Evaluation of thermal performance of automotive inverter with laminar busbars

Michal Frivaldsky
Department of mechatronics and electronics, Faculty of electrical engineering and information technologies
University of Zilina
Zilina, Slovakia
michal.frivaldsky@feit.uniza.sk

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***Abstract*— The paper deals with traction inverters used in the field of electromobility, while the focus of the study is, investigation of the thermal performance, when laminar busbars are used. Initially the specifications on the circuit configuration are being discussed. It is then followed by the component selection, while considering main circuit components, the DC link capacitor and power transistor modules represent essential parts for inverter design. Investigation of thermal performance is realized for semiconductor module, and busbars. For this purpose, the simulation model was developed, which contains all required definitions for investigation. With the use of simulation model, it is possible to study the influence of various circuit components, busbar geometry and the ways how they influence the thermal performance of the converter because of electric current flow.**

Keywords—traction inverter, DC-link capacitor, thermal performance, simulation

I. Introduction

Currently, e-mobility is gaining prominence within the field of transport systems. The demands for efficiency and power density are constantly increasing, even if electric vehicle is considered. In this field we talk about improvements regarding traveling distance and charging speed. One way how to reach high values of travelling distances is based on the increase of the voltage level of traction battery. This also brings advantages, especially in the form of faster charging and smaller requirements for the conduction of high values of the charging currents, which may result in the use of conductors with a smaller cross-section, thus saving on conductor materials as well [1] – [3]. Another possible way to increase efficiency is to reduce the weight of the components traction system of the vehicle, while increasing their performance. For such requirements, new semiconductor components that are able to operate at higher voltage levels must be used. Simultaneously focus is given on reduction of their dimensions sustaining higher power capability they can handle. Understandably, it is not enough just to design high-quality semiconductor components, but also all other components which are considered within the traction system of electric vehicle, while specifications must meet certain requirements [4] – [6]. In addition, it is necessary also to ensure effective power distribution from the traction battery to the electrical terminals of the engine. To ensure the highest possible efficiency of the vehicle's traction system it is necessary to minimize the power loss that arises on individual components, while each component require a specific method of minimization of the power losses [7] – [9].

This paper deals with the analysis of thermal performance which is influenced by components of the traction inverters. The calculations of main circuit components are given here, according to the defined nominal parameters. One of the main aims of this work is also analysis of the influence of busbar system on the thermal performance of designed inverter. The analyses are realized through FEM simulations. Proposed simulation model is developed for the purposes of the evaluation of various geometrical and material arrangement of busbar for traction inverters.

II. Specifications on the circuit configuration

In the field of electromobility, alternators are used to power electric vehicles motors, as their use is much more efficient compared to unidirectional engines. It follows that a power supply is required to power the electric vehicle alternating current. The primary task of the traction inverter (Fig. 1) is the conversion of direct current, which comes from an traction battery to drive an electric motor. In addition, traction inverters perform power flow control at regenerative braking, DC voltage boosting, switching protection and they must be able to regulate the output voltage and current for the traction motor based on speed and torque requirements.

It is necessary to realize that there are many configurations of electric and hybrid vehicles that contain the same basic components, i.e. traction battery, inverter, electric motor Differences within individual configurations are mostly in the number of engines used to power the vehicle, while nominal parameters also significantly differ between individual configurations. If pure electric vehicle is considered, then DC Voltage of battery systems is expected to be risen from 400 Vdc to 800 Vdc representing new standard [10] – [11]. Due to requirements on components selection and converter design itself, key nominal parameters are:

- DC voltage = 800 Vdc
- Maximum current = 300 A
- Switching frequency = 15 kHz

Above mentioned parameters are affecting selection criterions related to main circuit component, i.e. DC link capacitor and power transistors, while they mostly affect total thermal performance of inverter. DC link capacitor must be designed sufficiently to sustain power demands reflecting voltage ripple within DC link of the inverter. Consequently, the selection of power semiconductors is important as well, while for nominal current specifications, the transistor power modules are required for practical design. Fig. 1 shows block diagram of traction system considering recuperation converter (will be not included for analysis), motor inverter (point of interest) and electric machine.

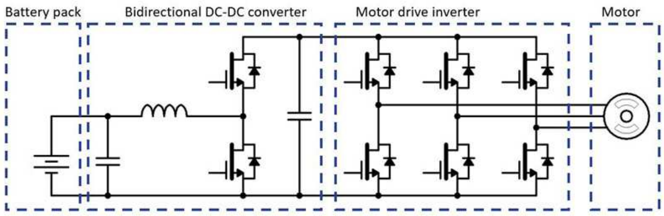

Fig. 1. Block diagram of the traction drive with power electronic components

III. Calculation of circuit components of automotive inverter (800 V/300 A)

At this point, focus was given on the calculation of circuit elements for traction inverter. According to the nominal parameters of the system, it is required to choose appropriate semiconductor components, calculate the capacitance value of the DC link circuit capacitor and to design a bus system that will serve to interconnect all power parts of traction inverter components.

SiC technology of power transistor is preferable for given parameters. For each phase of 3-phase system, the half-bridge module FF3MR12KM1 was selected, while these type is suitable due to high voltage and current rating [12], and due to package technology and plug and play driving circuit. Regarding cross reference design with competitive solutions, it is not the main topic of this research as main focus is given on development of thermal model, which supports possibilities of evaluation of bus-bas system influence, while initially laminar solution is considered here.

A. Calculation of DC link capacitor

For the procedure of calculation of nominal properties of DC link capacitor, the study from [12] was applied, while it is based on the analytical calculation of the RMS current stress on the DC-link capacitor of voltage-PWM converter systems.

Output phase current IN(RMS) was selected based on the requirements for the traction motor. ΔVRipple is allowed voltage ripple on the DC bus. The modulation index M was defined based on the maximum current of the capacitor for a given power factor Φ, while the power factor values being for motors with permanent magnets ranges from 0.7-0.95.

- Switching frequency – f_{sw} = 15 kHz
- Nominal phase current - $I_{N(RMS)}$ = 90 A
- Voltage ripple at DC link - $_{\Delta}V_{Ripple}$ = 13 $V_{p\text{-}p}$
- Modulation index - M = 0.65
- Power factor - Φ = 0.75

When sizing the DC link capacitor for inverter applications, limiting requirement is current ripple of capacitor. The input current of the inverter consists of two components, unidirectional DC and alternating AC part, while:

$$i = i_{ac} + i_{dc} = i_{ac} + i_{AVG} \quad (1)$$

The following applies to the RMS value of the input current:

$$I_{rms} = I_{ac}{}^2{}_{\_rms} + I^2{}_{dc} = I_{ac}{}^2{}_{\_rms} + I^2{}_{avg} \quad (2)$$

As frequency is being increased, the battery impedance increases and the capacitor impedance decreases, which is advantageous for high frequency alternating current flow. It is assumed, that the battery is a source of pure direct current, and the capacitor must supply all ac part of the current.

Based on this, we can assume that value of the capacitor current is equal to the value of the ripple current circulating within the inverter main circuit and thus applies to:

$$I_{ac\_RMS} = I_{C\_RMS} \quad (3)$$

Considering previous equation, it is possible to calculate RMS value for the capacitor current:

$$I_{C\_RMS} = \sqrt{}I^2{}_{RMS} - I^2{}_{AVG} \quad (4)$$

The calculation for the mean value of the inverter input current is obtained from the following relationship:

$$I_{AVG} = 2/T \int i \, dt \quad (5)$$

whereby by modifying (5) final formula for average value is as follows:

$$I_{AVG} = 3/4 * I_{N(RMS)} * M * \cos(\varphi) = = 3/4 * 90 * 0.65 * 0.732 = 32.102 \text{ A} \quad (6)$$

For the effective value of the current, similar approach was used, while the final formula for calculation is:

$$I_{RMS} = I_{N(RMS)} \sqrt{\{ 2\sqrt{3}\, \pi\, M\, (1/4 + \cos 2\, \varphi)\}} = 90 * \sqrt{\{ 2\sqrt{3}\, \pi * 0.65 * (1/4 + 0.7322)\}} = = 67.543 \text{ A} \quad (7)$$

Integrating (6) and (7) into (4) a final value of the current rating of DC link capacitor is:

$$I_{C\_RMS} = \sqrt{}I^2{}_{RMS} - \sqrt{}I^2{}_{AVG} = 59.426 \text{ A} \quad (8)$$

Another function of the capacitor is to compensate voltage fluctuations and ensure DC bus reinforcement. This is very important because voltage ripple is a cause of a current ripple within the individual phases, while the result is ripple of the torque [13]. So, the value of capacitance reflecting allowed voltage ripple can be calculated using (9).

$$C = I_{C\_RMS} * \Delta t / \Delta V = I_{C\_RMS} * \Delta V * f_{sw} = 304.75\ \mu\text{F} \quad (9)$$

B. Design of the busbar

The size of the conductor that affects the bus is very important in the calculation and design of the mechanical and electrical properties of the bus. The minimum thickness and width of the bus is determined based on the current demands. The electrical aspects include bus current density. The requirement is to ensure that the current density does not exceed value 5 A / mm^2. Based on this requirement, we must determine a sufficient cross-section bus. System parameters for bus-bar design:

- System current = 300 A
- Bus-bar current density = 5 A/mm2
- Bus-bar power rating = 100 kW

Minimal required area of the busbar is defined by system current and bus-bar current density, so minimal copper area is 60 mm^2. At this point, it must be noted that type of the busbar as well as geometrical parameters are affecting electrical parameters and in final thermal performance of inverter. Properties of selected busbar are:

$$S_{NOM} = w * h = 25\ mm * 3\ mm = 75\ mm^2 \qquad (10)$$

, where w is width and h is height of the busbar conductor.

Dealing with power dissipation, initially self-resistance of busbar must be determined (11):

$$R = \rho * l * S_{NOM} = 45.87\ \mu\Omega \qquad (11)$$

Then for the calculation of the value of power dissipation, next equation shall be used (12):

$$P = R * I^2\_{IN} = 45.87\ \mu\Omega * 300^2 = 4.128\ \text{W} \qquad (12)$$

For the purposes of simulation analyses of thermal performances, the determination of the resistance and power dissipation per volume unit must be also calculated (13) - (14).

$$R_{mm}{}^3 = \rho * l\ S_{NOM} = 17.2\mu\Omega \qquad (13)$$

$$P = R_{mm3} * J_{nom2} = \ 0.275\ m\text{W} \qquad (14)$$

IV. THERMAL ANALYSIS OF CONSIDERED AUTOMOTIVE INVERTER

At this starting point, it is very important to mention that the dimensions of the bus system should be designed to achieve not only low stray inductance, but also to provide optimal thermal performance. It means here that the limits of conductive and non-conductive bus materials will not markedly influence thermal limits of used semiconductor components [14].

Considered inverter is composed of three power transistor modules, while one is composed as half-bridge, i.e. it represent one leg (phase) of three-phase bridge inverter. Individual interconnections between inverter phases are realized with the used of busbar system, whereby for considered solution laminated buss bars are defined.

The design of laminated buses must therefore also address the issue of thermal problem. It is necessary to keep the bus temperature within a certain range depending on insulation material used. The operating temperature of the bus reaches a temperature within the range 70 ° C - 120 ° C. If this temperature is exceeded, there is a risk of damage of the insulating material and thus electrical insulation cannot be guaranteed between layers of the bus (if multi-layer arrangement is used). On the other hand, a low bus temperature means that the bus system is oversized due to the larger geometric dimensions, which leads to higher material costs.

A. *Thermal simulation model of the automotive inverter system*

According to the calculated and proposed parameters for the DC busbar the geometry model was made for the individual busses of inverter (Fig. 2). The process of busbar design is not a main aim of this paper; thus it is not discussed in detail here.

Thermal simulation model of the busbar considers also terminal and connector ports for positive and negative bus, DC-link capacitors, and power transistor modules.

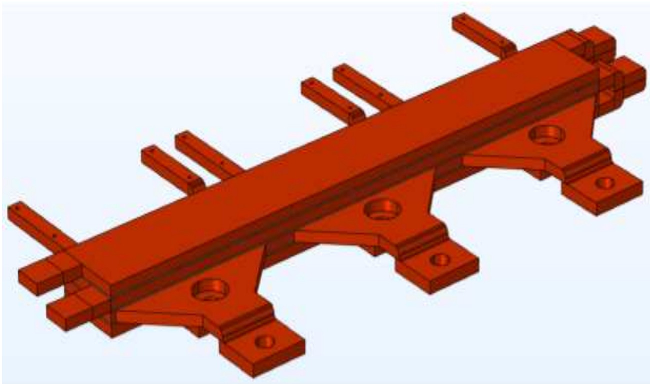

Fig. 2. Proposed geometry of busbar for designed inverter.

Consequently, due to requirements on high credibility of developed simulation model, the complex thermal simulation model of power semiconductor module was made (Fig. 3). The external dimensions of the modelled module are identical to the dimensions from selected transistor module FF3MR12KM1datasheet. Internal structure of the model considers power terminals and silicon power chips. Detailed internal structure was not possible to identify due to disability to search free media listing such details.

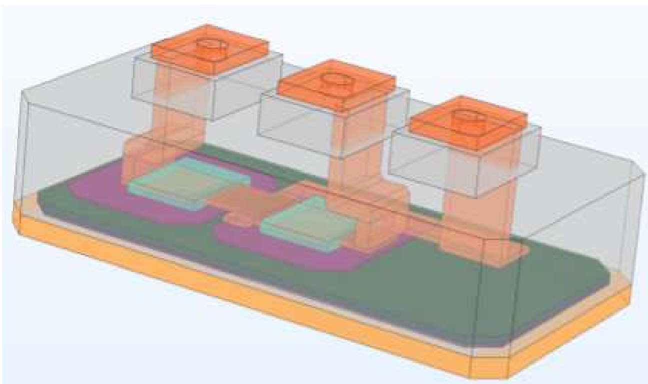

Fig. 3. FEM model of the power semiconductor module.

The last part of the simulation model is design of DC-link capacitors. Because calculation reflects the requirements of the single-phase system, for 3-phase system 3 capacitors must be used (Fig. 4).

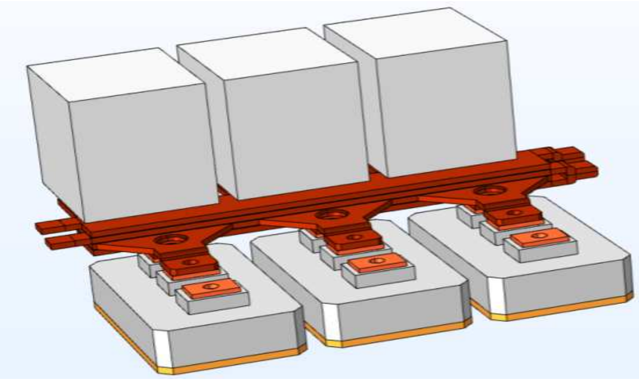

Fig. 4. Simulation model of inverter considering main circuit components.

B. Simulation Results

The main output of the simulation in the COMSOL Multiphysics program was thermal analysis of proposed one-way buses. Electrical interface combination current, heat transfer solid and electrical circuit we could analyze the behavior thermal properties of the bus depending on the parameters of the components and the current, which flows through it. If we ensure the correct current densities on the individual parts of the bus system, so the resulting bus analysis was correct.

During the simulations, we had the model simulated for 5 hours. The result of the simulation was gradually heating the bus. The bus temperature was initially the same as ambient temperature, i.e. it was 20 ° C. Over time, as current flowed through it, so did the bus was heated to a temperature of about 70 ° C - 120 ° C, which is the operating temperature bus. The time until the bus reached the operating temperature of the bus was in this in this case approximately 2 hours (Fig. 5).

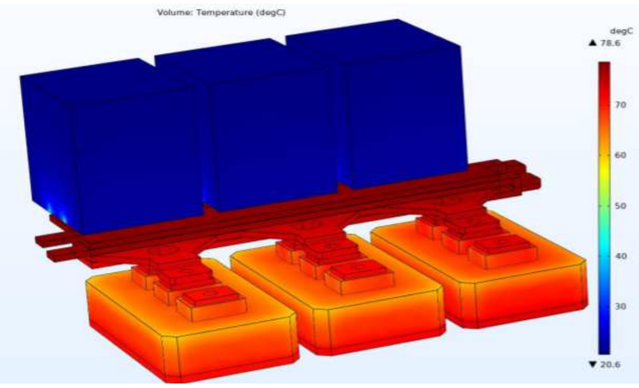

Fig. 5. Result of thermal analysis for nominal operational parameters of inverter (surface temperature distribution).

Bus temperature and time until it warms up to operating temperature are not always the same, as they depend significantly on the current flowing through the bus, the size and inductance of the load, or from the ambient temperature and from the cooling of the whole system.

The way the temperature rises and is distributed within inverter can be seen more in the detail from the initial results of the transient simulation. Power transistor module that is closest to the input connectors is heated as first (Fig. 6), but the difference between heating the first and the last module is not significant. Since the current flow continues to the internal structures of the modules their temperatures increase continuously until the steady state is reached. The temperature of the capacitors is low and stable within whole simulation range. This is due to fact, that within thermal analysis, their effect has been neglected, and the power dissipation for this component was not considered, because initially the influence of the busbar of inverter has been investigated.

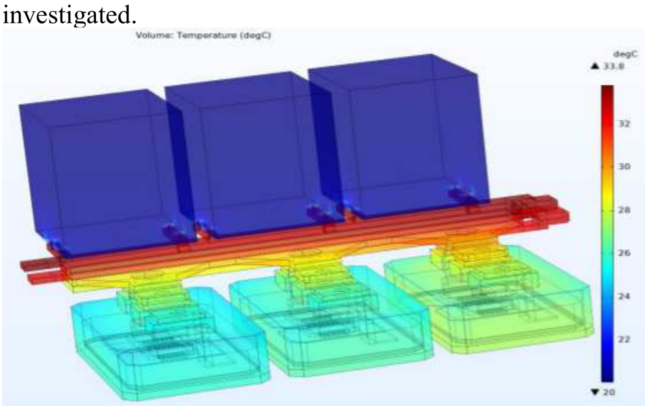

Fig. 6. Result of thermal analysis for nominal operarational parameters of inverter (surface temperature distribution)

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