifier taking into account efficiency of converters is:

$$P_{rect} = P_{inv} + P_{sc\_max} + P_{b\_max} + P_{inv\_los} + P_{BC\_los} + P_{SCC\_los} = 5770W \qquad (9)$$

where P_{BC_los} – battery charger losses, P_{SCC_los} – supercapacitor charger losses.

The power rectifier of such UPS must operate at input voltages 180-260V that give input current range 22-32A.

During the experiments the available transistors were IXSN35N120D1 (IXYS) that have maximum operating voltage 1200V and current 35A. This type of transistors cannot be used in the boost converter. They must include some more powerful transistor (for example IXYS's IXEN60N120D1, 1200B, 60A). An alternative solution assumes parallel connection of several modules. Then the power of each module is two times smaller, but the current – is below 35A.

Inductor was calculated based on procedure given in [6]. Iron powder core of 13.2 cm diameter was chosen. Current ripples were minimized in order to minimize power losses in the core. Since the operation frequency of the transistors is 10-20kHz then optimal inductance for chosen type of cores is 0.5-1mH. The maximum current for such configuration for inductor is 40A. For boost converter this inductor with this core is not adequate. There are two alternatives again. The first one – is to change core and the second one – is to use two modules in parallel connection. It was decided to use the second solution of both problems that requires other elements of the boost converter.

To choose the secondary heatsink and pump of the cooling system of the UPS its power losses must be calculated. Approximate loses were calculated based on [7] and shown in Table II.

TABLE II

LOSSES IN UPS

Converter type	Losses (W)
Inverter	P_{inv_los} - 140
Rectifier	P_{rect_los} - 220
SC charger	P_{SCC_los} - 60
Battery charger	P_{BC_los} - 20
SC discharger	P_{SC_los} - 100
Battery discharger	P_{B_los} - 90

The parallel connection of the charge/discharge modules assumes two modes of operation: inverter, rectifier and both buck converters or inverter and boost converter.

Maximum energy dissipation of UPS is expected in the first case:

$$P_{dis} = P_{rect\_los} + P_{inv\_los} + P_{SCC\_los} + P_{BC\_los} = 440W \qquad (10)$$

SCIENTIFIC PROCEEDINGS OF RIGA TECHNICAL UNIVERSITY
THE 50TH INTERNATIONAL SCIENTIFIC CONFERENCE „POWER AND ELECTRICAL ENGINEERING," OCTOBER 2009

Power Electronic Converters / Energoelektronikas Pārveidotāji

Based on the given data the secondary heatsink and pump were chosen. Pump performance, in the case of 4 in series connected primary heatsinks, is 2.4l/min. Secondary heatsink at such water flow, water temperature of $60C^0$ and ambient temperature of $25C^0$ can dissipate 500W.

VIII.   TESTING OF THE POWER MODULE

The module was assembled and tested. At the first stage the buck and boost configurations of the module were tested. Testing results are demonstrated in fig.7. DC-bus was supplied from rectifier with 550V. A high power resistor was used as the load of the converters.
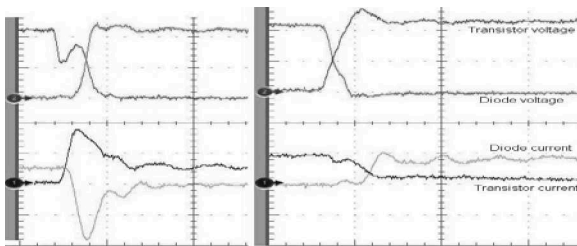

Fig.7. Transistor and diode switching process: left side – diode closing and transistor opening, right side – diode opening and transistor closing. (scale division for time – 200ns, for voltage – 250V, for current - 25A)

Also the modules were tested as a three-phase inverter (fig.8.). Loaded motor current is shown in fig.9. Transistors operating frequency is 5kHz.
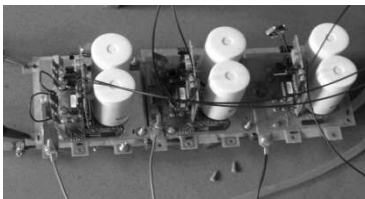

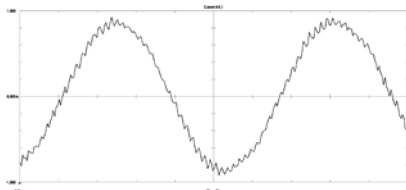Fig.8. Three connected versatile modules as a three-phase inverter for asynchronous motor driving

Fig.9. Inverter output current with asynchronous motor (scale division for current – 1.5A).

The experiments prove that bus bar construction gave good result and transistors switching happens with low overvoltages (below 20% from transistor voltage). The switch-off times of the transistors and diodes are below 200ns. It gave an opportunity to operate at 20 kHz with the currents up to 25A, as well as with acceptable power losses of IXSN35N120D1 transistors. The experiments revealed one significant problem with heat dissipation from the diodes. The smaller duty cycle leads to the longer conduction period of the diodes. Therefore their conduction loses are higher. As the thermal resistance of the diode (pn junction to case) is almost 2 times higher than the same of the transistor it raises the risk of the thermal damage of the diode. It means that in the case of large input to output voltage difference the maximum current of the buck configuration will be smaller than of the boost configuration.

One more drawback of construction was found during the experiments. Thickness of copper layers of the power printed circuit boards was estimated as too small. For this reason some parts of the board have increased temperature (60-70C) at currents higher than 25A.

IX.   CONCLUSIONS

Versatile modular converter was designed, assembled and tested. The bus bar based power board was found good and transistor has no high overvoltages (fig.7). This allows safe operation at 850V.

Modularity of the converter is a big advantage of its construction. One workbench with few modules allows prototyping and testing of various converters. It is easy to access any point of the circuit that gives the possibility to measure voltage or current at any point of the circuit.

In the case of necessity a higher output power can be reached by means of the parallel connection of few modules together.

Versatile construction of module has also disadvantage: such elements as inductor, DC-bus capacitor, transistors are calculated to the maximum and hardest operating conditions and, hence, have larger size and higher price. For example, in the case when 2 modules are connected as a full-bridge, and it has output voltage 230V, transistor could be calculated to 600V not to 1200V and capacitors could be calculated to 400V not to 800V. It would give lower price of the converter, but as it is not an industrial converter it was decided to use in all modules the same component.

Driver board is made in such way that in the case of the incorrect operation of the control system (when it commands both transistors to be open) the transistors are not switched on and the module in dot damaged. Besides that, in the case of too high duty cycle and, as consequence, of too high current of the transistor driver will switch it off.

REFERENCES

[1] Barry W. Williams, "Power Electronics: Devices, Drivers, Applications, and Passive Components", Chapter 5 – "Cooling of Power Switching Semiconductor Devices", 2006

[2] Lienhard IV J.H., Lienhard V J.H., "A heat transfer textbook", 3rd ed. – Cambridge, MA: Phlogiston press, 2006

[3] BEJAN Adrian, Allan D. KRAUS, „Heat Transfer Handbook", Hoboken, NJ: John Wiley & Sons, Inc , 2003

[4] Seri Lee, "Optimum Design and Selection of Heat Sinks", IEEE transactions on components, packaging, and manufacturing technology-part a, vol 18, no 4, December 1995

[5] J. Nagla, P. Saveļjevs, A. Cars, "Siltumtehniskie aprēķini piemēros", Rīga, Zvaigzne, 1982

[6] http://www.micrometals.com/software_index.html, Inductor Design Software 2008

[7] www.semikron.com , Application manual