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Investigation of a rectangular heat pipe radiator with parallel heat flow structure for cooling high-power IGBT modules

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ABSTRACT

The thermal management of insulated-gate bipolar transistor (IGBT) modules is a critical issue in the field of power electronics. According to the minimum thermal resistance principle, this study proposed a rectangular heat pipe radiator with parallel heat flow structure that can be used for cooling two 1700 V/1000 A IGBT modules. The prototypes of typical and novel heat pipe radiators were produced to validate the heat transfer enhancement of the novel structure. Performance evaluation and analysis were numerically and experimentally carried out, and the numerical results agreed well with the experimental data. Parametric studies were performed to analyze the effects of inlet air temperature, air volume, and heat load on the heat dissipation capability. The study found that the novel heat pipe radiator has a good start-up characteristic due to the parallel heat flow structure. Moreover, the performance enhancement of the novel heat pipe radiator is obvious at large heat loads. Experiment results show that the two IGBT modules with 3500 W could be cooled down to 67.8 °C when the air volume is 450 $m^3 h^{-1}$, which is 8.9% lower than that of a typical heat pipe radiator. The proposed novel structure improves thermal performance of the novel heat pipe radiator by significantly decreasing its thermal resistance by 22% in comparison with that of a typical heat pipe radiator.

1. Introduction

Insulated-gate bipolar transistor (IGBT) modules are commonly used as power semiconductors in various fields, including in industrial, automotive, and renewable energy applications [1]. IGBTs can be reliably turned on/off up to more than one million times. Therefore, the reliability of IGBT modules has become a critical issue [2]. Previous studies indicated that IGBTs could generate heat losses of up to a thousand watts during normal operations [3]. Such high heat fluxes significantly lead to high and less uniform chip temperature and degrade device performance and system reliability. The effective cooling of IGBT modules can improve reliability by eliminating overstress failures and reducing the severity of fatigue mechanisms at high temperatures, as well as the frequencies of thermal cycling. Effective cooling also enhances the performance of power electronic systems. Thus, the cooling technology of IGBT modules has received increasing attention.

The cooling of IGBT modules is primarily achieved with air-cooled or liquid-cooled heat radiators [4]. With regard to the air-cooled heat radiator, existing studies mainly focused on designing a novel structure. Han et al. [5] numerically and experimentally investigated the influence of air flow rate on the junction temperature of IGBT modules and adopted a porous medial model in heat sink blocks by improving simulation accuracy. Then, they compared the thermal performance of heat sinks with plate, perforated, and protuberance fins. The heat sink with the perforated fin had the best performance, cooling the IGBT module to 131.4 °C with 1300 W [6]. Chang et al. [7] designed a finned heat sinks filled with paraffin/graphite nanoplatelets composite phase change material for the thermal management of IGBTs and then used this material to enhance the thermal uniformity of heat sink base (345 mm × 120 mm). The experimental results showed that a 9 kW converter with three IGBT modules could be cooled down to 66.1 °C when the air flow rate was 5.2 m/s.

With regard to the liquid-cooled heat radiator, the studies mainly focus on direct cooling. Liu et al. [8] compared the indirect and direct liquid cooling systems. They found that direct liquid cooling using a

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microchannel cold plate could effectively reduce thermal resistance and cool size of IGBT modules. Sun et al. [9] experimentally demonstrated that the entire thermal resistance of a direct cooling heat sink was reduced by up to 33% compared with that of an indirect cooling heat sink. Wang et al. [10,11] proposed a novel AlCu-clad base plate and Al in-line pin–fin arrays with advantages of thermal efficiency, weight, and cost. Bahman and Blaabjerg presented a user-friendly optimization tool for direct water cooling systems for IGBT modules; this tool enables cooling system designers to identify an optimized solution depending on customer load profiles and available pump power [12]. Then, two-phase cold plates were introduced to cool high-flux IGBT modules. Jeremy et al. [13] presented a two-phase cooling method using R134a refrigerant to dissipate the heat energy generated by IGBT modules. They submerged power electronics in an R134a bath and tested simultaneous operations with a mock automotive air-conditioner. According to experimental results, the techniques proposed in these studies could maintain IGBTs within a reliable temperature range. Wang and McCluskey [14] established a first-order analytical model to analyze the thermal performance of R134a two-phase cold plate and found that the maximum IGBT temperature was 68.3 °C when a R134a two-phase cold plate was used to cool a 2400 W inverter module. By contrast, for single-phase cooling (ethylene glycol/water) at the same condition, the maximum IGBT temperature reached 115.2 °C. However, designing practical products for various types of IGBT is difficult. In addition, a hybrid thermoelectric water–cooling method was also introduced to cool the hot spot of IGBTs [14].

Note that the liquid cooling systems surpass the air cooling systems by supplying heat transfer coefficient several orders of magnitudes higher. However, the reliability of liquid cooling is considerably low due to liquid leakage. For instance, a 500 kV substation stopped running for a year due to the leakage of a water-cooled heat radiator in Dongguan, China. Generally, heat pipe radiator, featured with remarkable advantages in high heat transfer efficiency, high reliability, high efficiency without additional electric energy consumption and suitable working temperature for electronic devices, could be used to cool high heat flux IGBT chip [15]. Driss et al. [16] established a thermal resistor-capacitor network model of IGBTs as one heat pipe to simulate the junction temperature of IGBTs, as well as the heat pipe temperatures in response to periodic heat (40 W). The influence of cyclic ratio and switching frequency on the junction temperature of IGBT modules has also been studied. Smitka et al. [17] developed a loop heat pipe for cooling IGBTs and studied the impact of the amount of working fluid on the removal of waste heat from IGBTs. The findings showed that the loop heat pipe could cool the 400 W IGBT down to 100 °C when the filling ratio of the working fluid was between 60% and 70%.

According to the literature review presented above, only a few studies have explored the cooling of IGBT modules using heat pipe radiators with a relatively small heat load [4,18]. By considering the high reliability of heat pipe radiators, we introduced a forced-air convection heat pipe radiator for cooling large-scale and high-power IGBT modules. Hence, a large-scale heat pipe radiator was firstly fabricated according to the typical technology and then discussed using an energy flow model. To further enhance the heat dissipation ability of typical heat pipe radiators, we proposed a novel heat pipe radiator on the basis of the minimum thermal resistance principle. The impact of working conditions, i.e., ambient temperature, air volume, and heat load, was experimentally and theoretically studied to evaluate the heat dissipation performance of the novel heat pipe radiator.

2. Description of numerical simulation model and experimental setup

Simulation and experiment studies were conducted according to a project case to analyze and optimize the heat dissipation performance of a heat pipe radiator. In this case, the heat pipe radiator

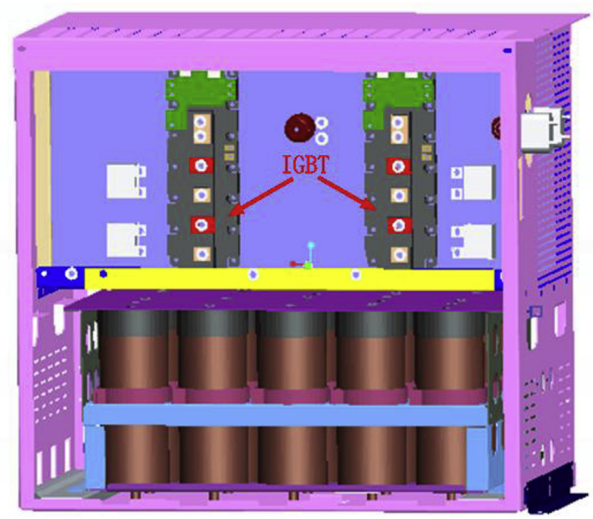

Fig. 1. The structure diagram of SVG with two IGBT modules.

(560 mm × 300 mm × 250 mm) was used to cool two 1700 V/1000 A IGBT modules of one static VAR generator, as shown in Fig. 1. The external size of the IGBT module was 62 mm × 150 mm. The heat load of each IGBT module was 1750 W, and the IGBT modules were vertically installed. Thus, the gravity type heat pipe radiator with the inclination angle of 5° was designed according to the engineering level. The condensed working fluid flowed back to the evaporator end by the force of gravity. The working fluid was boiled deionized distilled water, and the filling ratio was controlled in the range of 17–20 vol%.

2.1. Simulation model

A numerical simulation model was built using the finite element method, as shown in Fig. 2. The model consisted of two IGBT modules: one heat pipe radiator and one centrifugal fan and air conduct. The priority level of heat pipes should be higher than that of fins. The computational domains were meshed with a hexa unstructured grid, and the grid of the fins was refined. The simulation model was developed according to the following assumptions.

(1) The IGBT module is substituted using an aluminum block with eight electrical heating rods.
(2) The heat pipes are assumed to be heat conductors with high heat conductivity in the axial direction (12000 $Wm^{-1}K^{-1}$), and the value is obtained by combining the experiment and trial methods.
(3) The ambient temperature is maintained at a specific value.
(4) The material properties are non-temperature dependent.

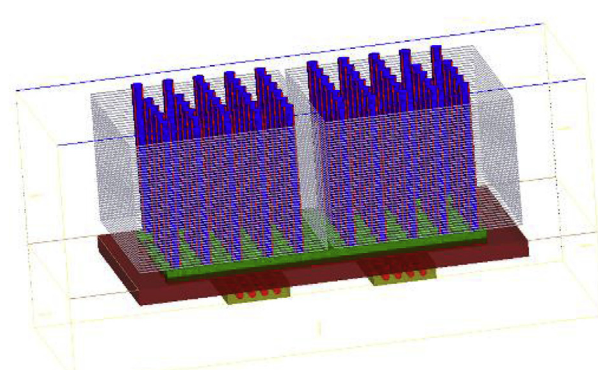

Fig. 2. Simulation model of heat pipe radiator cooling IGBT modules.