

A Medium-Voltage Transformer with Integrated Leakage Inductance for 10 kV SiC-Based Dual-Active-Bridge Converter

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Abstract— Medium-voltage (MV) dual-active-bridge (DAB) converters have become an emerging technology thanks to high-voltage silicon carbide (SiC) devices and nanocrystalline magnetic materials. However, the need of phase-shift inductance and insulation requirements for the MV DAB may complicate the design of the transformer and the MV DAB converter, which can also induce higher loss and occupy more space. In this paper, the leakage integration and insulation techniques are discussed for a 6.7-kV/850-V DAB converter, meeting both the inductance and insulation requirements of the MV DAB converter. Ferrite cores with air gaps are inserted between the LV and MV windings without introducing high loss, and the MV winding is selectively shielded to avoid high parasitics and meet the insulation requirement. Test results have verified the effectiveness of this design.

Keywords—Dual-active-bridge converters; leakage inductance; medium voltage transformer; high voltage insulation

I. INTRODUCTION

The medium-voltage (MV) dc/dc converters have been implemented widely where the high power and high voltage conversion are needed. Fast-switching and high-voltage wide band-gap semiconductor devices, as well as low loss and high saturation magnetic materials, have enabled more compact and efficient designs of the MV dc/dc transformers and converters, making the converters more efficient and power dense.

Over the years, there have been several successful MV transformer designs. In [1], hollowed shielded cable was utilized as the transformer winding, since the inner conductor and outer shielding can be seen as two sets of windings having a unity turns ratio, with a good insulation rating, and the center hollowed channel of the cable was used to provide coolant path for active winding cooling. In [2], an oil-type MV transformer was implemented in a 1.2 MVA shunting locomotive, similar to the conventional traction transformers, the transformer oil can serve as both the insulation material and the liquid coolant. The solid-state transformer (SST) is also a typical application, for microgrids, datacenter, or

renewable energy generation. In [3, 4], a GaN/SiC-based converter for the datacenter was proposed, by increasing the switching frequency up to 500 kHz to achieve a high-power density. Reference [5] introduces a transformer with casted silicone and epoxy to improve the insulation performance, and the MV winding was coated with a shielding layer to confine the electric field in the dielectric material inside the MV winding, so that the low voltage winding does not need to be encapsulated and has better cooling. In [6], 10 kV SiC devices were used as the MV side switch, so that the single stage can be realized for 7 kV to 400 V conversion. In [7], an air-insulated transformer was introduced, having a very high power density as all the winding conductors can be directly cooled by the air flow. An air-core transformer has been designed in [8] to have light weight. As the air core cannot constrain the magnetic field, proper magnetic shielding is needed.

A. Leakage Integration

For dual-active-bridge converters, the transmitting power is determined by the phase-shift and the series inductance between the two bridges. The series inductance for DAB converters should be sufficient for stable power conversion and also realizing ZVS to reduce switching losses. It should also be noted that the series inductance may also need MV insulation, which also impacts the volume and power density of the converter design, and hence may need to be integrated into the transformer.

An important effect on nanocrystalline tape-wound transformer is the eddy current in the lamination surfaces. As the lamination is mainly for eliminating the eddy current component in the magnetizing loop to reduce the core loss, it may not work on the leakage loop and may cause high eddy current loss [9]. Fig. 1 shows a thermal image during short circuit test of a core-type MV transformer, and the temperature distribution of the core is strongly uneven. Most of the heat has been concentrated on the outer surface of the core, where the eddy current is mainly concentrated. Similar phenomena have also been found in [10] and [11]. To tackle this issue, [10] introduced a ferrite shielding method to bypass the leakage flux so that the eddy current may not be generated in the lamination, but the effect is limited by test verification.

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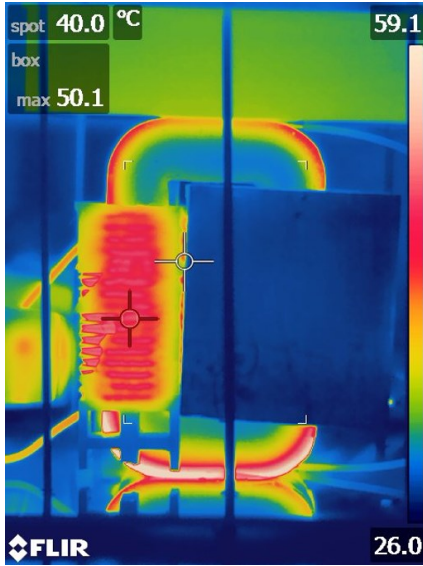


Fig. 1. Thermal image of a leakage inductance integrated core-type transformer with high eddy current loss.

Core type transformers can have high leakage inductance, and some of the leakage can be made further by central legs [11], and the adapted leakage layers can reduce the eddy current loss to a significantly low level. However, the structure of the dry-type MV winding has to fit into the core window with limited space, making the manufacturing process complicated.

B. Insulation and Parasitic Capacitance

The promising and environmentally friendly way of transformer insulation should be the dry-type insulation, which utilizes solid materials such as epoxy, silicone, or polyurethane as the insulation material, instead of using transformer oil. However, as the dielectric constants of the epoxy or silicone are usually above 3, while the transformer oil typically has a dielectric constant of 2.1-2.4, the parasitic capacitance of the dry-type transformer should have a larger parasitic capacitance [12, 13]. To confine the electric field of MV winding, and reduce common-mode electromagnetic interference, the MV winding may be shielded on the surface of the solid insulation, so that the LV windings and cores are not necessary to be encapsulated or cast, and therefore, the transformer cooling can be easier [5, 14]. However, due to the electric shielding on MV winding, the parasitic capacitance between the winding and ground also increases drastically [14]. In some applications, e.g., cascaded H-bridge (CHB) inverters, the common-mode voltage swing will be imposed on the transformer grounding capacitance, and causing significant switching losses on the CHB side devices. In Fig. 2, the transformer in dc/dc has high current spikes when the CHB devices switch and charge/discharge the parasitic grounding capacitance, causing significant switching losses. To reduce this effect, partial shielding can be chosen, so that only the critical surfaces are shielded while the other sides can remain unshielded [14].

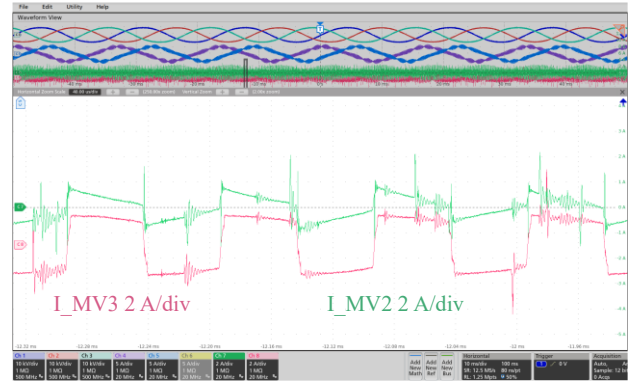


Fig. 2. Current spikes in transformers having high grounding capacitance.

C. Organization of the Paper

In this paper, a new leakage integration method having low eddy current loss will be introduced by using ferrite structures, and splitting nanocrystalline cores. In the meantime, dry-type transformer insulation consideration with partial shielding will be discussed. First, the leakage field of different types of transformer structures will be demonstrated, and the new structure having low eddy current loss will be introduced in Section II. Then, the dry-type insulation strategy will be discussed in Section III, with partial shielding. In Section IV, the transformer design based on the aforementioned method will be briefly discussed, and the test results will be shown. Finally, the conclusion will be drawn in Section V.

II. LOW LOSS LEAKAGE INTEGRATION

A. Leakage Integration with Ferrite Bridge

To begin with, the leakage inductance of the MV transformer should be clarified as the combination of the intrinsic leakage inductance that the transformer structure itself possesses without any external structures, and the external inductance that produced by structures which are artificially added to the transformer, i.e.

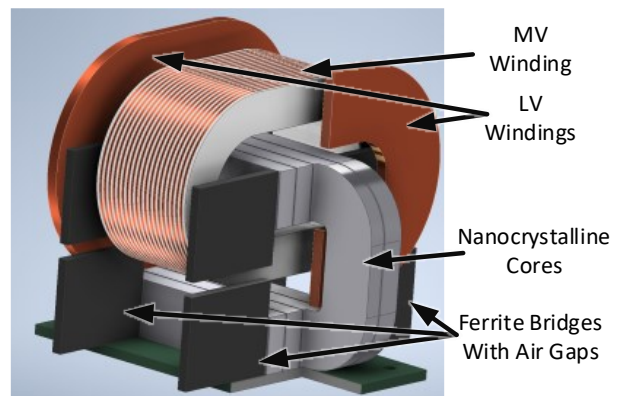


Fig. 3. Proposed transformer structure for leakage integration.

$$L_l = L_i + L_e \quad (1)$$

Where L_l is the leakage inductance, L_i the intrinsic leakage inductance, L_e the external inductance. To find the transformer structure with low eddy current loss and high leakage integration capability, the intrinsic inductance should be minimized to have low leakage loss, while the external inductance should be maximized to a level that is desired for the transformer design.

One possible structure having low intrinsic leakage inductance is the shell-type transformer. However, the coaxial shell-type transformer is excluded, as the LV and MV winding placed together may compromise the transformer cooling and make the leakage integration complicated. As in shell-type transformers, the windings can be split or interleaved, a new structure can be found with low intrinsic leakage and can be externally integrated with ferrite structures. The new structure is shown in Fig. 3. As the LV winding is split into two sets, and interleaved with the MV winding, the intrinsic leakage flux should be lower compared to the core-type and non-interleaved conventional transformer so that the eddy current should be low.

However, thanks to the ferrite bridges added between the

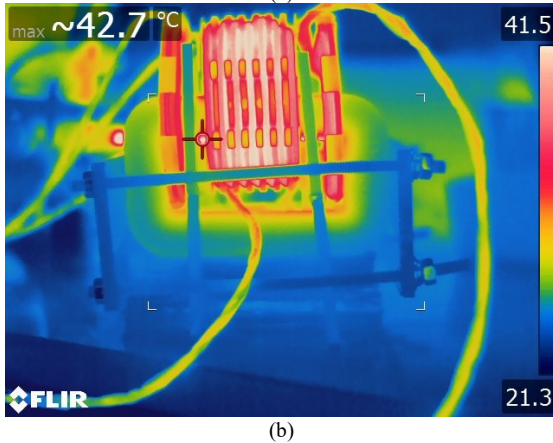
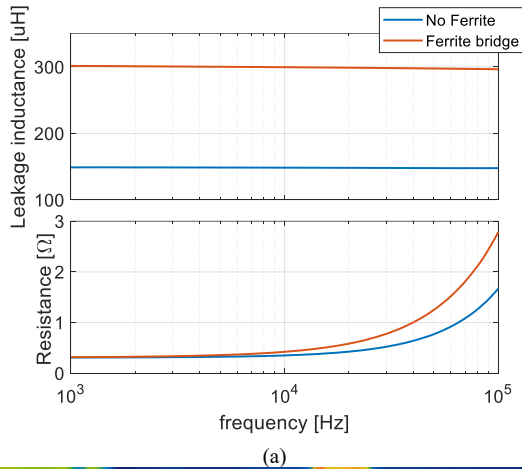


Fig. 4. Test results of the ferrite bridge (a) leakage inductance measurement, (b) thermal image during short-circuit test.

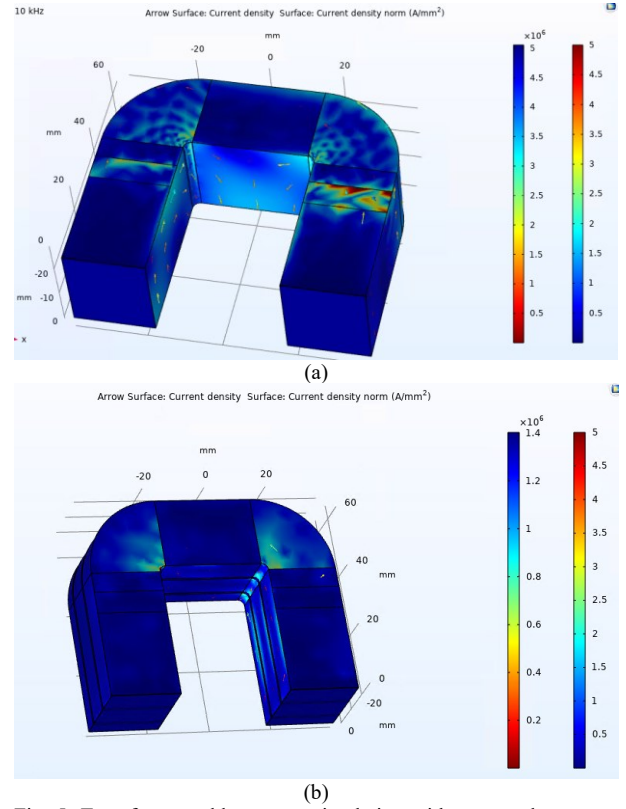


Fig. 5. Transformer eddy current simulation with proposed structure (a) one-piece transformer core, (b) split transformer cores.

LV and MV windings, high external leakage flux can be added and tuned by the air gaps. Even though the ferrite may introduce ferrite core loss when the transformer is loaded, as long as the flux density in the ferrite does not saturate, and the volume of the ferrite is relatively small, the overall loss when at short-circuit should be low compared to the other methods.

To verify the effectiveness of different structures, quick tests have been performed to test the losses and leakage inductance of the proposed structure. To make a fair comparison, the windings and core are set to the same as in Fig. 1. In Fig. 4 (a), as can be seen, without the ferrite bridge, the leakage inductance is around 150 μH , which is corresponding to L_i in (1), while after the ferrite bridge inserted, the leakage inductance increased to around 300 μH . That is, the external inductance of 150 μH has been added into the transformer. From Fig. 4 (b), the thermal image shows that unlike in Fig. 1 that the outer surface of the core was heated up, the surface of the inner window in Fig. 4 (b) was slightly heated, and the temperature rise is lower than in Fig. 1. The estimated eddy current loss is around 33 W, while in Fig. 1 it used to be 105 W.

B. Eddy Current Loss Reduction by Splitting Transformer Core

As can be seen in Fig. 4 (b), the shell-type transformer with interleaved winding still has some amount of eddy current loss on the inner surface of the transformer core, which may need to be further reduced. Note that the lamination reduces the

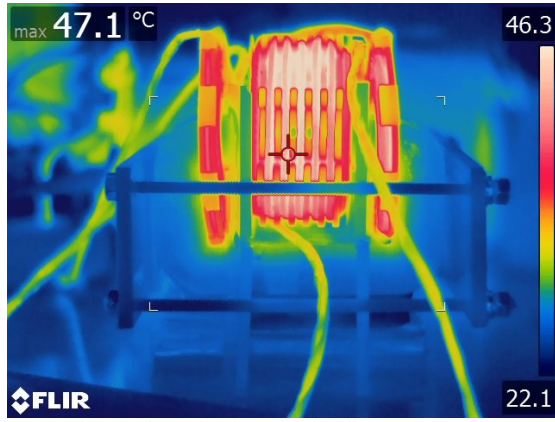


Fig. 6. Transformer short-circuit test with split core.

eddy current loss by cutting the solid area perpendicular to the magnetic field smaller, a similar strategy has also been adopted to reduce the gap losses for tape-wound nanocrystalline cores [15, 16]. The same measure can also be taken to reduce the eddy current loss induced by the leakage inductance.

Therefore, simulation with split cut cores has been performed. Originally, the transformer core used is 50 mm in depth, and can be replaced with 5 thinner cores with 10 mm in depth, as it can be wound easily with 10 mm wide nanocrystalline tape without any cutting process. The results are shown in Fig. 5. In Fig. 5 (a), the original one-piece transformer core has been used with 50 mm in depth, and in the inner window surface the current density of 2 A/mm² can be found with a wide range, and the loss was measured as 28 W. For Fig. 5 (b), the cores are cut into 5 smaller cores (mirrored part not shown). The area having eddy current is significantly shrank, only the edge regions have some current density around 2 A/mm², and the eddy current loss is measured as 9.4 W, which is 60% further reduced.

To verify the results, tests have also been done with replaced customized cores. From Fig. 6, the temperature of the eddy current surfaces has further decreased, and so did the total losses. For the proposed interleaved shell-type transformer, the total loss has been reduced to 111 W, and the estimated eddy current loss reduced to 9 W. From the thermal image it can be seen that the inner surface of the core now has no hot spot anymore. Therefore, the split core can further reduce the eddy current loss induced by the leakage flux.

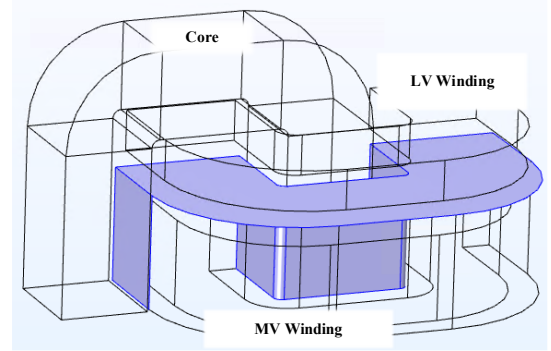
III. INSULATION DESIGN

The insulation design of the MV dc/dc transformer can be challenging, as one weakest point found in the entire transformer may be damaged. Also, the material properties play a more important role, as not only the performance of each material matters, the coordination between different materials may also impact significantly on the overall insulation performance.

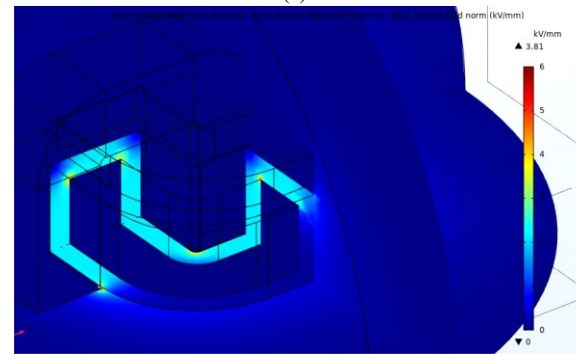
The insulation design starts with the material selection. Usually, the materials used do not only involve the insulating

TABLE I
ELECTRIC PROPERTIES OF SELECTED MATERIALS

Part Number	Dielectric Constant (Relative)	Electric Field Strength (kV/mm)	Loss Tangent	Use
Dow TC-4605 HLV	4.4	24	0.08	Encapsulant
SOMOS PerForm	4	26.3	-	3D print winding bobbin/case
Loctite E-60NC HV Putty	-	22	-	Epoxy adhesive
	3.03	22	-	Electric field shaping



(a)



(b)

Fig. 7. Transformer insulation simulation with partial shielding (a) transformer structure, with shaded surface shielded, (b) electric field simulation results.

dielectric material, but also mechanical structural materials. Hence, careful study of the electrical properties of the mechanical parts is also required. To form an even electric field inside the MV winding encapsulation, the dielectric constants of the insulating material, and other structural materials, e.g., bobbin and case, adhesives, should be as close as possible. The insulation rating should also match, to avoid the electric breakdown in a significantly weak material. Table II shows the electric properties of the selected materials used in insulation design.

Similar to the partial shielding in [14], only the critical surfaces are close to the ground potential should be shielded, as the ground and high potential difference may impose a high electric field in the air, causing corona or flashover during operation. Hence, a partially shielded transformer has been

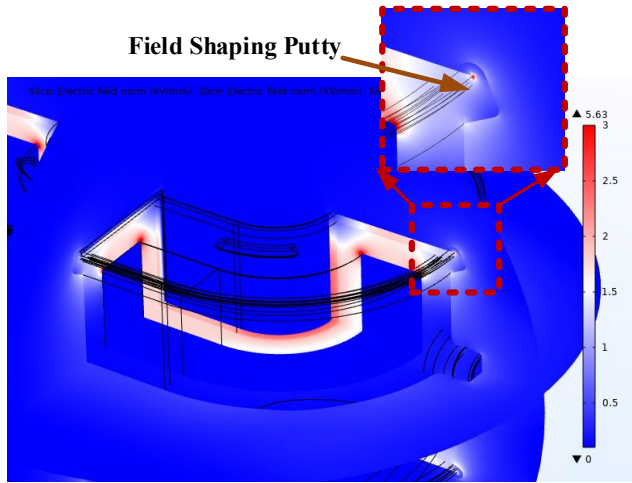


Fig. 8. Detailed insulation simulation with field shaping.

TABLE II
TRANSFORMER DESIGN PARAMETERS

Parameters	Values
Power Rating	16.7 kW
Voltage Rating	850/6.7 kV
Switching Frequency	10 kHz
Core	SC2062M1 (5x 10 mm depth cut)
Air Gap	2 x 0.2 mm
LV Winding	31 turn 259/AWG36 Litz Wire
MV Winding	244 turn 50/AWG36 Litz Wire
Ferrite Bridge	PLT64/50/4-3C95
Ferrite Bridge Air Gap	5 mm
Leakage Inductance	250 μ H/15.5 mH
Insulation Rating (MV to ground)	13.4 kV peak
Power Density	8.5 kW/L

simulated in Fig. 7. The field distribution is only partially even because of the partial shielding, and the electric field extends to the air where the surface is not shielded. With partial shielding, the capacitance between the high potential winding and shielding ground is 102 pF, which is reduced by 50% compared to the fully shielded winding. The electric hot spot now is the edges of the shielding layer, which could be as high as 6 kV/mm and may cause a breakdown in the air, which can be reduced by applying silicone putty to form a rounded corner with low curvature in the real prototype. The detailed simulation with the silicone putty is shown in Fig. 8. By applying the silicone putty, the field strength can be reduced to 1.5 kV/mm on the edges of the shielding surfaces.

IV. TRANSFORMER TEST

A. Transformer design

With the proposed leakage integration and insulation, the MV DAB transformer has been designed for a 10 kV SiC-based DAB converter, serving as a front end of a CHB inverter. The design parameters of the transformer are shown in Table II. The photograph of the MV transformer with LV and MV power stages is shown in Fig. 9.

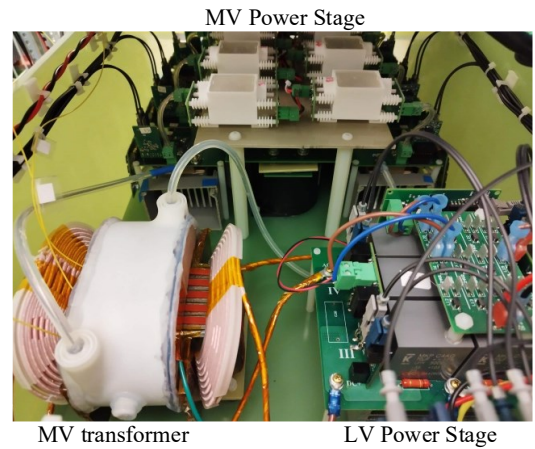


Fig. 9. Photograph of MV DAB transformer and DAB power stages

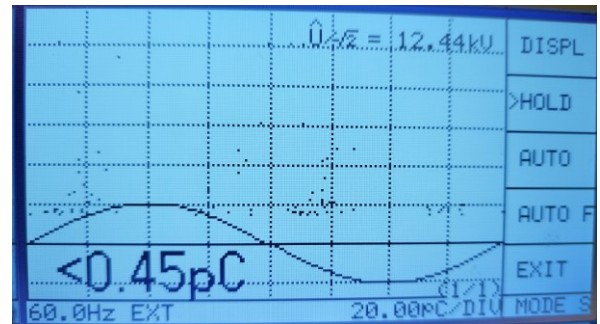


Fig. 10. PD test results of accumulative recording at 1.3 times of rated voltage for 3 minutes.

B. Transformer Test

After the transformer was built, several tests have been conducted to verify the design with leakage integration and insulation design. First, before the MV was applied, partial discharge (PD) test has been done to verify the winding and transformer insulation. The test followed IEEE standard C57.12.91-2020 that the MV winding was tested with a prestress of 1.8 times of rated voltage for 30 seconds, and then measured the PD level at 1.3 times of rated voltage for 3 minutes [17]. The test results are shown in Fig. 10. From the results, during prestress the PD level was around 45 pC, and most of the PD subsided after the voltage reduced to 1.3 times of rated voltage, even though occasionally some PD or corona discharge appears. Most of the PD value was below 50 pC, meeting the requirement of IEEE Std C57.12.91.

After the PD test was finished, two transformers have been installed in the DAB converter and connected with the CHB converter forming a two-stage converter, tested from no-load to full load condition. The test waveforms are shown in Fig. 11. From the test waveforms, the transformer works as expected DAB transformers for both no-load and full-load conditions, and the waveforms of the two transformers agree with each other. From the test, the total loss of transformer is estimated as 119.52 W, achieving an efficiency of 99.3%, and the eddy current loss is estimated as 33 W.

V. CONCLUSION

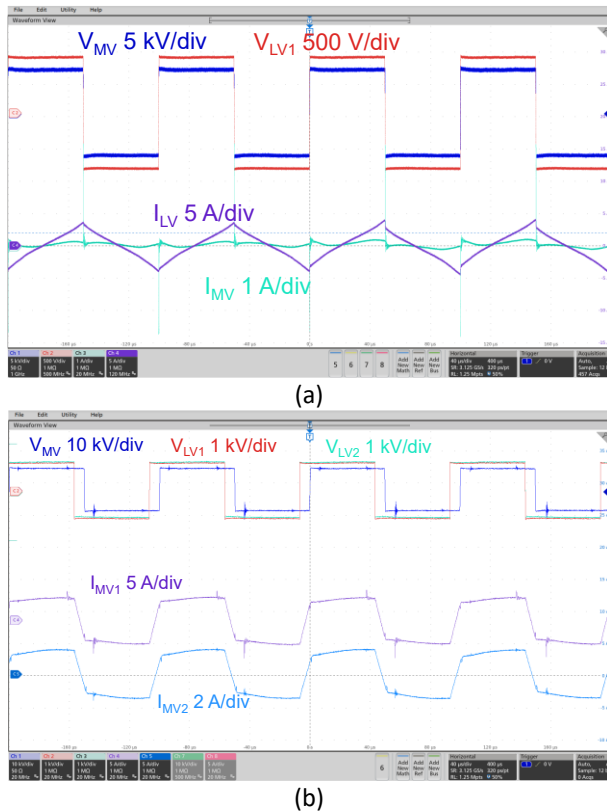


Fig. 11. Test results for MV DAB transformer/converter (a) no-load condition (b) full-load condition.

In this paper, a MV transformer design with low-loss leakage integration, as well as insulation design with field shaping has been introduced. Through the simulation and tests, the shell-type transformer with interleaved LV winding and ferrite structures can have better leakage integration capability and loss performance. The split transformer core can further reduce the eddy current loss induced by the leakage magnetic field, without sacrificing power density and other performances, but specification of manufacturer has to be followed when customizing the split cores. The insulation materials and insulation structure have been discussed to improve the insulation performance. Partial shielding is necessary for MV winding design because of reduced grounding capacitance, which may impact the switching losses of the converter having common-mode swings. Based on the discussions, a 850-V/6700-V 16.7-kW MV DAB transformer has been designed and tested. The MV winding has passed the PD standard in IEEE Std C57.12.91 up to 13.4 kV peak value, and the transformer achieved 99.3% power efficiency at full load condition, with the transformer having a power density of 8.5 kW/L.

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