Feasibility Study of High-Frequency Transformer with High-Voltage Insulation Structure for SST Based Medium-Voltage Multi-Level Converter

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***Abstract*— Due to the rapid spread of EVs, the demand for fast chargers is increasing at a faster pace. High-power density multiport EV fast charger by utilizing SST based multi-level converter has been proposed. The high-frequency transformer mounted in SST is key component to realize high power density considering medium-voltage insulation between grid side and EV side. Then, this paper presents high-frequency transformer design including winding specification and insulation structure design for solid-state transformer (SST) based medium-voltage multi-level converter. The winding specification for tens kW level is studied by experimental evaluation. The proposed transformer design can reduce electric field between core and high-voltage side coil by shield plate and potential fixing plate. Therefore, proposed transformer can achieve features of both high-voltage insulation and suppressing the increasing of volume compared to a conventional structure. This paper also shows the electric field simulation results and experimental results of developed transformer.**

Keywords*— High frequency transformer, High voltage insulaton, Multi-level converter, Solid State Transformer

I. Introduction

In industrial field, market of power electronics products, such as UPS, motor drive system for air conditioning fan and elevator and power conditioning system (PCS) for photovoltaic and wind turbine have been increasing for saving energy and corresponding the electrification in terms of sustainability. These systems whose capacity range is over several hundred kilowatts are required to be connected to Medium-Voltage AC grid. The conventional Medium-Voltage power converter system has heavy and huge line-frequency (LF) transformer, therefore reduction of size and weight were desired. To solve this issue, power conversion systems based on solid state transformer (SST) with high-frequency (HF) transformer have become an attractive technology to reduce size and weight of transformer by practical use of wide-band gap switching devices (SiC and GaN)[1][2]. By means of high-frequency modulation, the volume and weight of SST can be much smaller than those of LFT.

Recently, electrification in mobility field has been moved rapidly due to world trend of environmental sustainability. For rapid spread of EVs, it is expected that demand for fast chargers will be increased at a faster pace.

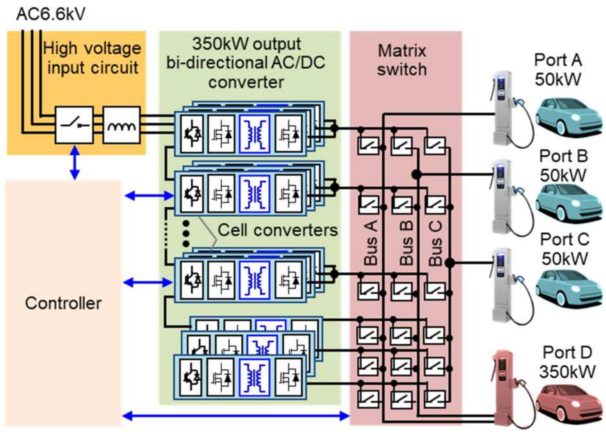


Fig. 1. System configuration of SST based medium-voltage converter for multi-port EV charger.

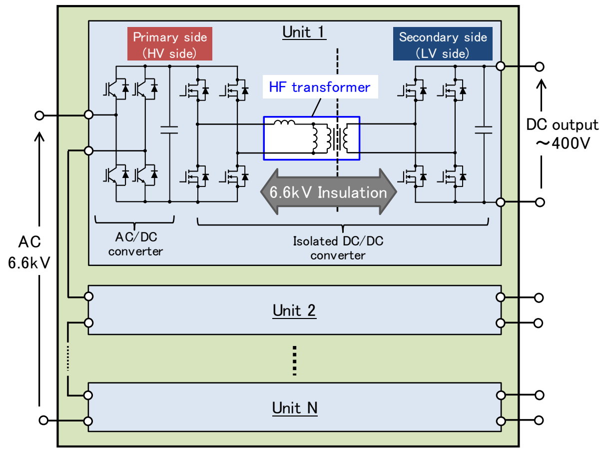


Fig. 2. Circuit schematic of AC/DC converter using SST unit in Fig.1.

Table I Specification of isolated DC/DC converter in Fig.2.

Item		Value
Rated power		17kVA
Typical operating frequency		>20kHz
Rated voltage	Input	>6.6 kVrms
	Output	400Vdc

And also, it is anticipated that adapting to multiple power output such as several kilowatt normal charging, tens kilowatt fast charging and hundreds ultra fast charging will be required for EV charger because of corresponding to EV types and usage scene. For these requirements, Multiport charging systems based on SST technology for smart building application was proposed to facilitate multiple EV chargers as shown in Fig.1[3][4]. Proposed system consists of input-series and output-series/parallel connected cell converters which includes AC/DC converter and isolated DC/DC converter as shown in Fig.2. The isolated DC/DC converter insulates between MV grid side and low voltage vehicle side by using HF transformer.

Therefor, specification of over kV level insulation and tens kW level capacity is required for HF transformer as shown in table I. For leveraging SST concept such as reducing size and weight compared with LF transformer, high power density design of HF transformer considering high-voltage insulation should be studied. To realize high power density of high-voltage HF transformer has been proposed in prior art researches [5]-[7]. However, these papers mainly presented insulation design of coil between primary coil and secondary coil. And winding design for tens kW capacity transformer is not mentioned in these papers.

In this paper, firstly, experimental study of winding specification for design of tens kW HF transformer is described. Secondary, insulation structure of HF transformer focusing on core potential for achieving kV level insulation is described. Finally, evaluation result of developed transformer is mentioned.

II. Experimental Study of Coil Specification for tens kW Transformer

The litz wire is commonly used for coil of HF transformer to suppress increasing of AC resistance due to skin effect and proximity effect. For tens kW level system. over thousand wires are needed for coil in terms of current density. However, there is practical limitation for increasing number of wires due to difficulty of winding by losing pliability. Using parallel winding is suitable to correspond to wide lineup in terms of productization. Here, we study possibility of parallel winding in terms of conduction loss by experimental evaluation. The specification of coils for using experimental is shown in Fig.3. Three winding condition including non-parallel winding as #1, two parallel winding as #2, and four parallel windings as #3 are evaluated. The diameter of strand is 0.06mm. Total number of strands is about 3500strands at each condition. USTC wire covered by tetron thread is used to maintain stranded structure for winding.

Measured results of AC resistance characteristics normalized by resistance of #1 coil at condition of 1kHz is shown in Fig.4. AC resistance was measured by impedance analyzer (4194A Agilent). AC resistance of parallel winding condition such as #2 and #3 is much larger than non-parallel winding condition #1. At the condition of frequency 50kHz, AC resistance of two parallel winding #2 is about 30% increasing compared to non-parallel winding #1. AC resistance of four parallel winding #3 is about 50% larger than non-parallel winding #1. From this result, it can be obvious that non-parallel winding would be utilized for coil of HF transformer using litz wire.

Item	#1	#2	#3
Number of turns	9Ts	←	←
Diameter of litz wire	0.06mm	←	←
Total number of strands	3430strands	3500strands (1750strands/winding)	3500strands (875strands/winding)
Parallel number of windings	1P	2P	4P
External view			

Fig. 3. Specification of coils for experimental evaluation

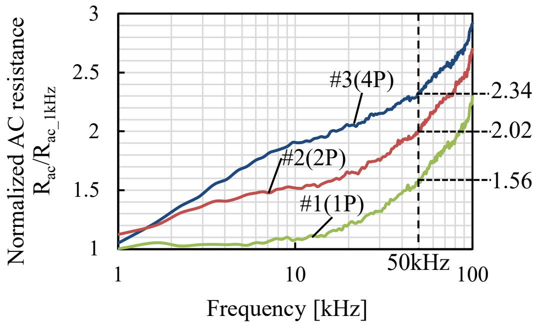


Fig. 4. Measured results of AC resistance characteristics

III. High-Voltage Insulation Design of HF Transformer

For high power density, PQ type core is attractive in magnetic design viewpoint. However, large window area is preferable to take clearance for high-voltage insulation design. At first glance, these are conflicting requirement for high-voltage HF transformer design. In this section, newly concept of HF design focusing on core potential to solve above conflicting is mentioned.

The comparison of transformer insulation architecture design using PQ core is shown in Fig.5. The HF transformer should provide the insulation safety function for overall system and it should be designed by considering the input medium-voltage level over 6.6kV. The core potential is basically fixed in low-voltage (LV) side in terms of easy mounting like conventional design in Fig.5. Therefore, high-voltage (HV) potential coil is surrounded by LV potential core. The requirement of high voltage insulation for conventional design should be considered between the HV potential primary coil and the LV potential secondary coil and between HV potential primary coil and LV potential magnetic core. It causes low power density due to large clearance between HV potential coil and LV potential core for easing electric field concentration.

On the other hands, proposed design divides HV side area and LV side area through shield plate in physically. The shield plate consisted of resin parts can provide creepage distance and clearance between primary side and

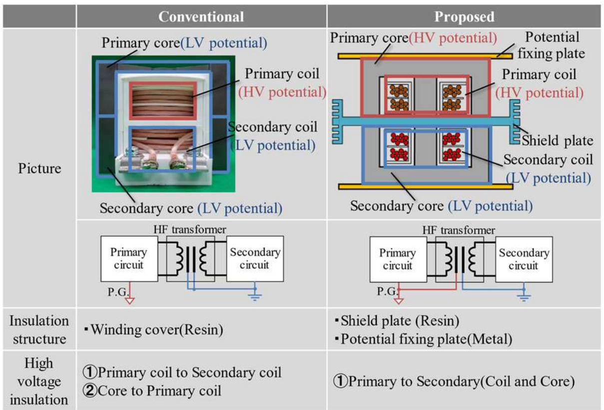


Fig. 5. Comparison of transformer insulation architecture design

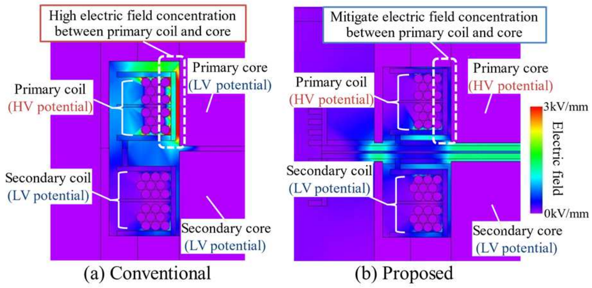


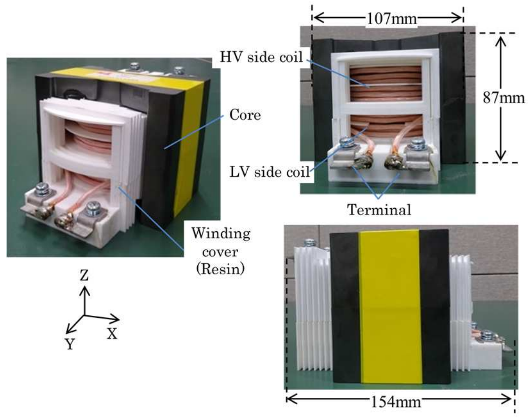
Fig. 6. Electric field simulation under rated voltage condition

secondary side. And core potential is also divided between primary core and secondary core by using potential fixing plate. The potential fixing plates are connected each circuit ground to fix core potential at each side as shown in Fig.5. 2D Electric field simulations are done by using JMAG. The simulation results of conventional and proposed design transformer are shown in Fig.6. From the results, proposed architecture design can ease electric field between primary coil and primary core drastically compared to conventional one. And maximum electric field strength can be reduced below 3kV/mm referred to general criteria of breakdown voltage of dry air at proposed architecture. However, electric field strength between primary core and secondary core is increased at proposed design because of differentiation of core potential. This causes potential of partial discharge between primary core and secondary core due to small air gap in shield plate. Partial discharge test of primary core point should be evaluated in experimental.

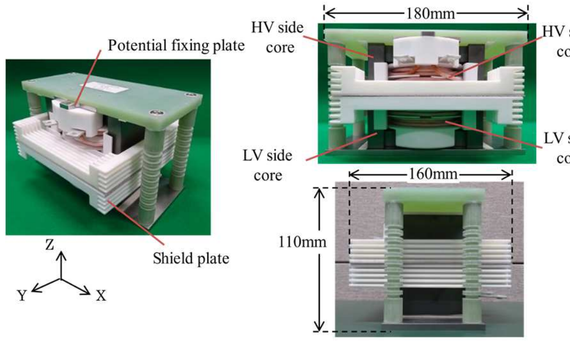
IV. Prototype and Insulatoion Test Result

A. *Prototype and Parasitic Inductance Test*

The HF transformers utilized conventional and proposed insulation design are developed for experimental evaluation as shown in Fig. 7. Fig.7 (a) shows the picture of conventional design transformer and Fig.7 (b) shows the picture of proposed design transformer. The specification of developed transformer is shown in table II. The insulation distance including clearance and creepage is designed by referring to IEC std to realize 6.6kV insulation.



(a) Conventional design



(b) Proposed Design

Fig.7. Picture of developed HF transformer

Table II Transformer specification

Item		Value	Remark
Core type		PQ107	Material: PC95
Number of turns	Primary side	N1=18Ts	ϕ=0.06mm, 1750strands
	Secondary side	N2=16Ts	ϕ=0.06mm, 1750strands
Insulation distance	Clearance	84mm	Reference : IEC std. Overvoltage Category: III Pollution degree: 3 Material group: I
	Creepage	138mm	

The length of each direction (x, y, z) is designed by considering case assembly design of SST unit. External dimensions of conventional and proposed design transformer are indicated in Fig.7. Outline volume of proposed design (3.2L) is over 2 times larger than conventional one (1.4L). However, it will not be special issue because the original case of SST unit has enough space for width and height. On the other hands, insulation distance for x and z direction in conventional design is limited by core size. It means that it is difficult to improve insulation specification in conventional design due to core size.

Parasitic leakage inductance and magnetizing inductance are measured and shown in Table III. The definition of inductance is shown in Fig.8. There is large leakage inductance of proposed design compared to conventional design transformer due to large core gap caused by shield plate. This causes the increasing of copper loss in transformer due to large magnetizing current. The method of suppressing large magnetizing current should be

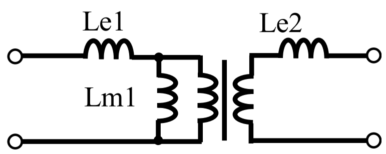
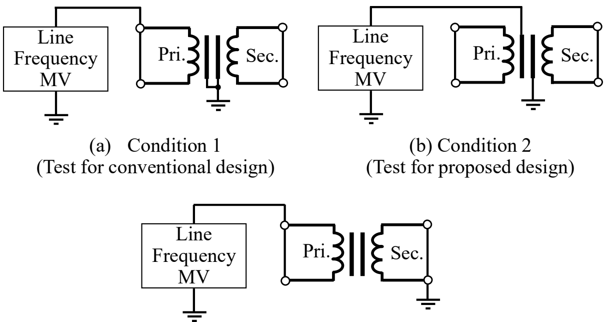


Fig.8. Definition of inductance for HFT

Table III Inductance of developed transformer

Item	Conventional	Proposed
Magnetizing Inductance: Lm	292μH	59.0μH
Primary Leakage Inductance: Le1	38.0μH	41.4μH
Secondary Leakage Inductance: Le2	18.0μH	32.8μH



(a) Condition 1
(Test for conventional design)

(b) Condition 2
(Test for proposed design)

(c) Condition 3
(Test for common)

Fig. 9. Partial discharge test setup

considered for converter design. This paper will discuss it in chapter V.

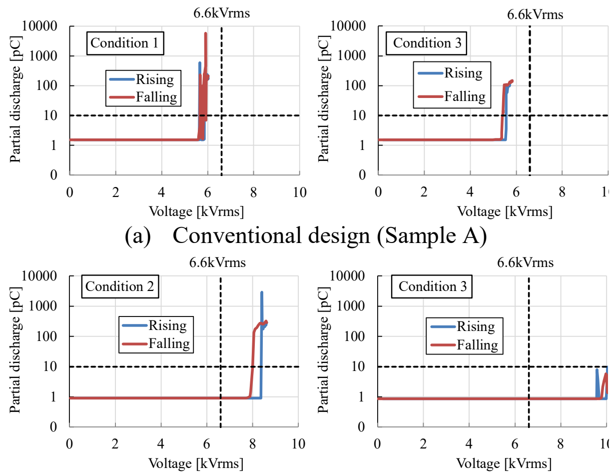
B. *Medium-Voltage Insulation test*

The transformer insulation capability is tested. Equivalent circuits under partial discharge test are shown in Fig.9. Condition 1 is test for conventional design. Condition 2 is test for proposed design. Condition 3 is test for common. Condition 1 can test capability of insulation between HV side coil and core fixed at LV side. At condition 1, primary side core and secondary side core are shorted. Condition 2 can evaluate capability of core insulation between primary core (HV side) and secondary core (LV side). At condition 2, primary coil and secondary coil are shorted and floated. Condition 3 can test capability of coil insulation between primary coil and secondary coil. At condition 3, primary core and secondary core are floated. In this paper, four samples including sample A-D listed as below are tested.

-Sample A,B : Conventional design

-Sample C, D : Proposed design

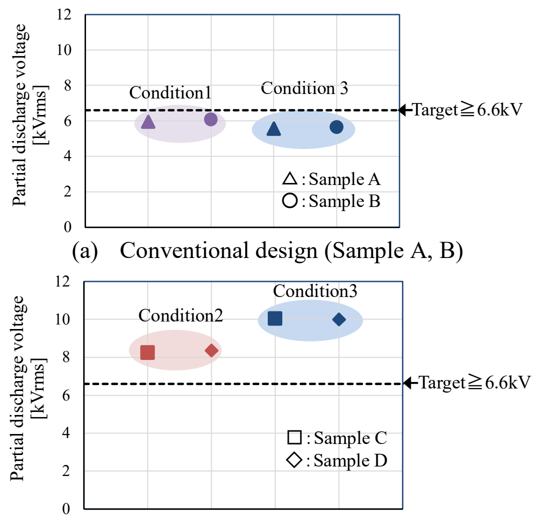
Test result of partial discharge is shown in Fig.10 and Fig.11. From these test results, partial discharge voltage of conventional design at both test condition is under target value (6.6kVrms). On the other hands, proposed transformer can achieve over 6.6kVrms insulation at both



(a) Conventional design (Sample A)

(b) Proposed design (Sample C)

Fig. 10. Partial discharge test results



(a) Conventional design (Sample A, B)

(b) Proposed design (Sample C, D)

Fig. 11. Partial discharge voltage

test condition. The insulation ability of proposed transformer can be improved about 30% compared to conventional transformer. And the difference of partial discharge voltage between sample C and sample D is small. It is obvious that proposed transformer design is practical insulation structure using for Medium Voltage system.

V. Isolated DC/DC Converter Design and Evaluation

From prototype evaluation result in chapter IV, magnetizing inductance of proposed design is smaller than conventional one. In this section, circuit topology for proposed transformer will be studied in terms of suppressing affect of magnetizing current. The most common topology for DC/DC stage in SST unit is a Dual Active Bridge (DAB) [8]. However, small magnetizing inductance directly affects switching loss in DAB topology due to large magnetizing current. On the other hand, resonant type topology has been studied in wireless transfer system for improving power transfer efficiency by reducing affect of small magnetizing inductance due to

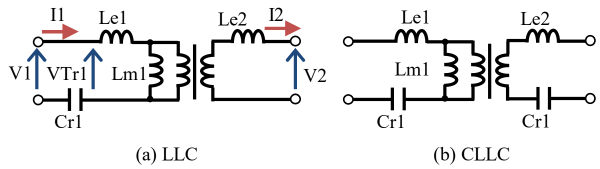


Fig. 12. Circuit topology for resonant type isolated DC/DC converter

Table IV Parameter of resonant capacitor

Transformer design	Conventional	Proposed	
Circuit topology	LLC	LLC	CLLC
Primary side capacitor: Cr1	350nF	450nF	450nF
Secondary side capacitor: Cr2	None	None	470nF

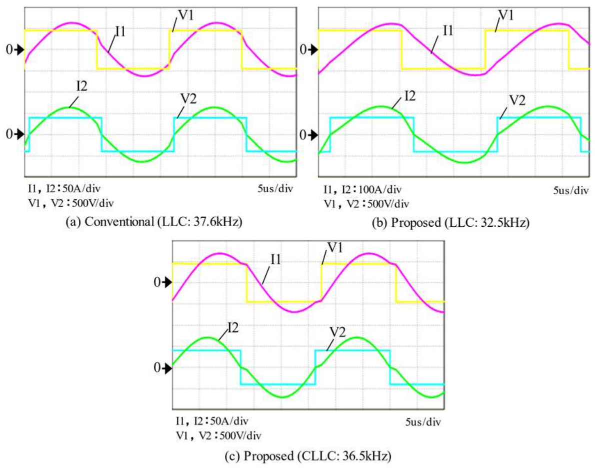
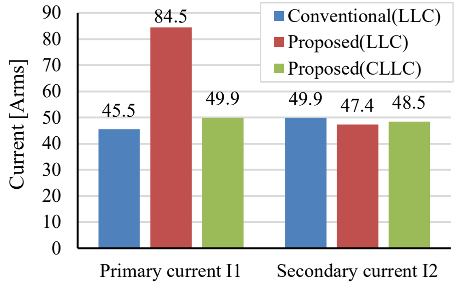
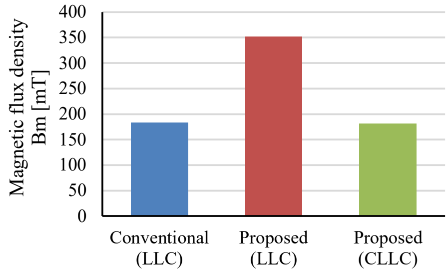


Fig. 13. Simulation waveforms at rated power condition (P=17kW)



(a) Primary and Secondary coil current



(b) Magnetic flux density (N1=18Ts, PQ107-PC95)

Fig. 14. Comparison of conduction current and voltage-time production at rated power condition (P=17kW)

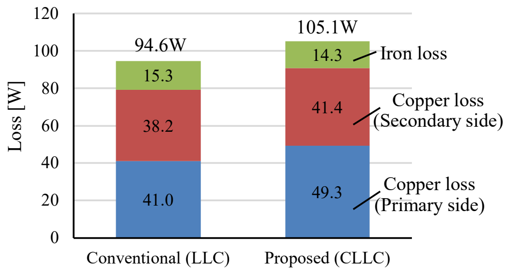
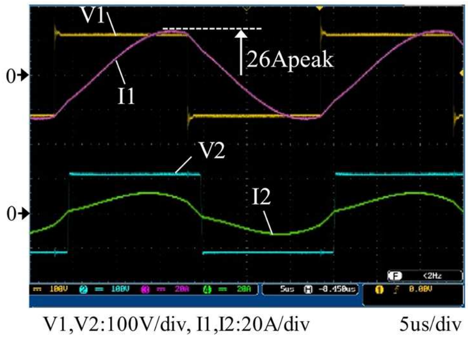


Fig. 15. Loss analysis result of transformer at rated power condition (P=17kW)

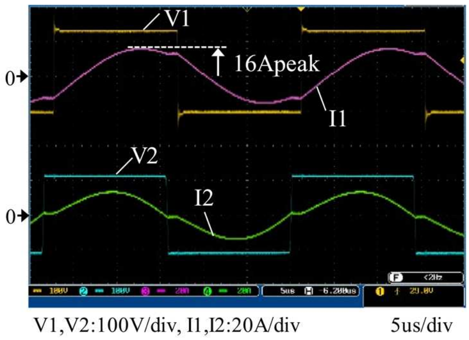
coupling condition. The characteristics of inductance in proposed design transformer is similar to wireless transfer coil. Then, resonant type circuit topology is studied for applying to proposed design transformer. The typical resonant topology used for wireless power transfer system is shown in Fig. 12 [9]. In the prior art [9], it was described that CLLC type topology using primary and secondary resonant capacitor has unique characteristics which can decrease primary current as compared to LLC type. CLLC is discussed as good candidate for circuit topology for proposed transformer. Parameter of resonant capacitor is shown in Table IV. Conventional design transformer using LLC and proposed design transformer using LLC are evaluated for comparison. Operating range of switching frequency is designed as from 30kHz to 50kHz for each case.

The simulation waveforms at rated power condition (P=17kW) are shown in Fig. 13. And comparison of conduction current and magnetic flux density calculated by using simulation result in Fig.13 are shown in Fig. 14. From Fig.13 and Fig.14(a), primary current I1 of LLC using proposed transformer is about 1.8 times larger than conventional one. On the other hands, CLLC using proposed transformer can decrease primary current about half compared to LLC with proposed transformer and be same level as LLC using conventional transformer. In terms of magnetic saturation viewpoint, magnetic flux density of LLC using proposed transformer is close to saturation area. The magnetic flux density of CLLC using proposed transformer can be reduced at the same level as LLC with conventional transformer. Loss analysis result of conventional transformer in LLC and proposed transformer in CLLC at rated power condition (P=17kW) is shown in Fig.15. Copper loss is calculated by using measured resistance and simulated current value. Iron loss is calculated by using simulated value of magnetic flux density and loss characteristics in data sheet. From this result, the increase of total loss in proposed transformer by applying CLLC topology can be suppressed to about 10% while improving insulation voltage compared to conventional transformer using LLC.

Fig.16 shows the experimental waveforms of LLC and CLLC topology using proposed transformer at the condition of output power is 1kW. It is observed that CLLC topology can reduce primary current about 40% as compared to LLC topology.



(a)LLC



(b) CLLC

Fig. 16. Experimental waveforms of with prototype transformer under 1kW output condition

From above study, CLLC topology with proposed transformer looks reasonable approach in terms of suppressing the increase of transformer loss due to the feature of small magnetizing inductance.

VI. Conclusions

The high frequency transformer design for solid state transformer based multiport EV charger is presented in this paper. From experimental study of winding structure, non-parallel winding would be utilized for tens kW level transformer to suppress AC resistance increasing compared to parallel winding. The impact of insulation design on the performance of high-frequency transformer has been evaluated. The proposed design focusing on core potential can reduce electric field compared with conventional transformer by electric field simulation. And the capability of 6.6kVrms insulation is demonstrated by partial discharge test. The appropriate circuit topology of insulated DC/DC converter for proposed design transformer is discussed at the transformer loss viewpoint due to small magnetizing inductance by simulation and experimental approach. It can be observed that CLLC topology can be suppressed primary current of transformer compared to LLC. Total transformer loss in proposed design using CLLC is same level as conventional transformer using LLC. From this study, it is clarified that proposed design transformer is reasonable approach in terms of improving insulation ability while suppressing increase of transformer loss.

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