The MEGACube 166kW/20kHz Medium-Frequency Transformer

ABSTRACT

High power DC-DC conversion constitutes the key enabling technology for the implementation of solid-state-transformers. Within these high-power DC-DC converters, the Medium Frequency (MF) transformer is one of the main components, as its task is to provide the primary to secondary isolation and the step-up ratio between the different voltage levels. Several options for the construction of this MF transformer have been reported with different considered core materials, winding arrangements, isolation concepts and thermal management, whereby the main realizations will be revised in this paper. Thereafter, the details of a 166kW/20kHz MF transformer will be presented together with the designed test-bench utilized for the continuous testing of the transformer.

INTRODUCTION

Solid-state-transformers (SST) are considered to be the future key enabling technology in several applications such as traction [1,2], renewable energy [3-5] and smart grids [6,7], among others. Within these SSTs, the high-power DC-DC converter, comprising the MF transformer, is one of the main components, as it provides the input to output step-up in voltage and the required isolation. In this context, a 1MW/20kHz converter linking a 1.2kV (low voltage, LV) to a 12kV DC (medium-voltage, MV) bus has been proposed [8] as part of the MEGACube project. In this converter, in order to achieve the efficiency goals, the MV side converter is built considering 1.7kV IGBTs, therefore a modularization of the converter is required, leading to the dual-active-bridge structure shown in Figure 1-a). Six of these modules would be required to reach the 12kV on the MV side, thus the power rating per module is fixed to 166kW (1MW/6).

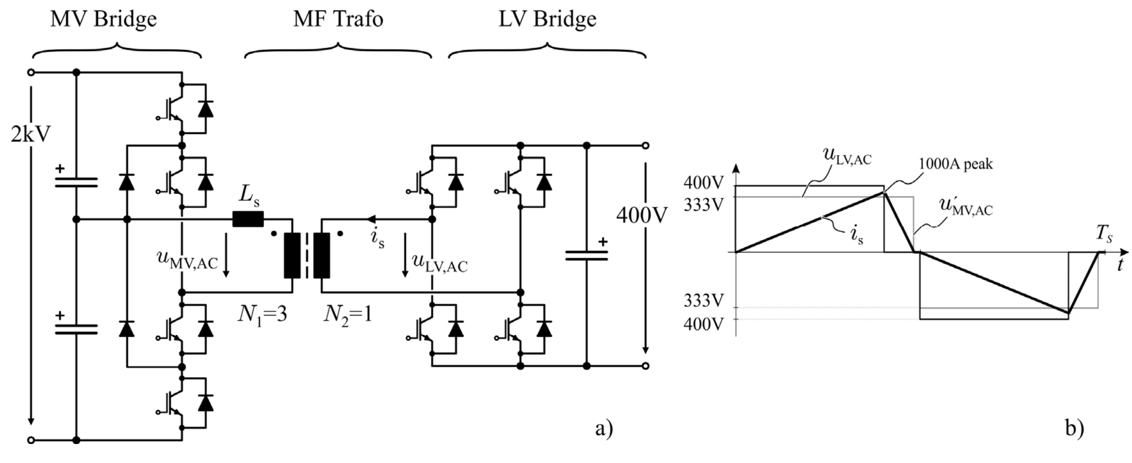


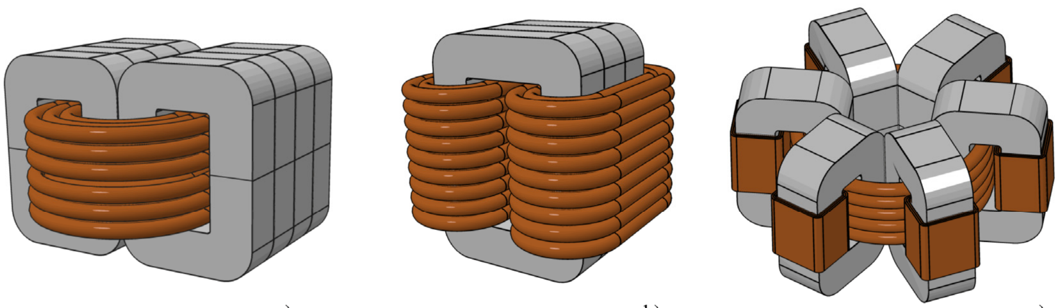
**Figure 1: MEGACube 166kW/20kHz DC-DC converter module:
a) circuit structure; b) transformer voltages and current.**

In order to achieve zero-current-switching on the MV side, the utilized modulation scheme is the triangular-current-mode [9], whereby the current and voltages on the transformer for this modulation are shown in Figure 1-b).

In this paper, the details of the design and construction of the aforementioned 166kW/20kHz will be presented. Moreover, an overview of the previously proposed MF transformer concepts, together with the different utilized core materials, winding arrangements, isolation concepts and thermal management will be presented.

TRANSFORMER CONCEPTS AND MATERIALS SELECTION

Different types of transformer concepts have been reported for MF high power DC-DC conversion, whereby the main ones are presented in Figure 2. The shell-type transformer concept (cf. Figure 2-a)), comprising a set of U cores arranged in an E core shape, has been considered in several applications [10-11]. Among its main advantages, the considerable amount of core area exposed for thermal extraction can be highlighted. The second considered transformer concept is the core-type arrangement [12], as shown in Figure 2-b). In this case, the area exposed for the extraction of the windings' heat is larger in comparison to the shell-type concept. A third considered transformer concept is a matrix-type arrangement [8]. Figure 2-c) shows an example with 6 cores. In this concept, each core constitutes a transformer with a common MV winding. By parallel connection of the LV windings, the required turns-ratio can be achieved.



a) b) c)

Figure 2: MF transformer concepts: a) shell-type; b) core-type; c) matrix-type.

Once the transformer concept has been established, the required core materials, winding arrangement, isolation and thermal management concepts must be addressed. A thorough revision of the previously reported utilized materials and concepts will be presented in the paper's final version together with the analysis of the associated trade-offs. With this analysis, the decision on the concept and material selection for the 166kW/20kHz transformer will be discussed.

DETAILS ON THE MEGACUBE TRANSFORMER

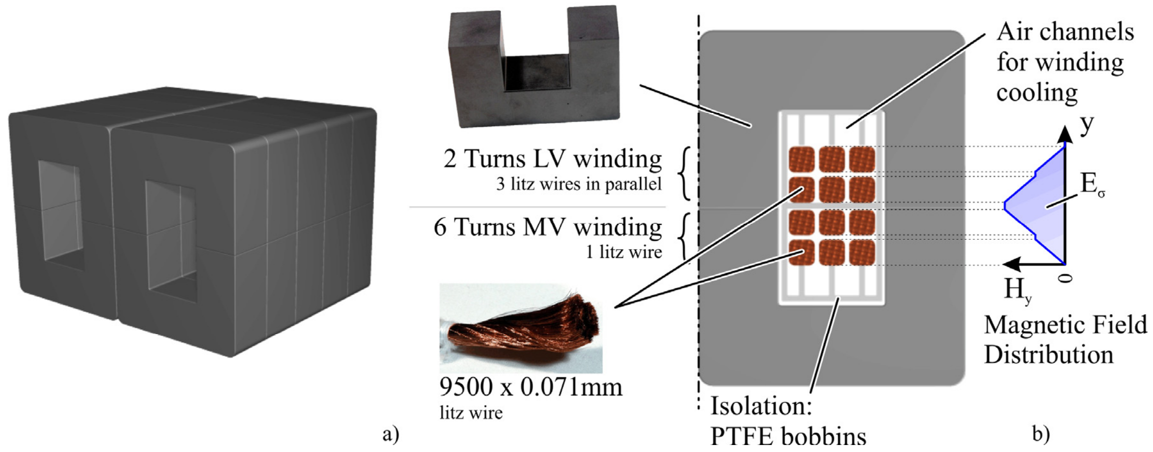


Figure 3: The MEGACube transformer: a) core arrangement; b) winding window.

For the MEGACube 166kW/20kHz modular transformer, a shell-type structure comprising ferrite cores was preferred in order to fulfill the high-efficiency goals. The core arrangement in shell-type structure comprising 20 N87 ferrite U cores is shown in Figure 3-a). The core losses considering the voltage waveforms shown in Figure 1-b) were calculated and experimentally measured, with values of 245W and 268 W respectively in nominal conditions. The winding window of the transformer is presented in in Figure 3-b). The winding is built using a 9500/0.071mm litz wire. The MV and LV windings are placed into a PTFE (Teflon) bobbin, whereby the LV winding is built with 3 paralleled litz wires achieving 2 turns for this winding. For the MV winding, a single litz wire is utilized to achieve 6 turns, i.e. reaching the required turns ratio of $N_1 : N_2$ = 3:1 (cf Figure 1-a)). The total losses, comprising HF effects as described in [13], were calculated, reaching a total value of 185W. The leakage inductance was tuned to the required 1.3 μH (LV side) by calculating the magnetic field distribution between the windings [13].

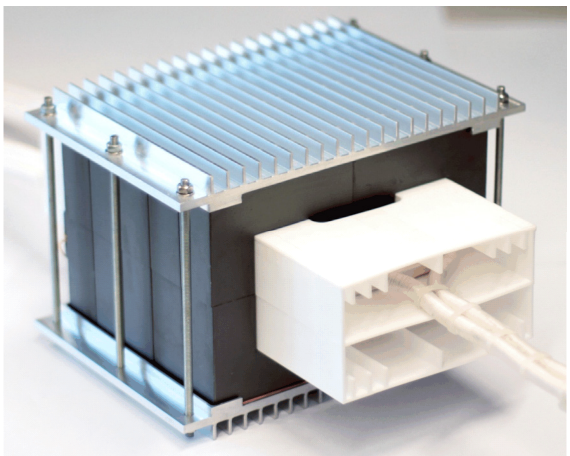


Figure 4: Constructed 166kW/20kHz MEGACube transformer.
Dimensions: 150mm/186mm/124mm.

A complete analysis, design and simulation (FEM) the transformer's thermal behavior has been performed and will be presented in the final version of the paper.

TRANSFORMER CONSTRUCTION AND TESTBENCH

The final construction of the 166kW/20kHz transformer is presented in Figure 4-a), where additional top/bottom pressing and cooling structures were included. In order to test the realized transformer, the test-bench shown in Figure 5-b) has been designed. This test-bench comprises a single 800V DC-link linking an NPC-based LV-bridge and a full-bridge structure for the MV side. With this structure, the energy supplied from one side of the transformer is fed back to the input side, therefore allowing the transformer to be tested at 135kW/20kHz of transferred power while only sourcing the losses dissipated in the circuit from the power supply side. This test-bench has been fully constructed (cf. Figure 5-b)) and the experimental results for the continuous test at 135kW/20kHz will be available for the final version of the paper.

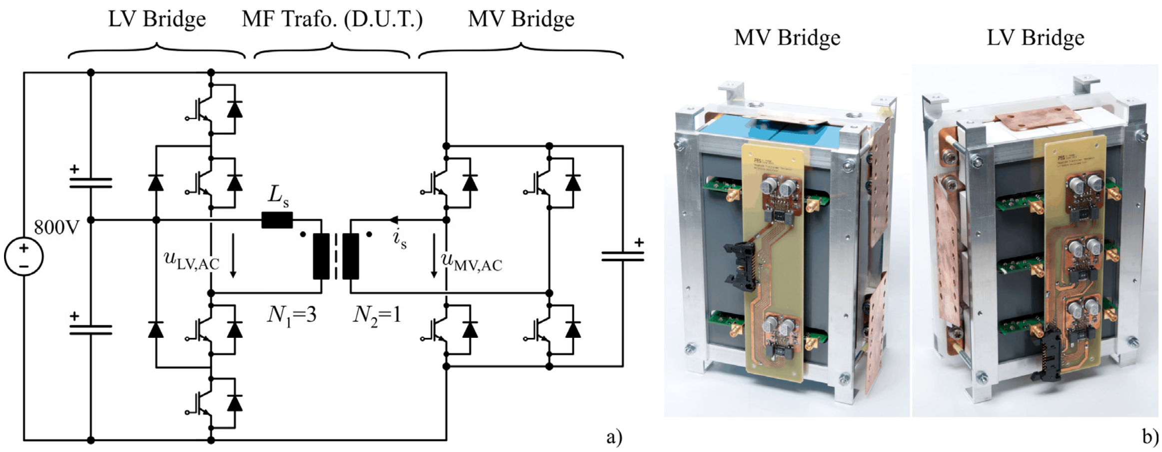


Figure 5: Testbench for continuous test of the MEGACube transformer: a) Circuit structure for feedback of energy; b) LV and MV bridges' realization.

CONCLUSIONS and FUTURE WORK

The design of a 166kW/20kHz MF transformer was presented. In order to realize this design, a revision of the previously proposed transformer concepts was performed. For the final version of the paper, an additional thorough revision of the previously utilized materials, isolation and thermal management concepts will be presented. The realized 166kW/20kHz transformer comprises ferrite cores, litz wires, PTFE isolation bobbins and its thermal extraction concept is forced air-cooling. In order to test this transformer under nominal conditions, a test-bench able to recirculate the energy was designed and constructed. With this test-bench, the results for continuous operation of the transformer will be performed and presented in the final version of the paper in order to compare them with the proposed simulation models.

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