The Choice of the Main Power Components in Electric Traction Converters

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***Abstract* – The choice of the power components of the electric traction converters for autonomous vehicles is a very important aspect in their design. The attention in this paper is first focused on the choice of the DC link capacitor, followed by choice of the IGBT modules, their testing and cooling. Then, the choice of power cables is approached. A dedicated test bench for electric traction converters for autonomous vehicles was designed and achieved. In defining the parameters of the test bench, various possible applications on battery-powered vehicles were taken into account, but also their performances, technical characteristics and functional characteristics. An important share belongs to the integrated propulsion/charging system of the Li-Ion battery developed by the company SC INDA SRL. It is already used in automotive on full-electric trucks and in the battery-powered electric locomotives.**

Cuvinte cheie: *vehicul autonomy, IGBT, condensator de current continuu, invertor, radiator, răcire, MELCOSIM.*

Keywords: *autonomous vehicle, IGBT, DC link capacitor, inverter, heat sink, cooling, MELCOSIM.*

I. Introduction

Currently, high voltage and current IGBTs are state-of-the-art power electronics modules for the electric traction converters for autonomous vehicles [1-5]. The IGBT itself is part of a complex power kit which includes besides the transistor, input capacitors, laminated bus bars, the cooling system, gate drives etc. For reliable operation the choice of these components is not an easy task considering the technical characteristics of the traction systems.

The best features of a high power IGBT module are closely related to a reliable and high quality protection for IGBT drivers [1]. The attention in [2] is directed towards the connection between a reliable operation of IGBT modules and three important requirements that they have to fulfill: high junction temperature limit, large safe operating area, high current capacity. Methods for obtaining IGBT switching frequency limits are discussed in [3]. A comparison between switching characteristics and losses of IGBT modules for traction applications is studied experimentally in [4]. Reference [5] describes the equations for the power losses evaluation and passive elements design.

The test bench described below includes the designed inverters in the final purpose of a subsidiary contract to the PACETSINEFEN project within the Competitiveness Operational Program, European Regional Development Fund [6]. A block diagram is presented in Fig. 1, where:

TR – three-phase transformer with control sockets;
R – three-phase rectifier;
INV1, INV2 – three-phase inverters;
Ct – DC link capacitor;
CF – braking chopper;
RF – braking resistor;
MAS1 – asynchronous machine (motor mode);
MAS2 – asynchronous machine (generator mode);
TUi – voltage transducers;
TCi – current transducers;
TG1, TG2 – speed transducers;
TCP – torque transducers;
UCR – electronic control unit.

The testbench consists of two asynchronous machines (MAS1, MAS2) mechanically coupled, the first one operating in motor mode and the second in generator mode. The rated power of each machine is 155 kW and in short-term overload mode they allow 390 kW. This ensures a wide range of tests with power up to 400 kW.The two asynchronous machines are supplied by two inverters INV1 and INV2 with PWM (pulse width modulation) control and variable frequency according to the operating modes. The two inverters have a classic structure and have a common DC link. The energy consumed by MAS1 in the motor mode is taken from MAS2 which operates in generator mode and motor – generator system losses are taken from the power supply

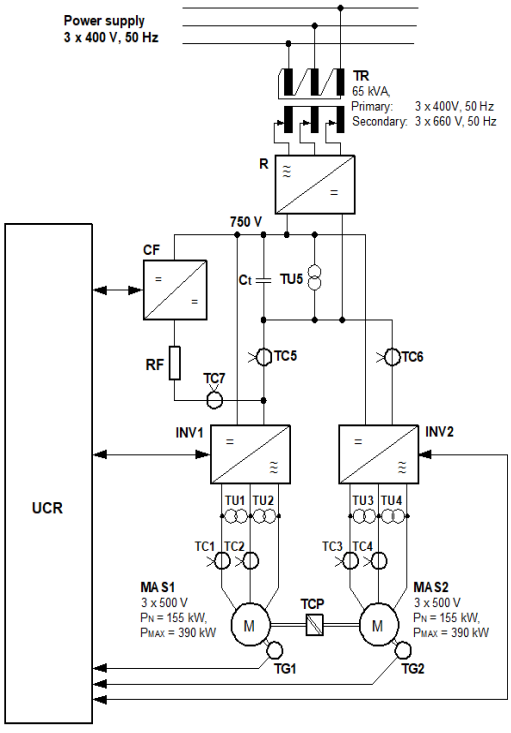


Fig. 1 The block diagram of the test bench.

(3x400 V, 50 Hz) through the transformer TR and rectifier R. For the situation of dynamic regime in the intermediate

circuit, an RF braking resistor is provided, the current through this resistor being controlled by the CF Braking Chopper.

The rest of the paper is organized as follows: Section II describe the choice of DC link capacitor. In section III, the main parameters of leading inverter are defined and his section deals with the choice of IGBT modules. It is followed by the IGBT modules verification in Section IV. Section V and VI are related to the choice of the cooling system and the power cables. Finally, some concluding remarks are drawn.

II. THE CHOICE OF THE DC LINK CAPACITOR

The following relationships are used to calculate the characteristic data for the inverter that supplies MAS1 [7]:

- Rated power,

$$S_{NINV1} = \frac{P_{1NMAS1}}{\cos\varphi_{MAS1}\cdot\eta_{MAS1}} = 188.6\ \text{kVA}\,, \quad (1)$$

where P_{MAS1}, $\cos\varphi_{MAS1}$, η_{MAS1} are the active power, the power factor and respectively the efficiency of machine MAS1.

As can be seen in the block diagram (Fig.1), the direct current intermediate circuit of the inverter INV1 is common with those of the inverter INV2, braking chopper CF and the filter of rectifier R and therefore the total capacitance value in the diagram was taken into account for the calculation of the capacitor bank.

To determine the required capacitance value we will consider the following conditions:

- ripple voltage alowed,

$$U_{RR} = 15\% \cdot U_{CC}\ ; \quad (2)$$

For rated voltage U_{CC} = 750V, it results U_{RR} = 112.5V.

- the inverter efficiency,

$$\eta_{INV1} = 93\ \%\ ;$$

- The input power of the inverter INV1,

$$P_{INV1} = S_{INV1} + p_{INV1} = 202\ \text{kW}, \quad (3)$$

where S_{INV1}, p_{INV1} are the rated power and power losses of the inverter.

To calculate the nedeed capacitance, it can be used the following approached equation [8]:

$$C_{tcalc} = \frac{P_{INV1}}{U_{RR}\left(U_{CC} - \frac{U_{RR}}{2}\right)f_R} = 8600\mu\text{F}\,, \quad (4)$$

where: f_R - the rectifier frequency, f_R=300Hz.

The RMS current through capacitor will be (approached equation) [8]:

$$I_{CRMS} = \frac{U_{RR}}{2\sqrt{2}} \cdot C_{tcalc} \cdot 2 \cdot \pi \cdot f_R = 646\ \text{A}\,. \quad (5)$$

The nedeed capacitance for the inverter INV1:

$$C_{INV1} = C_{tcalc} - (C_{INV2} + C_{CF} + C_R), \quad (6)$$

where:

C_{INV2} = 4380 µF - capacitance value of the inverter INV2;

C_{CF} = 1460 µF - capacitance value of the braking chopper CF;

C_R = 1460 µF - capacitance value of the rectifier R.

We obtain C_{INV1} = 1300 µF.

Two ZEZ SILKO **PVAJP 0 1,8/700** capacitors conected in parallel were selected with the main characteristics:

- rated capacitance C_N = 700 µF ± 10 %;
- rated DC voltage U_N= 1800V;
- insulation voltage U_i= 4800 V;
- maximum rms current I_{max}= 150 A;
- operating temperatures Θ_a = -25/+70 ˚C.

The selection criteria are met as follows:

$$C_t \geq C_{tcalc}; \quad (7)$$

$$U_N > U_{CCmax}; \quad (8)$$

$$I_{CRMS} \geq I_{CRMScalc}. \quad (9)$$

The inequality (9) results from the fact that all the capacitors in the common DC intermediate circuit are connected in parallel (8 capacitors that have the value Imax ≥ 150 A), the value of the total current they can supply will add up, exceeding the value resulting from the calculations.

I. THE CHOISE OF THE IGBT MODULE

The inverter output voltage is equal with the rated voltage of the electric machine [6].

$$U_{NINV1} = U_{NMAS1} = 500\ \text{V}_{\text{AC}}. \quad (10)$$

- The rated current phase of the inverter

Since the windings of the MAS1 electric machine are connected in star, the following results:

$$I_{NMAS1} = \frac{S_{NINV1}}{\sqrt{3}\cdot U_{NMAS1}} = 218\text{A}\,, \quad (11)$$

where: U_{NMAS1} – rated voltage of MAS1.

- Inverter overload power:

$$S_{SINV1} = 1{,}5 \cdot S_{NINV1} = 283\ \text{kVA}; \quad (12)$$

- Inverter overload phase current:

$$I_{SMAS1} = 1{,}5 \cdot I_{NINV1} = 327\ \text{A}; \quad (13)$$

- Inverter supply voltage range:

$$U_{CC} = 600 \div 900\text{V}_{\text{CC}}. \quad (14)$$

The power transistor shall be chosen with respect to the following relationships:

$$I_{TAVN} \cdot k_{SI} \leq I_{ccat}\ ; \quad (15)$$

$$U_b \cdot k_{SU} \leq U_{CEScat}\ ; \quad (16)$$

$$U_b = U_{cc}\ ; \quad (17)$$

$$I_{TAVN} = \frac{\sqrt{2}}{\pi} \cdot I_{SMAS1} = 147.2\ A\ ; \quad (18)$$

where:

I_{TAVN} - the average rated current through the transistor;

$I_{c\,cat}$ - the maximum permissible average current through the transistor;
k_{si} - the current safety factor;
U_b - the voltage that stresses the transistor in off state;
$U_{CES\ cat}$ - the maximum permissible voltage that stresses the transistor in off state;
k_{su} - the voltage safety coefficient;
U_{CC} - the intermediate circuit voltage.

Because the inverter is part of a research test bench where control errors may occur or higher power motors can be tested, the coefficients k_{su}= 1.8, respectively k_{si} = 10 were chosen resulting:

$$U_{CES\,cat} > 1500 \text{ V}; \quad (19)$$

$$I_{C\,cat} > 1500 \text{ A}. \quad (20)$$

The Mitsubishi **CM2400HC - 34H IGBT** module was preliminarily selected, with the main characteristics:

- capsule with a single IGBT - diode switching device;
- collector emitter voltage - V_{CES} = 1700 V;
- direct collector current I_C = 2400A;
- module dimensions : 190 x 140 mm.

An extract from the technical specification of this module is shown in Fig. 2. (a) and (b) [9].

III. Testing of the IGBT Module

Testing was done based on the **MELCOSIM Ver 5.4.0** application, developed by Mitsubishi for the selection of its own IGBT modules, arranged in the most common topologies.

MELCOSIM is designed for the calculation of the stationary and dynamic power losses that occur in modules as well as the temperature variation in the junctions of IGBT transistors and diodes in modules, due to both the direct conduction and switching of these semiconductor devices.

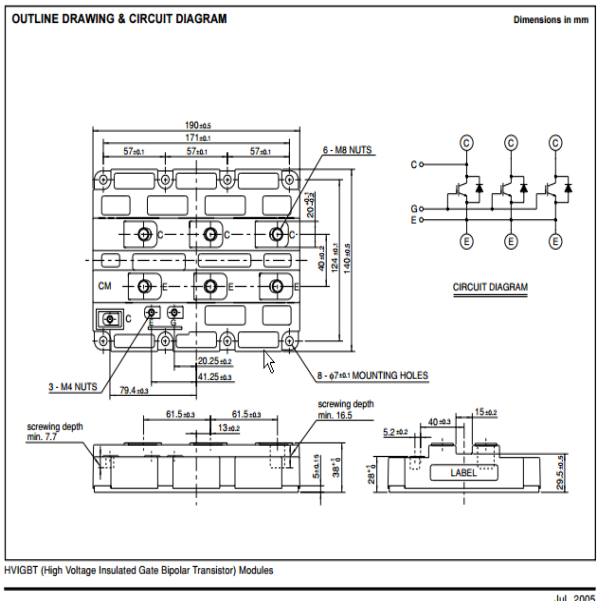
The corresponding data obtained for the specific dynamic thermal resistance of the power modules are used for the design, calculation and dimensioning of the heat sink.

A. *MELCOSIM Program Description*

The converter type (two or three levels) can be selected from the main screen and then, switching in the screens for input and output data is done. The input-output screens consist of four sections: the module code and type, the specified module property, the input field "Common Conditions" for the converter characteristic data and the output field for the calculation results.

MELCOSIM expects nine entries called "Common Conditions" to be able to calculate power losses and temperature in the junction: modulation strategy, output current Io, DC link *Vcc* voltage, switching frequency *Fc*, output frequency *Fo*, modulation factor *M*, load power factor *PFs* and the heat sink temperature measured directly below the *Ts* capsule.

The results field provides the following information: average power losses for IGBT and freewheel diode, divided into static and dynamic parts, total power loss of the module, heat sink temperature, average and maximum temperature in the transistor junction and in the freewheel diode. The graphics output provides the possibility to analyze power losses and temperature in junction by changing one of the application conditions parameters within the specification.



(a)

CM2400HC-34H

HIGH POWER SWITCHING USE INSULATED TYPE

3rd-Version HVIGBT (High Voltage Insulated Gate Bipolar Transistor) Modules

MAXIMUM RATINGS

Symbol	Item	Conditions	Ratings	Unit
V_{CES}	Collector-emitter voltage	V_{GE} = 0V, T_j = 25°C	1700	V
V_{GES}	Gate-emitter voltage	V_{CE} = 0V, T_j = 25°C	±20	V
I_C	Collector current	T_C = 80°C	2400	A
I_{CM}		Pulse (Note 1)	4800	A
I_E (Note 2)	Emitter current		2400	A
I_{EM} (Note 2)		Pulse (Note 1)	4800	A
P_C (Note 3)	Maximum power dissipation	T_C = 25°C, IGBT part	17800	W
T_j	Junction temperature		−40 ~ +150	°C
T_{op}	Operating temperature		−40 ~ +125	°C
T_{stg}	Storage temperature		−40 ~ +125	°C
V_{iso}	Isolation voltage	RMS, sinusoidal, f = 60Hz, t = 1min.	4000	V
t_{psc}	Maximum short circuit pulse width	V_{CC} = 1150V, V_{CES} ≤ 1700V, V_{GE} = 15V, T_j = 125°C	10	µs

ELECTRICAL CHARACTERISTICS

Symbol	Item	Conditions	Limits Min	Limits Typ	Limits Max	Unit
I_{CES}	Collector cut-off current	V_{CE} = V_{CES}, V_{GE} = 0V, T_j = 25°C	—	—	36	mA
$V_{GE(th)}$	Gate-emitter threshold voltage	I_C = 240mA, V_{CE} = 10V, T_j = 25°C	4.5	5.5	6.5	V
I_{GES}	Gate leakage current	V_{GE} = V_{GES}, V_{CE} = 0V, T_j = 25°C	—	—	0.5	µA
$V_{CE(sat)}$	Collector-emitter saturation voltage	I_C = 2400A, V_{GE} = 15V, T_j = 25°C (Note 4)	—	2.60	3.30	V
		I_C = 2400A, V_{GE} = 15V, T_j = 125°C (Note 4)	—	3.10	—	
C_{ies}	Input capacitance	V_{CE} = 10V, f = 100kHz, V_{GE} = 0V, T_j = 25°C	—	210	—	nF
C_{oes}	Output capacitance		—	30.0	—	nF
C_{res}	Reverse transfer capacitance		—	10.1	—	nF
Q_G	Total gate charge	V_{CC} = 850V, I_C = 2400A, V_{GE} = 15V, T_j = 25°C	—	19.8	—	µC
V_{EC} (Note 2)	Emitter-collector voltage	I_E = 2400A, V_{GE} = 0V, T_j = 25°C (Note 4)	—	2.30	3.00	V
		I_E = 2400A, V_{GE} = 0V, T_j = 125°C (Note 4)	—	1.85	—	
$t_{d(on)}$	Turn-on delay time	V_{CC} = 850V, I_C = 2400A, V_{GE} = ±15V	—	—	1.60	µs
t_r	Turn-on rise time	$R_{G(on)}$ = 0.27Ω, T_j = 125°C, L_s = 80nH	—	—	1.30	µs
E_{on}	Turn-on switching energy	Inductive load	—	810	—	mJ/pulse
$t_{d(off)}$	Turn-off delay time	V_{CC} = 850V, I_C = 2400A, V_{GE} = ±15V	—	—	2.70	µs
t_f	Turn-off fall time	$R_{G(off)}$ = 0.27Ω, T_j = 125°C, L_s = 80nH	—	—	0.80	µs
E_{off}	Turn-off switching energy	Inductive load	—	870	—	mJ/pulse
t_{rr} (Note 2)	Reverse recovery time	V_{CC} = 850V, I_C = 2400A, V_{GE} = ±15V	—	—	2.70	µs
Q_{rr} (Note 2)	Reverse recovery charge	$R_{G(on)}$ = 0.27Ω, T_j = 125°C, L_s = 80nH	—	630	—	µC
E_{rec} (Note 2)	Reverse recovery energy	Inductive load	—	330	—	mJ/pulse

Note 1. Pulse width and repetition rate should be such that junction temperature (T_j) does not exceed T_{opmax} rating (125°C).
2. The symbols represent characteristics of the anti-parallel, emitter to collector free-wheel diode (FWDi).
3. Junction temperature (T_j) should not exceed T_{jmax} rating (150°C).
4. Pulse width and repetition rate should be such as to cause negligible temperature rise.

(b)

Fig. 2 Extract from the technical specification of the IGBT module CM2400HC-34H.

All calculation results can be exported to a text file [10].

B. IGBT Module Testing in Overload Conditions

Testing the IGBT module in overload conditions was performed using the MELCOSIM application with the following input data (Fig 3):

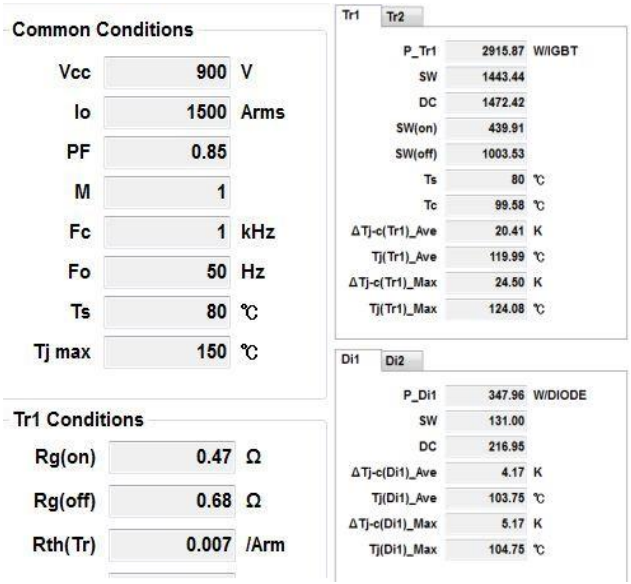


Fig. 3 „Common Condition" and „Result" fields for overload testing.

Vcc - the maximum value for the DC circuit voltage, equal to the voltage that stresses the transistor in off state, respectively equal to the voltage limited by the braking chopper (CF) that is set to the value of 900 Vdc;

Io - The maximum output current of the asynchronous machine adjusted until the program no longer returns invalid messages.

The valid returned parameters correspond to the most unfavorable situation in which the device can operate for the chosen conditions, resulting:

$$I_O \gg I_{SMAS1}\,. \qquad (21)$$

C. IGBT Module Testing for Operation in Rated Conditions (Fig 4):

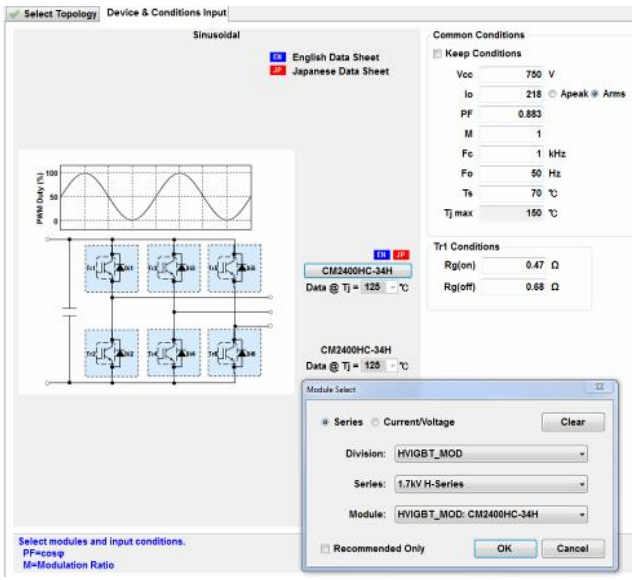


Fig. 4 The „Device & Components" screen for IGBT module testing at the rated condition operation.

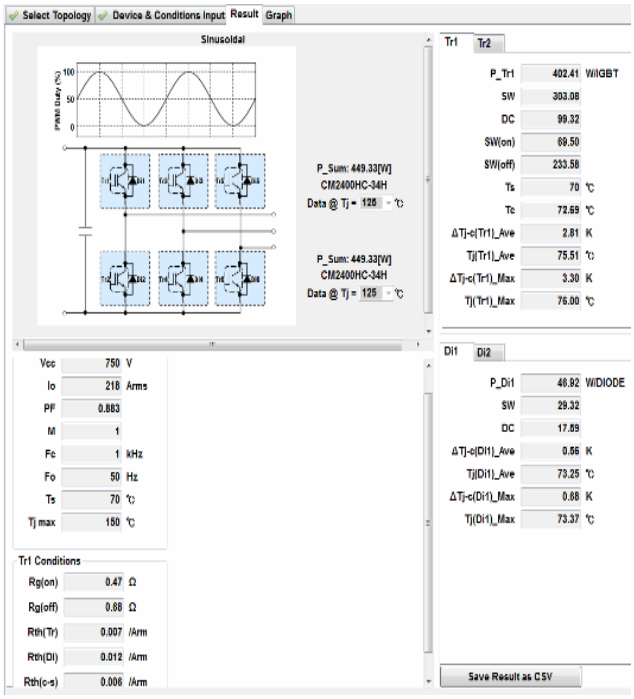


Fig. 5 "Result" screen with the characteristic values for the semiconductor components corresponding to a phase of the inverter.

The following parameters for the operation at rated load values have been introduced (Fig. 4 and Fig. 5):

- Input voltage *Vcc* (U_{ININV1}) = 750 V ;
- Output rated current *Io* (I_{NMAS1}) = 218 A_{RMS};
- Machine power factor *PF* ($\cos\varphi_{NMAS1}$) = 0.883;
- Modulation factor *M* = 1;
- Switching frequency *Fc* = 1 kHz;
- Converter output frequency *Fc* = 50 Hz;
- Heat sink temperature Ts = 70 °C.

The following considerations were considered in order to choose the gate control resistances which are relevant for the turn on and for the turn off process of the IGBT transistors, respectively:

- achieving minimal switching losses in both turn on and turn off by choosing the lowest possible resistance values;
- the peak current of the gate control devices.

The following values have been chosen using the data sheets:

- conduction input resistance $R_{g(ON)}$ = 0.47 Ω/1W;
- blocking resistance $R_{g(Off)}$ = 0.68 Ω/1W.

IV. CHOOSING THE COOLING SYSTEM

The heat transfer diagram (Fig. 6) can be drawn up with the values obtained in the "Result" screen [11].

The "Graph" screen can generate the dissipated power versus time characteristic for two modules belonging to the same phase, giving additional information when multiple capsules are mounted on the same heat sink (Fig. 7).

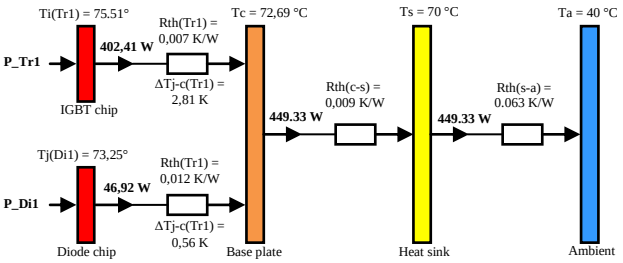


Fig. 6 The heat transfer diagram for the chosen IGBT module.

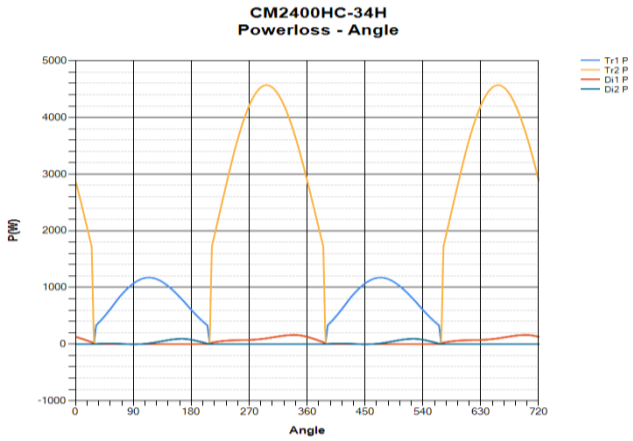


Fig. 7 Power dissipation versus time dependence for modules 1 and 2 of the inverters.

The heat transfer resistance between ambient and heat sink is:

$$Rth_{s-a} = \frac{T_c - T_a}{P\ Sum} - Rth_{c-s} = 0.063\ \text{K/W}, \quad (22)$$

where:

T_c - case temperature;
T_a - ambient temperature;
P_Sum - total power dissipated by the module due to the conduction and commutation losses.

A heat sink is chosen from the catalog in order to meet the condition:

$$Rth_{s\text{-}a}cat < Rth_{s\text{-}a}calc, \quad (23)$$

where:

$Rth_{s\text{-}a}calc$ - calculated thermal resistance heat sink – ambient;
$Rth_{s\text{-}a}cat$ - thermal resistance heat sink – ambient catalog value.

A heat sink with the profile shown in Fig. 8 having a length of 250 mm, manufactured by MECCAL type **P200 83** was chosen [12].

From the thermal transfer curves shown in Fig. 9,it can be seen that, provided an air speed of *Vair* = 7.2 m/s through the heatsink with a length of 250 mm, the following resistance is obtained:

$$Rth_{s\text{-}a}cat = 0.051\ \text{K/W}, \quad (24)$$

which is less than the value in (22), so the cooling system is chosen properly.

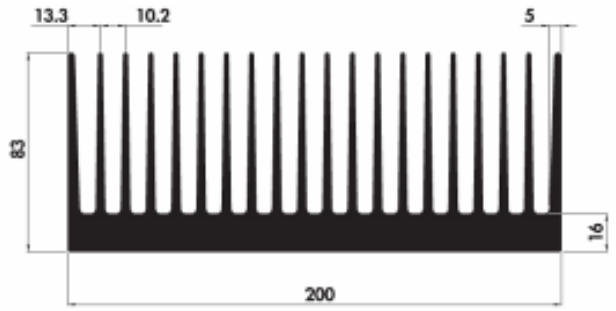


Fig. 8 Transversal section through the heat sink.

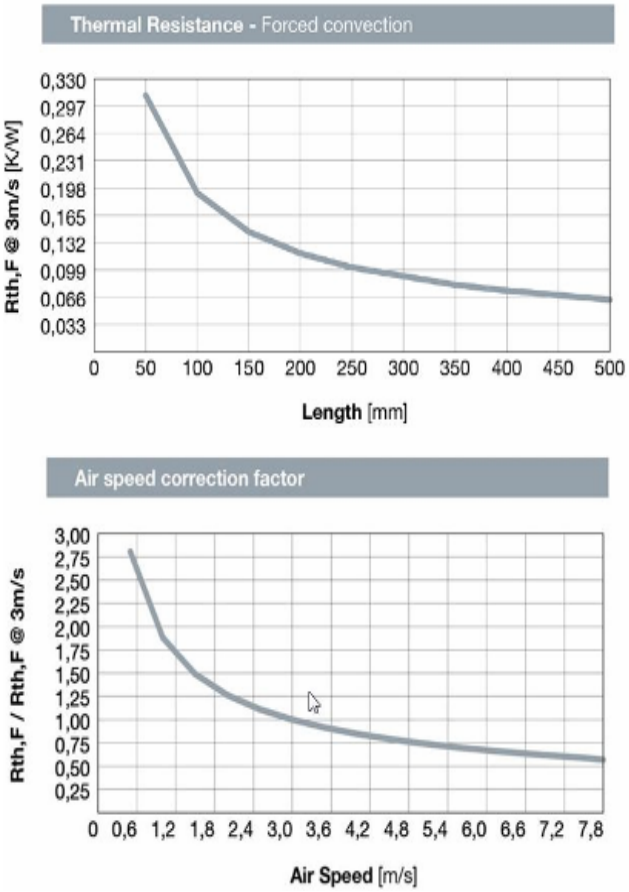


Fig. 9 The thermal transfer curves for the P200 83 heat sink.

V. The Choise of the Power Cables

The following characteristics of the inverters must be taken into account when dimensioning the cables:

- application: railway inverters;
- input voltage: 900 Vdc;
- rated current: 218 A;
- overload current: 327 A.

The cables used for railway rolling stock comply with the standard SR EN 50355:2014 "*Railway applications - Railway rolling stock cables having special fire performance - Guide to use*" [13].

The size of the cable section must be chosen from the standardized cable sections. When choosing the conductor section, the following factors will be taken into account:

- Electrical stresses in insulation, which are due to the operating voltage;

- Electrical stresses due to the intensity of the current flowing through the circuit and which must be lower than those allowed;
- Thermal stresses of the cables due to long-term, overload or short-circuit currents, taking into account the values indicated by the manufacturer and the application of the correction coefficients due to the positioning of the cables during installation as well as the maximum ambient operating temperatures.

The range of HELUTHERM 145 cables produced by HELUKABEL meets the required conditions [14].

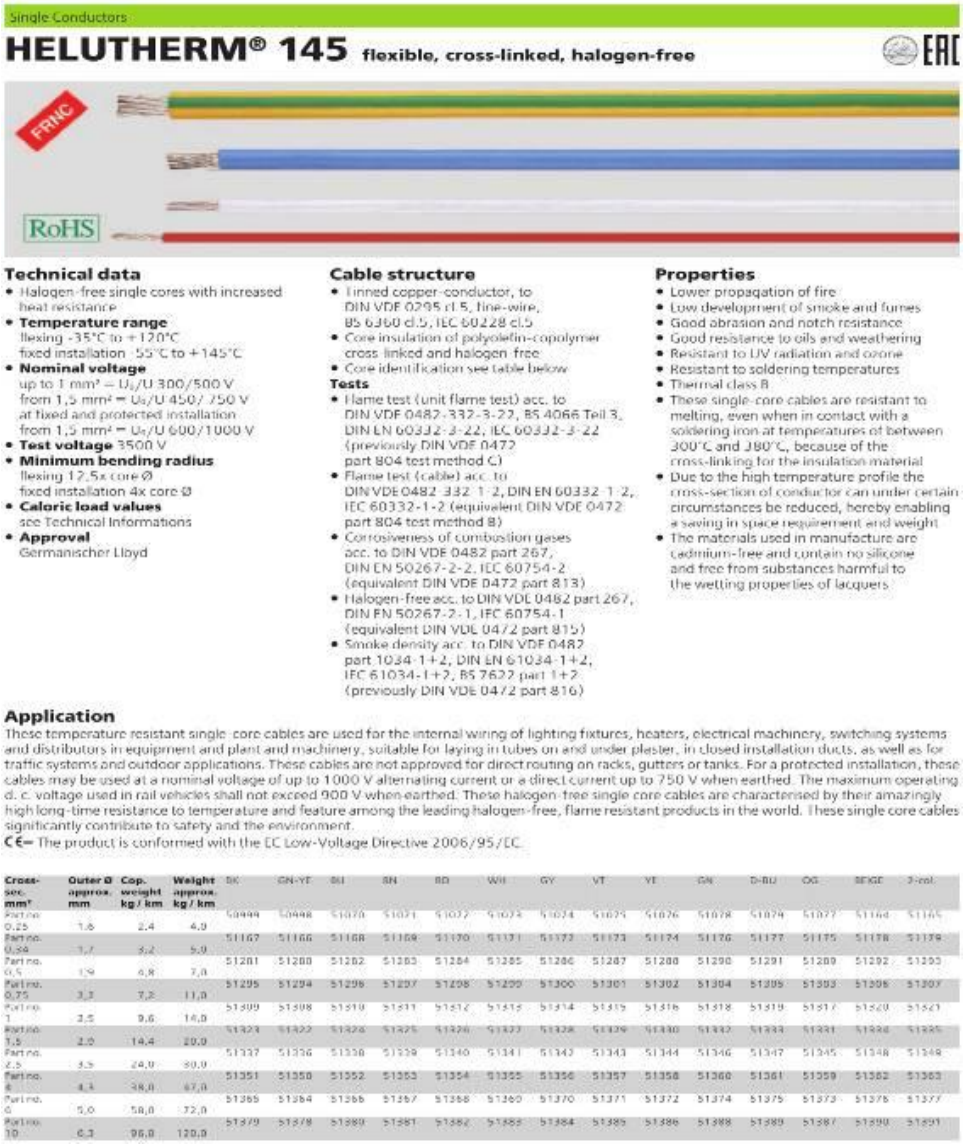
Fig. 10 shows the catalog sheet for this type of cables and in Fig. 11 is figured the table of allowed currents and correction coefficients.

According to the catalog sheet, the selection criteria are met as follows:

- Electrical stresses in insulation, which are due to the operating voltage:
  - for cables up to 1 mm^2 U_0/U 300/500 V;
  - for cables from 1.5 mm^2 U_0/U 450/750 V;
  - at fixed and protected installation from 1.5 mm^2 U_0/U 600/1000 V.
- Electrical stresses due to current intensity in the case of outdoor positioning:
  - for outdoor wiring situation 70 mm^2 cable supports a current of 391 A, bigger than overload current – 327A.

Cables with the following codes were chosen:

- 51476 - 70 mm^2 black cable;
- 51340 - 2.5 mm^2 red cable;
- 51338 - 2.5 mm^2 blue cable;
- 51298 - 0.75 mm^2 red cable izolated in SCSI tube;
- 51296 - 0.75 mm^2 blue cable izolated in SCSI tube.



Single Conductors

HELUTHERM® 145 flexible, cross-linked, halogen-free

FRNC

RoHS

Technical data
- Halogen-free single cores with increased heat resistance
- **Temperature range**
  flexing -35°C to +120°C
  fixed installation -55°C to +145°C
- **Nominal voltage**
  up to 1 mm² = U_0/U 300/500 V
  from 1,5 mm² = U_0/U 450/ 750 V
  at fixed and protected installation
  from 1,5 mm² = U_0/U 600/1000 V
- **Test voltage** 3500 V
- **Minimum bending radius**
  flexing 12,5x core Ø
  fixed installation 4x core Ø
- **Caloric load values**
  see Technical Informations
- **Approval**
  Germanischer Lloyd

Cable structure
- Tinned copper-conductor, to DIN VDE 0295 cl.5, fine-wire, BS 6360 cl.5, IEC 60228 cl.5
- Core insulation of polyolefin-copolymer cross-linked and halogen-free
- Core identification see table below

Tests
- Flame test (unit flame test) acc. to DIN VDE 0482-332-3-22, BS 4066 Teil 3, DIN EN 60332-3-22, IEC 60332-3-22 (previously DIN VDE 0472 part 804 test method C)
- Flame test (cable) acc. to DIN VDE 0482-332-1-2, DIN EN 60332-1-2, IEC 60332-1-2 (equivalent DIN VDE 0472 part 804 test method B)
- Corrosiveness of combustion gases acc. to DIN VDE 0482 part 267, DIN EN 50267-2-2, IEC 60754-2 (equivalent DIN VDE 0472 part 813)
- Halogen-free acc. to DIN VDE 0482 part 267, DIN EN 50267-2-1, IEC 60754-1 (equivalent DIN VDE 0472 part 815)
- Smoke density acc. to DIN VDE 0482 part 1034-1+2, DIN EN 61034-1+2, IEC 61034-1+2, BS 7622 part 1+2 (previously DIN VDE 0472 part 816)

Properties
- Lower propagation of fire
- Low development of smoke and fumes
- Good abrasion and notch resistance
- Good resistance to oils and weathering
- Resistant to UV radiation and ozone
- Resistant to soldering temperatures
- Thermal class B
- These single-core cables are resistant to melting, even when in contact with a soldering iron at temperatures of between 300°C and 380°C, because of the cross-linking for the insulation material
- Due to the high temperature profile the cross-section of conductor can under certain circumstances be reduced, hereby enabling a saving in space requirement and weight
- The materials used in manufacture are cadmium-free and contain no silicone and free from substances harmful to the wetting properties of lacquers

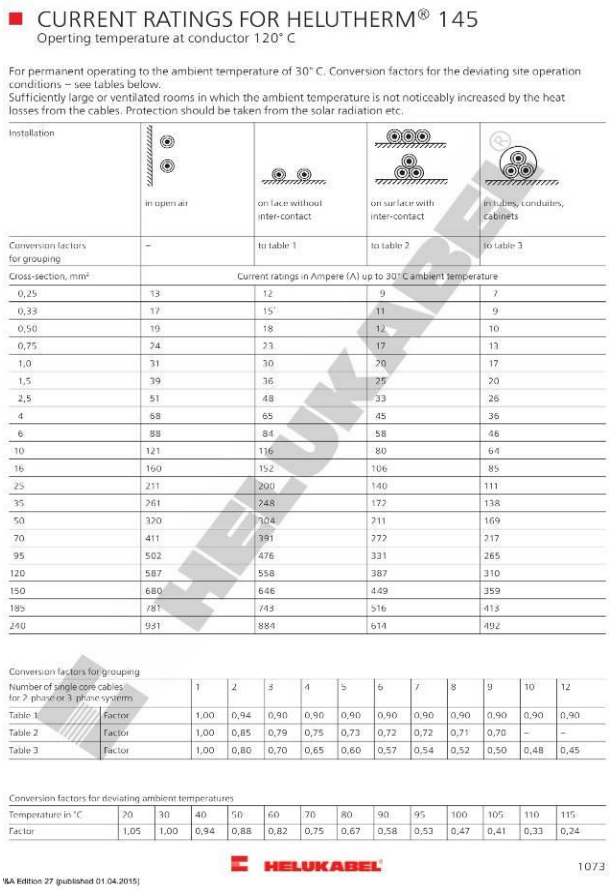
Application

These temperature resistant single-core cables are used for the internal wiring of lighting fixtures, heaters, electrical machinery, switching systems and distributors in equipment and plant and machinery, suitable for laying in tubes on and under plaster, in closed installation ducts, as well as for traffic systems and outdoor applications. These cables are not approved for direct routing on racks, gutters or tanks. For a protected installation, these cables may be used at a nominal voltage of up to 1000 V alternating current or a direct current up to 750 V when earthed. The maximum operating d. c. voltage used in rail vehicles shall not exceed 900 V when earthed. These halogen-free single core cables are characterised by their amazingly high long-time resistance to temperature and feature among the leading halogen-free, flame resistant products in the world. These single core cables significantly contribute to safety and the environment.

CE The product is conformed with the EC Low-Voltage Directive 2006/95/EC.

Cross-sec. mm²	Outer Ø approx. mm	Cop. weight kg/km	Weight approx. kg/km	BK	GN-YE	BU	BN	RD	WH	GY	VT	YE	GN	D-BU	OG	BEIGE	3-col.
Part no.				50444	50446	51070	51071	51072	51073	51074	51075	51076	51078	51079	51077	51164	51165
0,25	1,6	2,4	4,0														
Part no.				51167	51166	51168	51169	51170	51171	51172	51173	51174	51176	51177	51175	51178	51179
0,34	1,7	3,2	5,0														
Part no.				51281	51280	51282	51283	51284	51285	51286	51287	51288	51290	51291	51289	51292	51293
0,5	1,9	4,8	7,0														
Part no.				51295	51294	51296	51297	51298	51299	51300	51301	51302	51304	51305	51303	51306	51307
0,75	2,3	7,2	11,0														
Part no.				51309	51308	51310	51311	51312	51315	51314	51315	51316	51318	51319	51317	51320	51321
1	2,5	9,6	14,0														
Part no.				51323	51322	51326	51325	51326	51327	51328	51329	51330	51332	51333	51331	51336	51335
1,5	2,9	14,4	20,0														
Part no.				51337	51336	51338	51339	51340	51341	51342	51343	51344	51346	51347	51345	51348	51349
2,5	3,5	24,0	30,0														
Part no.				51351	51350	51352	51353	51354	51355	51356	51357	51358	51360	51361	51359	51362	51363
4	4,4	38,0	47,0														
Part no.				51365	51364	51366	51367	51368	51369	51370	51371	51372	51374	51375	51373	51376	51377
6	5,0	58,0	72,0														
Part no.				51379	51378	51380	51381	51382	51383	51384	51385	51386	51388	51389	51387	51390	51391
10	6,3	96,0	120,0														

Fig. 10 HELUTHERM 145 cable catalog sheet.



CURRENT RATINGS FOR HELUTHERM® 145
Operting temperature at conductor 120° C

For permanent operating to the ambient temperature of 30° C. Conversion factors for the deviating site operation conditions – see tables below.
Sufficiently large or ventilated rooms in which the ambient temperature is not noticeably increased by the heat losses from the cables. Protection should be taken from the solar radiation etc.

Installation	in open air	on face without inter-contact	on surface with inter-contact	in tubes, conduites, cabinets
Conversion factors for grouping	–	to table 1	to table 2	to table 3
Cross-section, mm²	Current ratings in Ampere (A) up to 30°C ambient temperature			
0,25	13	12	9	7
0,33	17	15	11	9
0,50	19	18	12	10
0,75	24	23	17	13
1,0	31	30	20	17
1,5	39	36	25	20
2,5	51	48	33	26
4	68	65	45	36
6	88	84	58	46
10	121	116	80	64
16	160	152	106	85
25	211	200	140	111
35	261	248	172	138
50	320	304	211	169
70	411	391	272	217
95	502	476	331	265
120	587	558	387	310
150	680	646	449	359
185	781	743	516	413
240	931	884	614	492

Conversion factors for grouping

Number of single core cables for 2 phase or 3 phase systems		1	2	3	4	5	6	7	8	9	10	12
Table 1	Factor	1,00	0,94	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90	0,90
Table 2	Factor	1,00	0,85	0,79	0,75	0,73	0,72	0,72	0,71	0,70	–	–
Table 3	Factor	1,00	0,80	0,70	0,65	0,60	0,57	0,54	0,52	0,50	0,48	0,45

Conversion factors for deviating ambient temperatures

Temperature in °C	20	30	40	50	60	70	80	90	95	100	105	110	115
Factor	1,05	1,00	0,94	0,88	0,82	0,75	0,67	0,58	0,53	0,47	0,41	0,33	0,24

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Fig. 11 Current ratings for HELETHERM 145.

VI. Conclusions

The research conducted in this paper highlights the fact that when choosing the force components for a test – experimentation bench designed to test various control strategies for traction converters, it is necessary to consider the addition of bigger safety coefficients than usual at their technical characteristics covering some control errors which may occur. It has also been shown that a forced ventilation cooling system is suitable, cheaper and less complex than a liquid cooling one.

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Contribution of authors:
First author – 50%
First coauthor – 30%
Second coauthor – 20%

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