New Intelligent Semiconductor Transformer With Bidirectional Power-Flow Capability

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***Abstract*— This letter proposes a new intelligent semiconductor transformer (IST) which consists of a bidirectional ac/dc resonant converter, dc/dc converter, and dc/ac converter. This structure pro-vides good voltage-balancing performance on the high-voltage side and a simple control method for bidirectional power flow. The pro-posed IST was verified though building and testing a single-phase 2 kVA (1.9 kV /127 V) prototype. A three-phase transformer can be implemented with three units of the proposed IST.**

Keywords*— AC/DC resonant converter, bidirectional power flow, hybrid switching, input voltage balancing, intelligent semi-conductor transformer (IST).

I. INTRODUCTION

THE intelligent semiconductor transformer (IST) was pro-posed by the Electric Power Research Institute (EPRI) to replace the conventional transformer in railway systems where light weight is critical [1], [2]. IST can easily solve this problem because it operates at a much higher frequency with the reduc-tion of magnetic components. Various kinds of IST proposed previously have disadvantages, such as unidirectional power flow and complex control of a high-side converter for balancing the dc voltage [3]–[5]. In this letter, a new IST with bidirectional power-flow capability is proposed.

II. SYSTEM CONCEPT

Fig. 1 shows a conceptual diagram of the proposed IST, which is composed of a bidirectional ac/dc resonant converter, dc/dc converter, and dc/ac converter. In the proposed IST, a single-phase input voltage of 1900 V is converted to a full -bridge-rec-tified voltage of 320 V through the bidirectional ac/dc reso-nant converter with a fixed duty ratio. The full-bridge- rectified voltage is converted to the constant dc voltage of 700 V through the bidirectional dc/dc converter with a variable duty ratio. The constant dc voltage is converted into a single-phase voltage of 127 V through the bidirectional dc/ac converter.

One key issue of IST is system efficiency. The dc/dc con-verter and dc/ac converter operate in a hard -switching pattern, while the ac/dc resonant converter operates in a soft-switching pattern. In order to reduce the switching losses, the dc/dc con-verter and dc/ac converter utilize the hybrid-switching scheme.

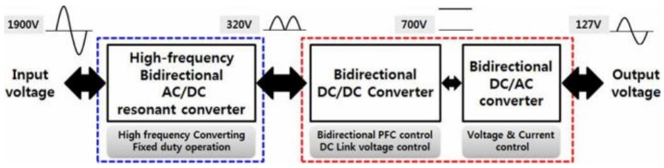

Fig. 1. Power circuit for the proposed IST

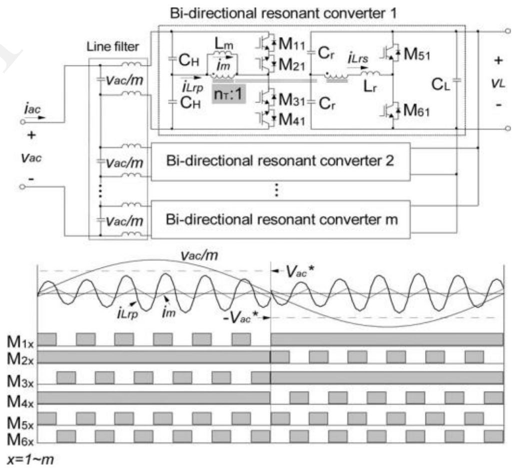

Fig. 2. AC/DC resonant converter and switching scheme.

III. SYSTEM STRUCTURE

Fig. 2 shows the bidirectional ac/dc resonant converter of the proposed IST, which is a half- bridge resonant converter with a voltage -double rectifier. This converter adopts back -to-back switches in the primary side to operate under ac input voltage. The primary side is connected in series to reduce the voltage stresses in the primary switches, while the secondary side is con-nected in shunt to reduce the current stresses in the secondary switches. The circuit parameters are described in Table I. Three resonant converters, which operate with 50-kHz switching, are connected in series to handle the input voltage of 1900 V.

The voltage balancing in the primary switches can be easily accomplished because the input- to-output gain of each converter module is determined only by its transformer -turn ratio n_T if the resonant frequency f_r is equal to the switching frequency f_{sr} . This structure offers bidirectional power flow according to its input and output conditions so that the intentional bidirectional control is not needed.

As show in control signals in Fig. 2, M_{1x} and M_{3x} are used for the high-frequency chopping during the positive half cycle of line voltage and M_{2x} and M_{4x} are used during the negative

TABLE I
SELECTED DEVICES AND KEY PARAMETERS

	Device		Value		Value
M_{1x}~M_{4x}	IKW40N120H3	C_H	0.2μF	L_r	30μH
M_{5x},M_{6x},M_7~M_{10}	BSM50GB120D	C_L	0.7μF	L_m	1mH
M_{7a} ~M_{10a}	FQA13N80	C_b	1mF	L_1, L_2	3mH
D_{7a} ~D_{10a}	FES16JT	C_r	0.25μF	n_T	2

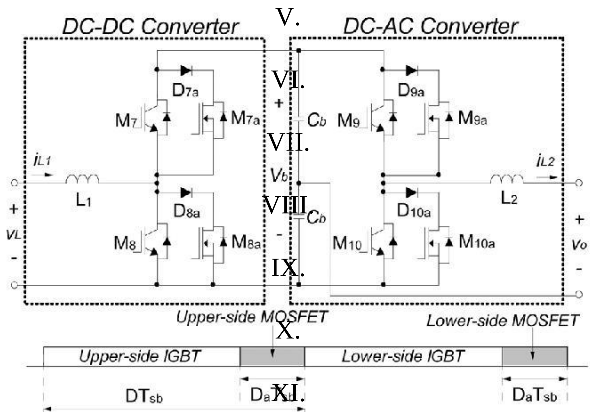

FIG. 3. DC/AC CONVERTER STAGE AND HYBRID-SWITCHING SCHEME

half cycle. To make a current path for zero- voltage switching(ZVS) operation, primary switches should be in the conducting state when they are not in switching operation. M_{5x} and M_6 always operate under an entire line cycle because they are used like a rectifier's line frequency ac voltage as well as the resonant frequency ac voltage.

Fig. 3 shows a circuit diagram for the bidirectional dc/dc and dc/ac converter, which has a typical structure comprised of two half-bridge converters. In order to reduce the switching loss, metal–oxide semiconductor field-effect transistor (MOSFET)- assisted insulated- gate bipolar transistor (IGBT) switching, which is called hybrid-switching, was adopted. Generally, IGBT has a longer tail current during the turn-off process than the MOSFET. The IGBT is responsible for turn-on and the conduction period, while the MOSFET is for the turn -off period by using a short gating pulse just after the turn -off of IGBT [6]. So both converters can operate with 25-kHz switching.

XII. EXPERIMENTAL RESULTS

In Fig. 4(a), the left graphs show the input voltage, input current, resonant current, and rectified voltage of the ac–dc resonant converter in the high- voltage side during the forward power flow. And the right graphs show the input voltage, input current, output voltage, and output current of the dc–ac converter in the low -voltage side during the forward power flow. In Fig. 4(b), the left and right graphs show the same voltages and currents as explained in Fig. 4(a) during the reverse power flow. The measured voltages and currents confi rm that the proposed IST operates properly. The total harmonic distortions (THDs) of the input voltage and current and the output voltage and current are less than 5%.

In Fig. 4(c), the first waveforms are the input voltage and current, and the rectified voltage. The second waveforms show the rectified voltage and current. The third waveforms show the

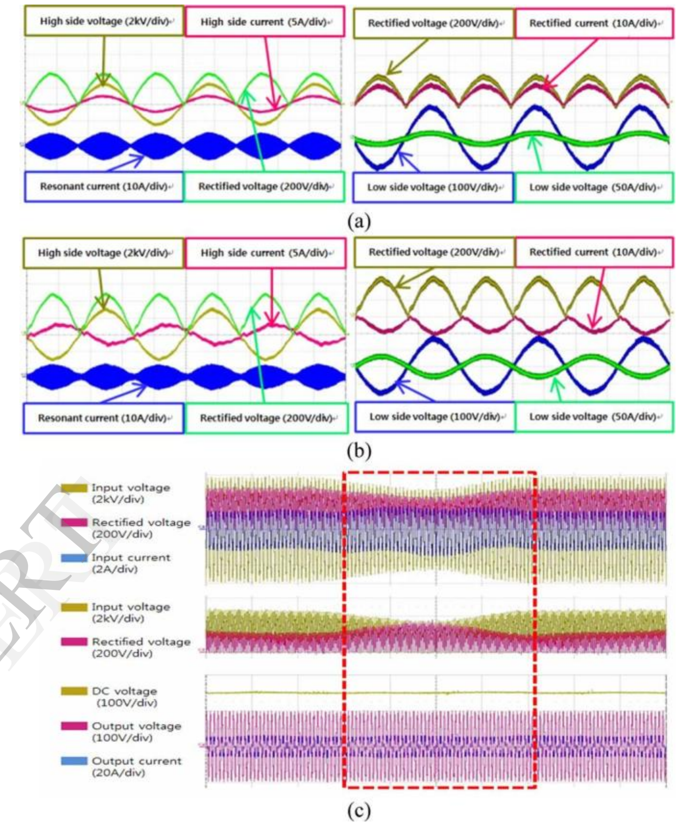

Fig. 4. Operation analysis: (a) forward power flow, (b) reverse power flow, and
(c) input voltage sag in forward power flow.

or full quotation. When quotation marks are used, instead of a bold or italic typeface, to dc-link voltage, the output voltage, and the output current in the forward power flow when voltage sag occurs. The input current and the rectified current slightly increase during the sag period to maintain constant output power. The dc-link voltage is maintained with 700 V through the voltage control of the dc–dc converter. The output voltage and current are maintained as a constant value regardless of the input voltage sag. According to the loss analysis results, the proposed IST has rather lower efficiency. The measured efficiency and the power factor in the forward power flow were 82% and 0.99, respectively, and those in the reverse power flow were 80% and 0.97, respectively. So the efficiency has to be improved. One solution could be to re-place the IGBT switches with the SiC MOSFET. But cost is still a burden.

XIII. CONCLUSION

This letter proposes a new IST. This structure provides good voltage -balancing performance on the high-voltage side and a simple control method for bidirectional power flow. The proposed IST was verified though building and testing a single-phase 2-kVA (1.9 kV /127 V) prototype. The measured efficiency is rather low up to now. Future work will focus on efficiency improvement.

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