Experimental Study on Adaptability of Fully-immersed Liquid Cooling IGBT Module

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Abstract. IGBT converter valve is the core component of the flexible HVDC transmission system, and the failure caused by the thermal problem and the decrease of equipment reliability become the bottleneck of the development of flexible HVDC transmission technology toward large capacity. It is experimentally proved to be an effective way to reduce the junction temperature of IGBT module by using the fully-immersed liquid cooling technology. In this paper, the operation reliability of IGBT module immersed in the liquid cooling medium is studied by carrying out the adaptability experiment of fully-immersed liquid cooling IGBT module. The operation process of fully-immersed liquid cooling IGBT module is monitored, and the research methods of signal observation and energy spectrum analysis are used to diagnose the failed IGBT module in the experiment. The failure mode and cause of the fully-immersed liquid cooling IGBT module are obtained, which provides guidance and technical support for the optimal design of high reliability fully-immersed liquid cooling IGBT module.

1. Introduction
To achieve large-scale remote transmission of renewable energy, flexible HVDC transmission technology based on insulated gate bipolar transistor (IGBT) has become a research hotspot in the field of power transmission and smart grid. High voltage and large capacity are the development trends of flexible HVDC transmission technology [1,2,3]. The transmission capacity of flexible HVDC transmission system is mainly limited by the junction temperature of IGBT converter valve, the higher the power density of IGBT, the more serious the heating. High junction temperature or excessive temperature gradient may cause IGBT module failure. Therefore, strengthening heat dissipation and controlling the temperature level of IGBT converter valve are important guarantee for stable operation of flexible HVDC transmission system.

At present, the IGBT converter valve of flexible HVDC transmission system mostly adopts water cooling, which belongs to indirect cooling mode with forced circulation [4,5]. The cooling capacity of water cooling is limited and the system is complex. At the same time, the conductivity of cooling water becomes a serious hidden danger to the safety of the system. It is of great significance to develop safe and efficient novel cooling technology applying to the IGBT converter valve. The fully-immersed liquid cooling technology adopting environmentally friendly liquid cooling medium (coolant) with high insulation voltage and low boiling temperature uses the latent heat of vaporization to remove heat and has the advantages of high cooling efficiency, uniform temperature distribution,
simple system structure and high reliability [6,7], which is expected to become an effective method to realize the efficient heat dissipation of IGBT converter valve.

With water cooling, the heat generated by the IGBT module is mainly released through the bottom plate, and the heat dissipation of IGBT module is unidirectional. While with the fully-immersed liquid cooling, the IGBT module is treated with silica gel removal firstly, and then soaked in the insulating coolant. The IGBT chips are in direct contact with the coolant and the heat is dissipated in both directions through the chip surface and the bottom plate. There are essential differences between the coolant and silica gel in heat transfer principle and material properties.

In order to study the operation reliability of IGBT module under fully-immersed liquid cooling mode, the adaptability experiment of fully-immersed liquid cooling IGBT module is necessary and preferentially carried out. An experimental platform is set up to make the IGBT module operate in a certain working condition for a long time in the coolant. The operation process of the fully-immersed liquid cooling IGBT module is monitored, and failure analysis on the failed IGBT module is carried out. The failure mode of IGBT module with fully-immersed liquid cooling and the cause of failure are obtained. The research results provide guidance for the optimal design of fully-immersed liquid cooling IGBT module.

2. Heat dissipation principle of fully-immersed liquid cooling IGBT module

The heat dissipation principle of fully-immersed liquid cooling IGBT module is shown in figure 1. The boiling temperature of the coolant under a standard atmospheric pressure is about 45°C.

![Figure 1. Principle of fully-immersed liquid cooling IGBT module.](image)

Firstly, the heat of IGBT module is taken away by specific heat absorption and natural convection of the coolant until the mainstream temperature of the coolant reach the saturation temperature under the corresponding pressure. Then the coolant turns to the saturated nuclear boiling condition, and the heat of IGBT module is carried away by the latent heat of vaporization of the coolant. The gaseous coolant rises to the condenser, transfers the absorbed heat to the secondary cooling water or surrounding cold air, and returns back to the liquid coolant area, thus completing the self-circulation process [7]. Because of the low boiling point and high vaporization latent heat of the coolant, the temperature level of IGBT module can be effectively controlled, and the temperature distribution of IGBT module is uniform. In addition, the boiling state of the coolant will automatically change with the heat flux of IGBT module, and the system can be self-adaptive and self-adjusting.

3. Adaptability experiment design of fully-immersed liquid cooling IGBT module

3.1. IGBT module and operation circuit for experiment

In the experiment, Infineon "FF600R12ME4" IGBT module which has a typical half bridge topology is selected. The module’s rated voltage is 1200V, rated current is 600A. The two switches of the up and down bridge arms are composed of three IGBT chips and three freewheeling diodes (FWD). The module’s picture and equivalent circuit are shown in figure 2 and figure 3. Terminals numbered 1-11 are the power terminals and test terminals of the IGBT module.
Use the selected IGBT module to build a buck circuit as the operation circuit in IGBT adaptability experiment, as shown in figure 4. The buck circuit is composed of DC regulated power supply, IGBT module and LCR circuit. Apply low voltage level to the gate of IGBT upper switch to make it in the off state, and apply square wave drive signal with fixed frequency and duty cycle to the IGBT lower switch to make it work in the on-off state.

The buck circuit’s device parameters and operation parameters are shown in table 1.

### Table 1. Device parameters and operation parameters of buck circuit.

| No. | Parameters      | Value   | No. | Parameters      | Value   |
|-----|----------------|---------|-----|----------------|---------|
| 1   | Input voltage  | 600V    | 5   | Duty cycle     | 1/3     |
| 2   | Output voltage | 200V    | 6   | Load resistance | 20Ω     |
| 3   | Output power   | 2000W   | 7   | Inductance Ls  | 1mH     |
| 4   | Switching frequency | 10kHz | 8   | Output capacitance | 380 μF |

### 3.2. Design of adaptability experiment platform

The schematic diagram of the adaptability experiment platform is shown in figure 5. The IGBT module is placed in the seal chamber and immersed in the insulating coolant. The DC regulated power supply and LCR circuit are placed outside the seal chamber and connected with the IGBT module through seal adapters. The control board outputs PWM signals to ensure the IGBT module operate in the certain working condition. The oscilloscope is connected with IGBT test terminals to monitor Vge (No.1 and No.2 terminals) and Vce (No.8 and No.2 terminals) of the down bridge arm switch. The NTC-thermistor (No.5 and No.6 terminals) is led out to monitor the junction temperature of IGBT.

In this experiment, the heat generated by IGBT module is transferred to the coolant, and then all of them are naturally discharged through the surface of the seal chamber without secondary cooling water. The pressure gauge and valve above the seal chamber are used to monitor and regulate the internal pressure of the chamber. During the experiment, the pressure in the chamber is kept at a standard atmospheric pressure. In order to observe the operation state of IGBT module in coolant, the seal chamber has two transparent glass observation windows. The picture of the adaptability experiment platform is shown in figure 6.
4. Adaptability experiment and failure analysis of fully-immersed liquid cooling IGBT module

4.1. Adaptability experiment of fully-immersed liquid cooling IGBT module

Firstly, connect the IGBT module to the driver and place them in the seal chamber, then connect external LCR circuit and DC regulated power supply through seal adapters, and lead out the IGBT test terminals. Secondly, a proper amount of coolant is injected into the seal chamber, and 24-hour pressure maintaining test is conducted to ensure air tightness of the chamber. Finally, connect the oscilloscope and other test equipment, turn on the DC regulated power supply, and adjust the circuit to the specified operation state.

The circuit signals to be monitored during circuit operation are as follows:
- Circuit input voltage \( V_{in} \)
- Circuit output voltage \( V_{out} \)
- IGBT lower switch gate voltage \( V_{ge} \)
- IGBT lower switch collector-emitter voltage \( V_{ce} \)
- IGBT NTC-thermistor value

When \( V_{in} = 600V \), the output voltage of the test circuit is 203.6V. The waveform of \( V_{ge} \) and \( V_{ce} \) of IGBT lower switch is shown in figure 7. The spike in \( V_{ge} \) is due to the introduction of test leads, which has no impact on the operation of IGBT module.

When the junction temperature of IGBT module reaches steady state, the measured value of IGBT NTC-thermistor is 2.09kΩ. According to the data book, the junction temperature of the IGBT module is about 50°C. The operation state of the fully-immersed liquid cooling IGBT module is shown in figure 8. The coolant has entered boiling state, and the junction temperature of IGBT module is only slightly higher than the boiling point of the coolant.

4.2. Failure analysis of fully-immersed liquid cooling IGBT module

After a period of continuous operation, a certain fully-immersed liquid cooling IGBT module happened to be failed, the circuit stopped working and the DC circuit breaker connected between the...
DC regulated power supply and the buck circuit tripped. The failure detection shows that the upper switch (between terminals No.4 and No.10) of the IGBT module is damaged. Remove the driver and examine the internal part of the module, as shown in figure 9.

The position marked by the red circle in figure 9 is the failure point of IGBT module. It is found that the IGBT module has overcurrent between the upper copper substrates connected with the positive power terminal (No.3 terminal) and the negative power terminal (No.4 terminal), and the IGBT chip of up bridge arm near the overcurrent point is damaged, leading to the module failure. At the same time, there is a few black reactant inside the IGBT module.

In order to analyze the failure reason of IGBT module with the fully-immersed liquid cooling mode, the black reactant inside the IGBT module was detected by means of scanning electron microscope(SEM) and energy dispersive spectrometer(EDS) [8]. The energy spectrum of the black reactant are shown in figure 10.

![Image](image1.jpg)

**Figure 9.** Internal picture of the failed IGBT module.

![Image](image2.jpg)

**Figure 10.** Energy spectrum of the black reactant.

The main elements of black reactant in IGBT module are: C, O, Si, Cu, S, Cl. Among them, C, O and Si are from the residual silica gel, Cu is from the copper substrate of the IGBT module, and S and Cl are some unexpected elements.

The energy spectrum analysis of 7 kinds of non-metallic materials used in the adaptability experiment is carried out, and the results are shown in table 2.

| No. | Non-metallic material                             | Main element         |
|-----|--------------------------------------------------|----------------------|
| 1   | IGBT shell                                       | C, O, Br, Si         |
| 2   | PCB                                              | C, O, N, S, Cl       |
| 3   | Heat shrinkable tube                             | C, O, Mg             |
| 4   | Insulation skin 1 (bus)                          | C, O, N, Cl          |
| 5   | Insulation skin 2 (signal wire of control board) | C, O, N, Cl          |
| 6   | Insulation skin 3 (IGBT test wire)               | C, O, N, F           |
| 7   | Insulation skin 4 (600V power supply wire)       | C, F                 |

It can be seen from the above table that S element mainly comes from PCB, and Cl element mainly comes from PCB, insulation skins of the bus and control board signal wire.

According to the element proportion in figure 10, the black reactant contains Cu$_2$S, which is a kind of gray black glossy crystal or powder with good conductivity. Copper and sulfur can react to form Cu$_2$S under heating condition. The reaction equation is as follows:

$$2Cu + S \xrightarrow{\Delta} Cu_2S$$  \hspace{1cm} (1)

To sum up, the reason for the failure of the fully-immersed liquid cooling IGBT module can be predicted. During the operation of fully-immersed liquid cooling IGBT module, the copper substrate of IGBT module reacts with S from non-metallic materials to form conductive Cu$_2$S, which makes the insulation strength between copper substrates in the IGBT module decrease. Among them, the voltage
between the copper substrates connected with the positive and negative power terminals is equal to the input voltage of the buck circuit, which is the weak part inside the IGBT module. The insulation strength drop leads to the breakdown of this part, resulting in the IGBT module over-current failure.

5. Conclusions
In order to promote the application of fully-immersed liquid cooling technology in IGBT converter valve, this paper carried out the adaptability experiment research of fully-immersed liquid cooling IGBT module, and analyzed the failure mechanism of the IGBT module. The reason for the failure of the fully-immersed liquid cooling IGBT module is predicted to be the copper substrate reacting with S from non-metallic materials to produce conductive Cu$_2$S, which makes the insulation strength between copper substrates connected with positive and negative power terminals of the IGBT module decrease, thus results in the IGBT module overcurrent failure. Because the PCB of IGBT driver contains S element, it is difficult to replace the material. On the premise of ensuring the heat dissipation efficiency, a protective layer can be sprayed inside the IGBT module to isolate the copper substrate from S, then to prevent the formation of Cu$_2$S. The feasibility of this method is still under further study, and further research results are expected to be published in the near future.

6. References
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Acknowledgments
This work was supported by the National Natural Science Foundation of China under Grant No. 51777201.