

Experimental Evaluation of IGCT Converters with Reduced di/dt Limiting Inductance

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Abstract—Integrated gate commutated thyristor (IGCT) shows excellent potential in high-power converters owing to its advantages of low on-state voltage, low cost, and high reliability. However, a di/dt limiting inductor and a clamp circuit must be added to IGCT converters to protect the freewheeling diodes (FWD) from severe reverse recovery, leading to additional size and losses. So far, the di/dt is still limited to 1kA/μs in most of the IGCT converters, even the maximum turn-off di/dt of up-to-date fast recovery diodes has already reached up to 5.3kA/μs. In this paper, the maximum di/dt of both IGCT and diode is studied. The current commutation process of the clamp circuit is analyzed. The switching losses of IGCT, diode and clamp circuit are tested at different di/dt from 1.1kA/μs to 19.4kA/μs. Results show that the switching losses of IGCT converters will be reduced by 40% with lower di/dt limiting inductance. A back-to-back power cycling test of two half-bridge IGCT converters at 2200V/1500A and 150Hz verifies the long-term reliability of IGCT converters at maximum di/dt of 5.2kA/μs.

Keywords—IGCT, fast recovery diode, di/dt, clamp circuit, switching loss, double-pulse test, back-to-back power cycling test

I. INTRODUCTION

With the development of social economy, more and more high power electronic converters are required. Compared with insulated gate bipolar transistor (IGBT), IGCT has a higher voltage and current capacity, higher reliability, lower on-state losses, and lower cost. [1]-[3] The application of IGCT is limited because its switching frequency is relatively low. However, voltage source converter based high voltage dc transmission technology (VSC-HVDC) provides a promising application for IGCT because the power rating of converters in VSC-HVDC projects are incredibly high. Furthermore, the switching frequency of modular multilevel converter (MMC), which is the most common topology for VSC-HVDC converters, is only several hundred hertz and one of the most significant disadvantages of IGCT is avoided. [4]-[9]

One of the optimization directions of IGBT converters is to reduce the stray inductance. However, a di/dt limiting inductor must be added to IGCT converters to limit the di/dt of the circuit. Otherwise severe reverse recovery caused by high di/dt will damage the FWD. [10] The di/dt limiting inductor causes high turn-off overvoltage, which must be limited by the clamp circuit. These additional parts lead to extra size and losses of

IGCT converters. In two-level and three-level converters, only one di/dt limiting inductor and clamp circuit are needed. Unfortunately, the MMC converter is made up of hundreds of submodules and all of the submodules require individual di/dt limiting inductors and clamp circuits, which is one of the most significant obstacles of IGCT in MMC converters.

So far, the maximum di/dt is still limited to 1kA/μs in most of the IGCT converters, and a 3~4 μH inductor must be installed in the converters. With the development of power semiconductor devices, the maximum turn-off di/dt of up-to-date fast recovery diodes has already reached up to 5.3 kA/μs, which means that the di/dt limiting inductor can be hopefully reduced to 0.3μH and the performance of IGCT converters will be significantly improved. This paper analyzes the possibility and potential benefits of reducing the di/dt limiting inductance by tests, which provides instructions for the design of novel IGCT converters. The rest of the paper is organized as follows. In Section II, the current commutation process of the clamp circuit and di/dt limiting inductor is analyzed. In Section III, the maximum di/dt of both IGCT and diode is studied. In Section IV, the switching processes of IGCT, diode and clamp circuit are analyzed with different clamp circuits and di/dt from 1.1kA/μs to 19.4kA/μs. Results show that the switching losses of IGCT converters will be reduced by 40% with lower di/dt limiting inductance. In Section V, a back-to-back power cycling test of two half-bridge IGCT converters at 2200V/1500A and 150Hz verifies the long-term reliability of IGCT converters at maximum di/dt of 5.2kA/μs.

II. ANALYSIS OF THE CLAMP CIRCUIT AND DI/DT LIMITING INDUCTANCE OF IGCT CONVERTERS

In half-bridge converters, the turn-on process of the IGCT and the turn-off process of the FWD are simultaneous. In Fig.1(a), S2 is turned off and the load current is flowing into the converter through D1. Once S2 is turned on, D1 will be turned off by the DC line voltage and the load current will commute to S2, which is shown in Fig.1(b). Another situation is given in Fig.1(c), S1 is turned off and the load current is flowing out of the converter through D2. Once S1 is turned on in Fig.1(d), D2 will be turned off by the DC line voltage and the load current will commute to S1.

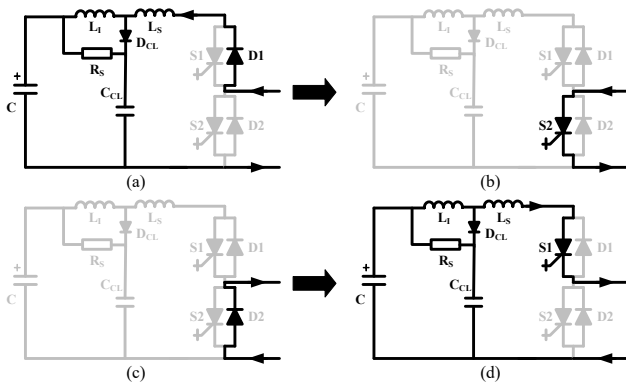


Fig. 1. Current commutation process of half-bridge IGCT converters

Because the turn-on process of IGCT is a positive-feedback process, the speed of the current commutation is only determined by the external circuit. The di/dt of IGCT converters is limited by the stray inductance L_s and the di/dt limiting inductance L_l . [11] The maximum di/dt can be calculated from L_s , L_l and the dc line voltage V_{DC} :

$$\frac{di}{dt} = \frac{V_{DC}}{L_s + L_l} \quad (1)$$

For typical 2.5kV half-bridge MMC submodules, the stray inductance is about 70~120nH, which means that the maximum di/dt will reach up to 20kA/ μ s without additional di/dt limiting inductor. High turn-on di/dt of IGCT will cause localized conduction and hot spots, which could destroy the IGCT. [12] While high turn-off di/dt of FWD will cause devastating reverse recovery. [13] So far, whether the IGCT or the diode is the bottleneck of di/dt is unknown. According to the datasheet, the maximum di/dt of IGCT and the compatible diode is 1kA/ μ s, which means that the di/dt limiting inductance must be higher than 2.5 μ H. Considering the safety tolerance, the di/dt limiting inductance is usually 3~4 μ H. [14][15]

The energy stored in the di/dt limiting inductor will be released once the current is interrupted, generating overvoltage on the IGCTs and diodes. To prevent the devices from being broken down by the overvoltage, RCD clamp circuit is added to absorb the energy. As shown in Fig.2, once the current is interrupted, some of the energy in L_l will be absorbed by C_{CL} while the rest will dissipate on R_s . The voltage of C_{CL} will be higher than the DC line voltage during the current commutation, leading to the energy feedback from C_{CL} to C.

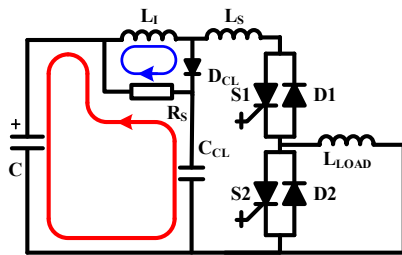


Fig. 2. Energy dissipation path of clamp circuit

III. MAXIMUM DI/DT OF IGCT AND DIODE FOR SINGLE SWITCHING

A single-pulse test has been carried out to confirm the maximum turn-on di/dt of IGCT. The test platform is shown in Fig.3. The tested IGCT is TEG CAC4000-45. The capacitor C1 is 20 μ F, which is connected to the IGCT with ultra-low stray inductance and serves to provide turn-on surge current of IGCT. The capacitor C2 is 2.5mF and provides continuous current. Once C1 and C2 are charged, S1 will be turned on for 80 μ s. In Fig.4, the capacitor voltage is 1400V and the turn-on surge current is 24.7kA. In this case, the turn-on di/dt of IGCT is 19.3kA/ μ s and the IGCT is still operational. Once the capacitor voltage increases to 1500V in Fig.5, the IGCT is destroyed and fails to turn off. At this point, the surge current is 26.7kA and the turn-on di/dt is 23.7kA/ μ s.

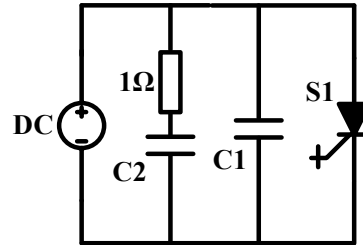


Fig. 3. Single-pulse test circuit

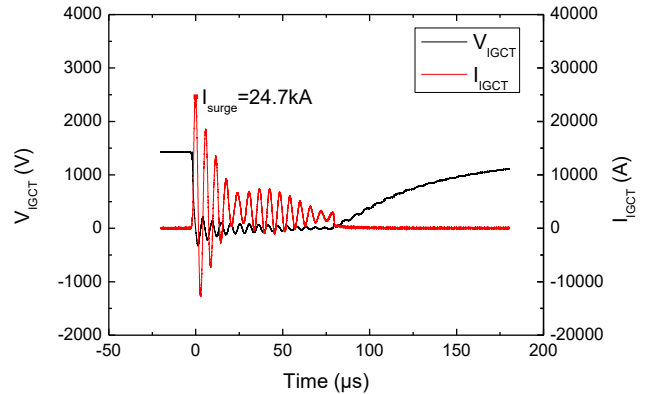


Fig. 4. Single-pulse test of IGCT at 24.7kA and 19.3kA/ μ s

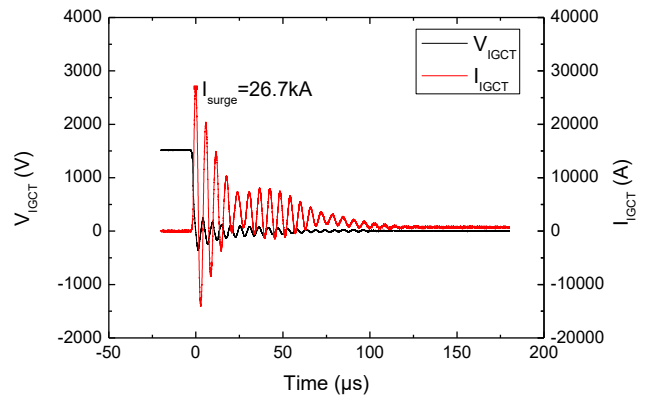


Fig. 5. Failure of IGCT at 26.7kA and 23.7kA/ μ s

The maximum turn-off di/dt of the diode is analyzed by double-pulse tests. The tested diode is ABB 5SDF 20L4521, of which the maximum decay rate of on-state current is $5.3\text{kA}/\mu\text{s}$. [16] During the test, the turn-off di/dt of diode increases from $1.1\text{kA}/\mu\text{s}$ to $19.4\text{kA}/\mu\text{s}$. After demonstrating several successful turn-off processes at 3.5kA and $19.4\text{kA}/\mu\text{s}$, the diode explodes. It's evident that the high turn-off di/dt dramatically increases the failure rate of the diode.

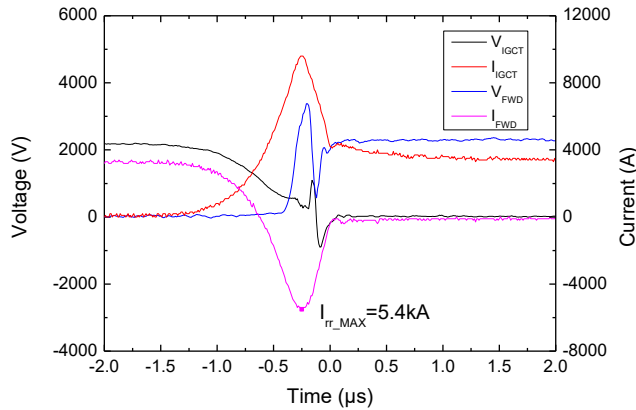


Fig. 6. Turn-off waveform at 3.5kA and $19.4\text{kA}/\mu\text{s}$



Fig. 7. Exploded diode

It can be seen that the di/dt limit of both IGCT and FWD is less than $20\text{kA}/\mu\text{s}$. The FWD is more vulnerable than IGCT against high di/dt .

IV. ANALYSIS OF IGCT, DIODE AND CLAMP CIRCUIT AT DIFFERENT DI/DT

A. The Half-bridge IGCT Converter

To evaluate the potential benefits of reducing the di/dt limiting inductance, the switching losses of IGCT, diode and clamp circuit with different RCD snubber circuits and different di/dt should be studied. Therefore a half-bridge IGCT converter is built. The converter is designed and constructed according to the standard of high power MMC submodules. In order to adjust to variable di/dt limiting inductance, an interface is added to the converter. A multi-output water-cooled inductor can be used as variable inductor from $0.7\mu\text{H}$ to $3\mu\text{H}$. Because the production of water-cooled inductors with ultralow inductance is challenging, the di/dt limiting inductor from $0.1\mu\text{H}$ to $0.7\mu\text{H}$ is replaced by a copper bar. The length of the copper bar is adjustable and the inductance of the copper

bar is calculated by FEM simulation. Fig.8 shows the diagram of the IGCT converter and Table I gives its parameters.

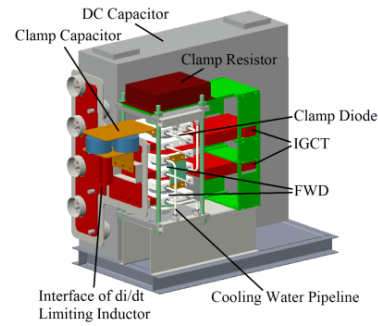


Fig. 8. Half-bridge IGCT converter

TABLE I. PARAMETERS OF THE CONVERTER

Parameters	Value
IGCT	TEG CAc4000-45
IGCT Gate Power Supply	SW32-24D35U
Diode	ABB 5SDF 20L4521
DC Capacitance	9mF
DC Line Voltage	2200V
Load Inductance	$300\mu\text{H}$
Stray Inductance	$0.12\mu\text{H}$
di/dt Limiting Inductance	$0\sim 1.95\mu\text{H}$
Clamp Resistance	$0.2\Omega\sim 0.6\Omega$
Clamp Capacitance	$2\sim 10\mu\text{H}$
Clamp Diode	TEG ZKx1100-45
Junction Temperature	35°C

B. Design of the Clamp Circuit

The clamp circuit limits the turn-off overvoltage and determines the dynamic response of the converter. To optimize the design of clamp circuit, double-pulse tests with different resistance and capacitance at $1.1\text{kA}/\mu\text{s}$ and 3.5kA are carried out.

Fig.9 shows the test waveform with different clamp capacitance at 3.5kA . As the capacitance increases, the turn-off voltage of IGCT reduces and its oscillation cycle increases. It is evident that higher clamp capacitance will provide better protection to IGCTs, but the size and losses of the converter will also increase. Fig.10 shows the test waveform with different clamp resistance. As the resistance reduces, the turn-off voltage of IGCT reduces and its oscillation also reduces. When the clamp resistance is 0.4Ω or 0.6Ω , the voltage of IGCT will oscillate severely, which could threaten the reliability of IGCT. Based on the results, the clamp capacitance is $10\mu\text{F}$ and the clamp resistance is 0.2Ω in the final design.

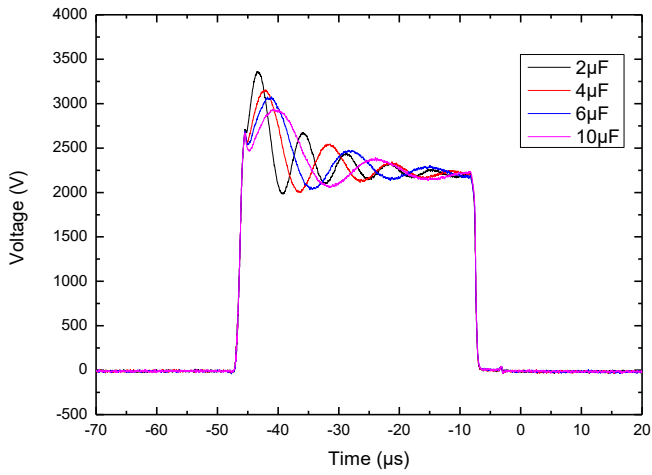


Fig. 9. Turn-off voltage with different clamp capacitance

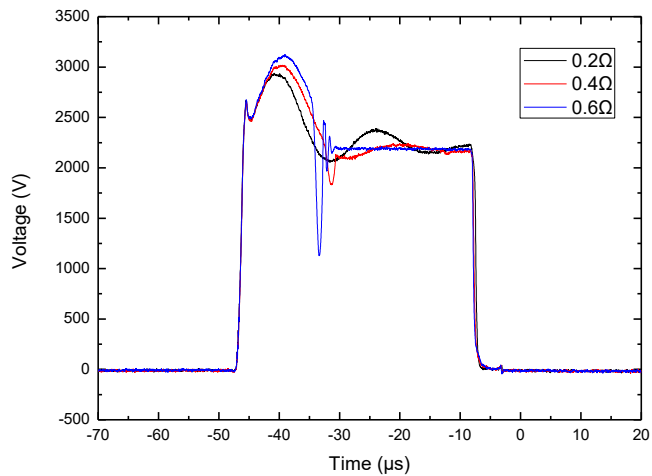


Fig. 10. Turn-off voltage with different clamp resistance

C. Test results and Analysis

To analyze the performance of IGCT converter, a series of tests at 3.5kA are carried out. Fig.11 shows the relationship between the total inductance and the maximum di/dt of the IGCT converter. The test results perfectly match equation (1).

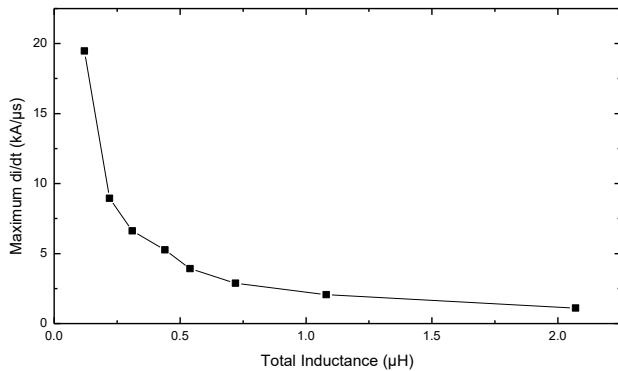


Fig. 11. Relationship between the total inductance and the maximum di/dt

Fig.12 and Fig.13 show the relationship between the di/dt limiting inductance and the switching process. As the inductance reduces, the turn-off overvoltage of IGCT drops, leading to lower turn-off energy of IGCT. However, the reduced inductance also causes violent reverse recovery, which increases the reverse recovery current of FWD, the turn-on energy of IGCT, and the turn-off energy of diode.

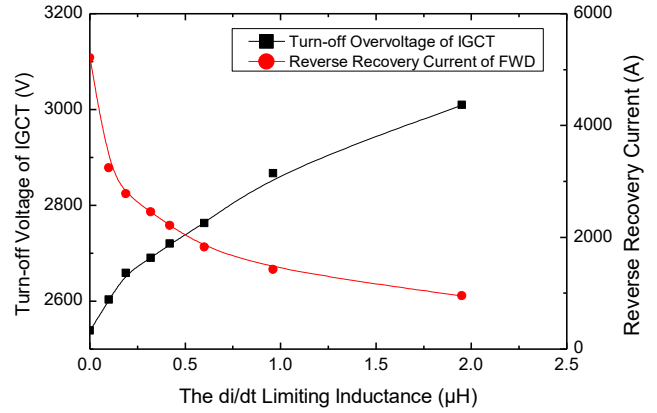


Fig. 12. The peak voltage and current

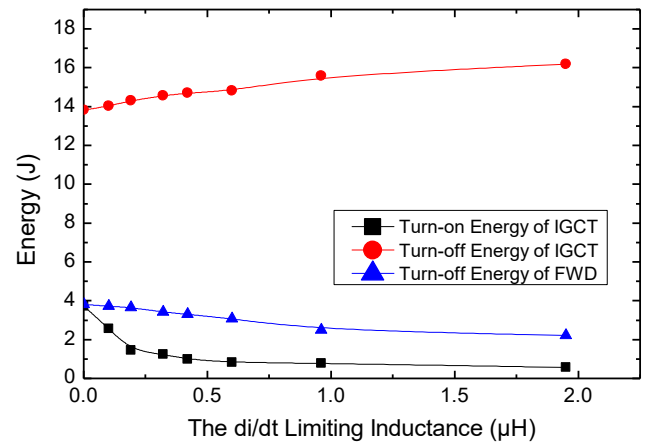


Fig. 13. Switching energy of IGCT and FWD

The energy requirement of increasing the current of inductor L from zero to I is LI^2 , which is the red line in Fig.14. When IGCT turns off, the clamp capacitor will be charged and some of its energy will be released to the DC capacitor, which is described in Section II. Results show that 75% of the energy stored in the inductor will be dissipated.

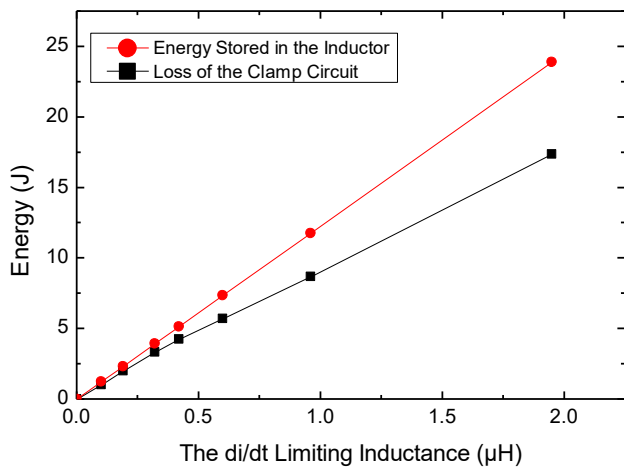


Fig. 14. Losses of the clamp circuit

Fig.15 shows the total switching losses of IGCT converter. If the inductance can be reduced to about $0.32\mu\text{H}$, which means the di/dt is $5.2\text{kA}/\mu\text{s}$, the switching losses of IGCT converters can be reduced by 40%. Using di/dt limiting inductance lower than $0.3\mu\text{H}$ is risky and has no meaning for losses reduction.

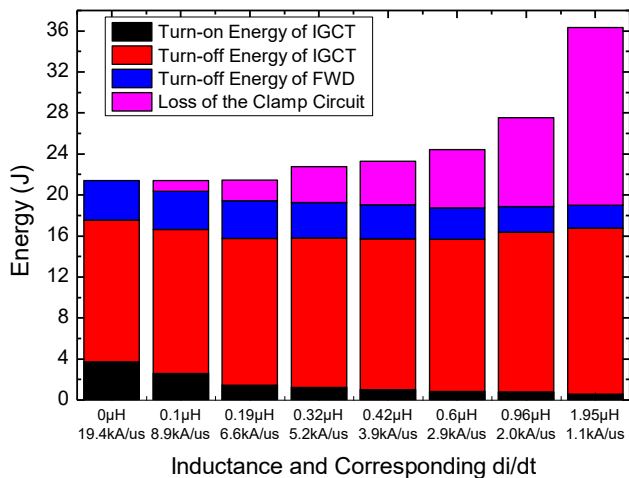


Fig. 15. Total switching losses of IGCT converter

V. BACK-TO-BACK POWER CYCLING TEST OF IGCT CONVERTERS

A. Test Platform

To verify the long-term reliability of IGCT converters with reduced di/dt limiting inductance, a back to back power cycling test is carried out. [17] As shown in Fig.16, two half-bridge IGCT converters are connected via a 1mH inductor. By changing the phase difference of the output voltage, current will keep circulating within the two converters. The DC power supply will provide the losses of the system. The DC line capacitors of the two converters are connected to guarantee the voltage balance.

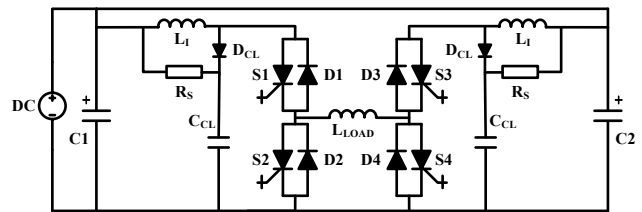


Fig. 16. Test circuit

A 100kW DC power supply system, which is shown in Fig.17, is built to provide the losses during the test. Fig.18 shows the test platform.

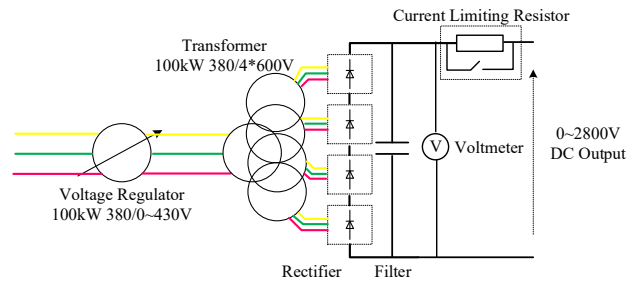


Fig. 17. DC power supply for the power cycling test

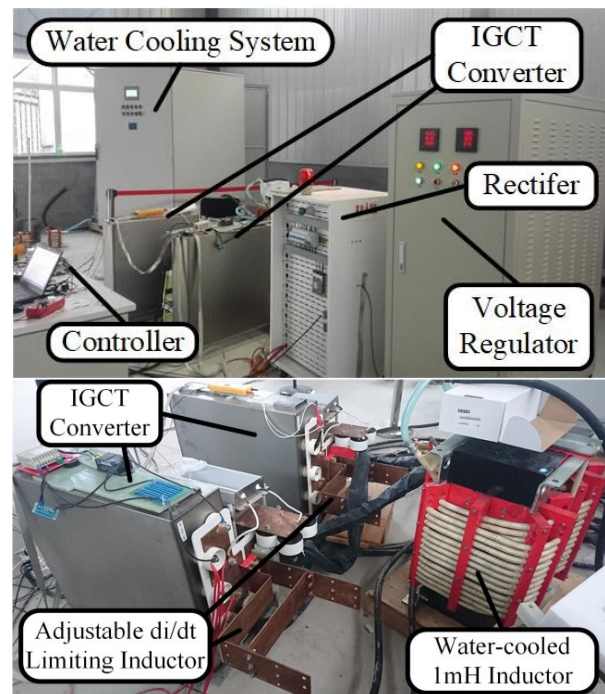


Fig. 18. Back-to-back power cycling test platform

B. Test Results

The test platform runs for 2.5 hours at $2200\text{V}/1500\text{A}$, 150Hz and $5.2\text{kA}/\mu\text{s}$. The maximum turn-off current of IGCT reaches 2.4kA . The di/dt limiting inductance is $0.32\mu\text{H}$, which is only one-eighth of the recommended value while the

converters work well. The losses of each IGCT converter are 6.1kW. Fig.19 shows the test waveform and Fig.20 shows the temperature distribution of the converter. Details of the test are given in Table II.

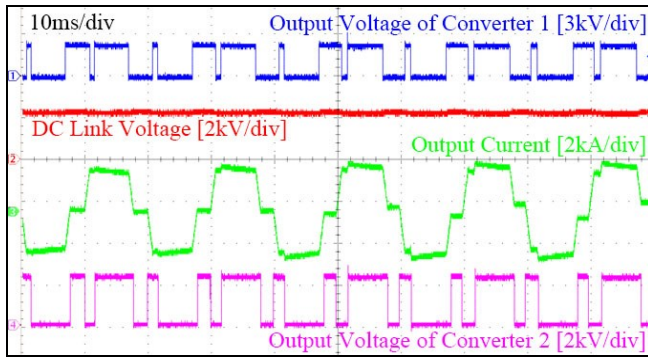


Fig. 19. Test waveform at 2200V/1500A and 150Hz

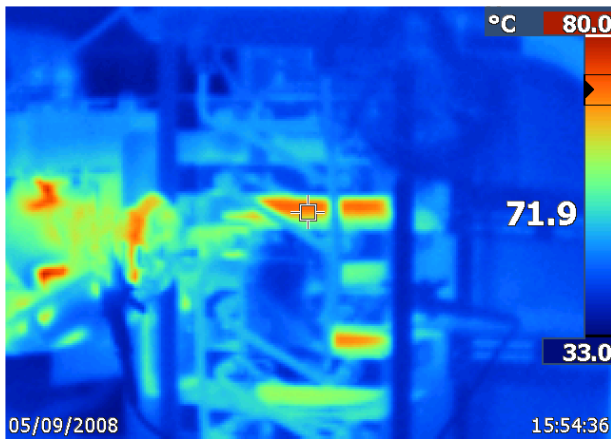


Fig. 20. Temperature distribution of the IGCT converter

TABLE II. DETAILS OF THE TEST

Parameters	Value
DC Line Voltage	2200V
RMS Current	1500A
Maximum Current	2400A
Switching Frequency	150Hz
Phase Difference	43°
Current of DC Source	15.5A
Gate Power Consumption of IGCT	15.6W
Room Temperature	39°C
Water Flow	4.95m ³ /h
Water Temperature	Input: 50.5°C Output: 64.3°C
Total Losses of each IGCT converter	6.1kW

VI. CONCLUSION AND FUTURE WORK

This paper verifies that IGCT converters can operate smoothly at 5.2kA/μs with the help of newly-developed fast recovery diodes. In this case, the losses of IGCT converters are considerably reduced owing to the reduced di/dt limiting inductance. The size and complexity of IGCT converters are also improved. Limited by the water-cooling capability of the test platform, the maximum RMS current is only 1500A. A new test platform with enhanced water-cooling system is under construction and the test of 2800A diodes at higher current will be carried out. To increase the accuracy of losses analysis, the double-pulse tests at high junction temperature will be carried out soon afterward.

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