

Advances in Two-Phase Cooling for Next Power Electronics Converters

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ABSTRACT This article deals with a comprehensive analysis and performance evaluation of a fully integrated two-phase cooling system for power converters. A suitable test bed has been properly manufactured to perform the experimental campaign for the evaluation of the benefits and to deploy a dedicated management procedure of the two-phase cooling. The system is tested under real operating conditions, in which the system is employed for cooling a 1200-V 100-A insulated-gate bipolar transistor (IGBT) power module of an inverter controlling a permanent magnet synchronous machine. The experimental results show the inverter temperature behavior in start-up for different flow rates of coolant and different temperatures of the fluid on the secondary system. In the steady-state operation, using lower coolant flow rates in the primary circuit achieved equal or even better cooling for the IGBT module compared with higher flow rates. With respect to traditional cooling approaches, the proposed arrangement allows a greater extraction of the heat at a very low flow rate of the cooling fluid, even with standard industrial grade heat sinks, which motivates the use of this cooling technology for the next generation of power electronics converters.

INDEX TERMS Cooling, electrical drives, power modules, two-phase cooling (TPC).

I. INTRODUCTION

The current trend of vehicle manufacturers, in accordance with the European directives for the control of greenhouse gas emissions, increasingly focuses on the production of vehicles equipped with hybrid or fully electric traction instead of the traditional internal combustion engines [1]. As a result, the transportation and the electric power generation sectors are going to be revolutionized in the years to come, implying in inevitable changes in the automotive and electric drives for propulsion and generation markets. The technologies used so far for cooling electric drives usually explore the natural or forced convection of air or the recirculation of a coolant, which usually consists of a solution of water and ethylene glycol, inside a closed circuit that releases heat through a heat exchanger. Although these cooling systems are well characterized and easy to implement, they do not have

sufficient performance to cool the power modules of future electric drives, which are expected to require much higher heat exchange than those of nowadays. Then, it is expected that a different topology of cooling electric drives emerges as a solution. The two-phase cooling (TPC) systems, which, theoretically, have superior performance compared with traditional cooling systems, are strong candidates to this purpose.

From a practical point of view, the quantity of interest when speaking of heat transfers is the amount of heat dissipated in the unit of time $\dot{Q} [W] = dQ/dt$. The study of this quantity is important as it gives the idea of how the temperature of the surface changes over time. In general, the cooling of an electronic component can be achieved by exploiting different heat transfer methods: conduction, convection, and radiation. These modes can also occur simultaneously, even if usually one is dominant over the others. For example, in natural

convection-based cooling systems, thermal radiation can play a key role; on the contrary, in systems that exploit the forced convection of fluids, its contribution is usually negligible.

A TPC system uses the latent heat of vaporization that any liquid absorbs during its evaporation to remove the heat from a hot surface. Evaporation occurs when the surface temperature reaches and exceeds the saturation temperature of the liquid at certain saturation pressure, and it is typically manifested by the formation of vapor bubbles at the surface–liquid interface. Since for most liquids the latent heat of vaporization is about two orders of magnitude greater than the sensible heat, TPC systems present potential for high heat absorption per unit volume of fluid. Furthermore, the convective heat transfer coefficients reached in the evaporators of TPC systems can be one order of magnitude greater than those of the respective single-phase systems [2], causing the thermal resistance between the evaporator and the refrigerant to be lower and facilitating the heat exchange.

A further advantage of TPC systems is that they are able to strongly reduce the temperature oscillations on the surface to be cooled [2], [3], [4]. Indeed, if the pressurization of the system is kept constant, the evaporation of the coolant occurs isothermally. Nevertheless, the boiling temperature increases as the pressurization increases, and therefore, in two-phase systems, it is possible to control the evaporation temperature by controlling the pressurization of the circuit. Besides that, thanks to its greater effectiveness, it is possible to use significantly lower flow rates of the coolant to manage the same thermal power dissipation when compared to liquid-cooled systems [5]. This gives the possibility to reduce the size of the system and, consequently, reduce weight, cost, and overall dimensions while maintaining performance unchanged.

Passive TPC systems called thermosyphons do not use any active component, such as pumps or compressors, capable of artificially pressurizing the circuit [6], [7], [8], [9], [10], [11], [12]. Inside the thermosyphon, the devices are submerged into the dielectric liquid. The heat produced by the devices produces vapor bubbles that are driven into the upper region of the container, where the vapor condenses and drips back into the liquid pool [3]. In the passive *two-phase thermosyphon* proposed in [12], the authors present a numerical simulation based on a mathematical model valid for the natural convection regime and then validate the results through experimental tests. The numerical and experimental approach confirmed that the system can dissipate a thermal power of about 1500 W while maintaining the average surface temperature of the evaporator below 70 °C. In [7], a passive TPC for automotive power electronics is proposed. In this case, the tests were carried out using a volume of 250 cm³ of two different types of refrigerants: 330 g of HFC-245fa and 280 g of HFO-1234yf. With 250 cm³ of HFC-245fa, the system is able to dissipate 3.5 kW of heat under steady-state conditions without drying out. In addition, the results indicated that the system is capable of dissipating even greater heat loads. For the entire range of thermal powers, the authors calculated the total thermal resistance between the heaters and both the tested refrigerants,

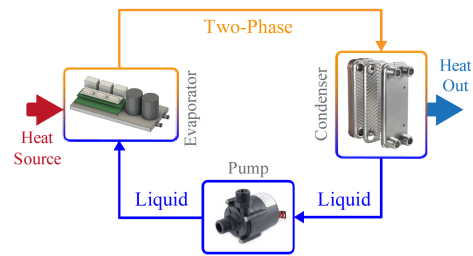


FIGURE 1. Basic representation of a PTCP system.

demonstrating that it decreases as the heat flow increases. This fact is not surprising if it is considered that as thermal power increases, the quantity of liquid that passes into the vapor phase increases, and therefore, the convective coefficient increases.

In [2], a vapor compression two-phase loop (VCTPL) built with conventional automotive air conditioning components (such as condenser, expansion valve, compressor, and vapor and liquid lines) is presented. In general, VCTPL systems are particularly interesting from a technical point of view because they are the only ones capable of bringing the refrigerant temperature below the room temperature. This feature can be particularly useful in cooling lithium-ion battery packs, for example, which should be kept at a maximum temperature of 40 °C. In extremely hot environments, therefore, these are the only systems capable of satisfying this specification.

There are also the pumped two-phase cooling (PTPC) systems [4], [13], [14], [15], [16], in which the pressurization of the circuit is ensured by a centrifugal or gear pump capable of compressing only the liquid phase, as illustrated in Fig. 1. A comprehensive review of recent developments in PTPC systems can be seen in [17], and the state of the art on PTPC systems technologies can be checked out in [18]. In [4], the PTPC system is used for cooling an insulated-gate bipolar transistor (IGBT) electrical drive system based on 1200-V 450-A power electronic modules. The system is also tested with air and water. The use of the two-phase fluid allowed the use of a smaller quantity of liquid (one-sixth the mass flow), a smaller pump for low-flow operation, and smaller tubing diameters, when compared to an equivalent water-cooling system designed for use within the same type of cabinet and to dissipate the same power module heat loads.

Overall, one of the most significant advantages of PTPC systems is the reduction of the required refrigerant flow rate for cooling and the reduced temperature fluctuations on the cooling surface. For instance, for dissipating 1 kW of thermal power with a water-cooled single-phase system, a flow rate of around 2.9 L/min is necessary, while with a PTPC system, a flow rate of only 0.35 L/min is sufficient [16].

Although encouraging results on the performance of TPC systems are found in the literature, still not enough has been done yet. In fact, most of the tests that have been done so far for cooling electrical drives tend only to simulate the power electronics usually through resistance banks and

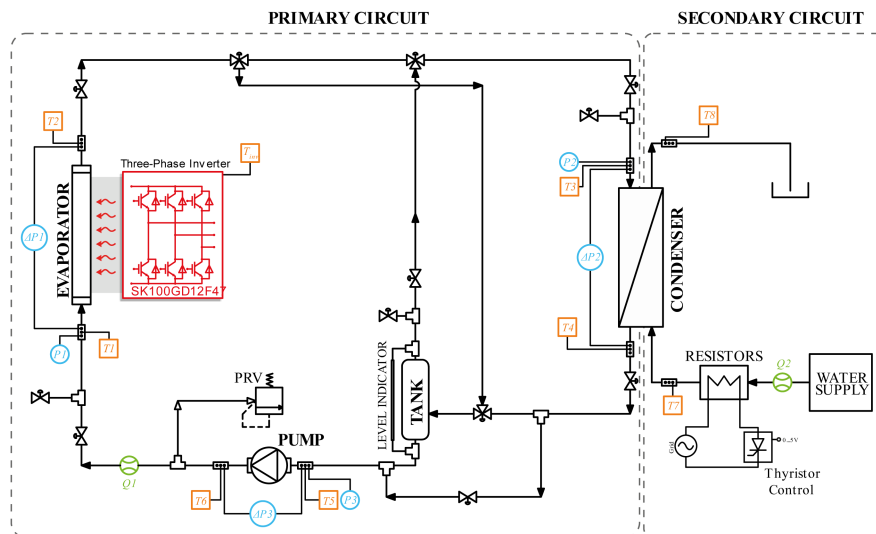


FIGURE 2. Schematic for the proposed PTPC system.

do not take into consideration whatsoever the possibility of cooling also the electrical machine. In order to characterize the performance of these systems in a more complete way and to make them feasible from an industrial point of view, it appears necessary to evaluate their performance in a real case scenario and under real operating conditions. According to this, the aim of this experimental work is to characterize the performance of a PTPC prototype for cooling a 1200-V 100-A IGBT power module of the inverter controlling a permanent magnet synchronous machine (PMSM).

II. DESIGNED PTPC SYSTEM

The schematic of the proposed PTPC system is presented in Fig. 2. First, it can be seen that there are the evaporator, where the heat power source is coupled, the low-flow rate centrifugal pump, and the water-cooled condenser. The system can be divided into the primary and secondary circuits (of the condenser). In the primary circuit, the coolant performs the TPC of the heat power source attached to the evaporator. The secondary circuit hosts the liquid that extracts the heat from the condenser. As can be seen in the schematic, the secondary circuit has a source of heat as well, which could be used to increase the temperature of the secondary circuit emulating different ambient temperatures. In this work, this heat source is formed by resistors connected to suitable heat exchangers and fed by a controlled thyristor rectifier, which allows to control the temperature of the liquid (water) that will flow in the secondary circuit. The temperature regulation is done by connecting the resistors to a thyristor control. This will be useful to observe the impacts in the primary circuit due to a change in temperature in the secondary circuit. The selected water-cooled condenser consists of 20 plates having a cross section of 214.5×80.7 mm and 1.98-mm thickness each. Auxiliary components, such as quick-disconnect fittings, valves, pressure relief valve, tank, and sensors, are

TABLE 1. Measured Quantities of the Proposed PTPC System

Pressures	
Evaporator inlet pressure	P_1
Evaporator differential pressure	ΔP_1
Condenser inlet pressure	P_2
Condenser differential pressure	ΔP_2
Pump suction pressure	P_3
Pump differential pressure	ΔP_3
Temperatures	
Evaporator input, output	T_1, T_2
Condenser input, output (coolant)	T_3, T_4
Pump suction/delivery	T_5, T_6
Condenser input, output (water)	T_7, T_8
Internal Inverter Temperature	T_{inv}
Volumetric Flow Rate	
Coolant volume flow	Q_1
Water volume flow	Q_2

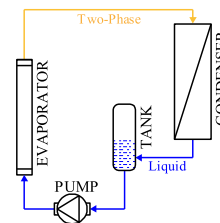


FIGURE 3. Operating layout without vapor separation.

also present in the system. The measured quantities are listed in Table 1.

The hydraulic system is designed to be able to allow different configurations and connections among the components. First, the valves can be arranged, so the operating layout of Fig. 3 is obtained. In this way, the cooled liquid on the output of the condenser is sent by the pump to the evaporator, where the liquid absorbs the heat produced by the power heat source, partially evaporating as expected and generating a two-phase mixture with a composition that varies according to the operating point. The mixture that leaves the evaporator

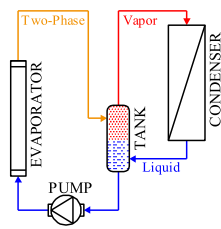


FIGURE 4. Operating layout with vapor separation.

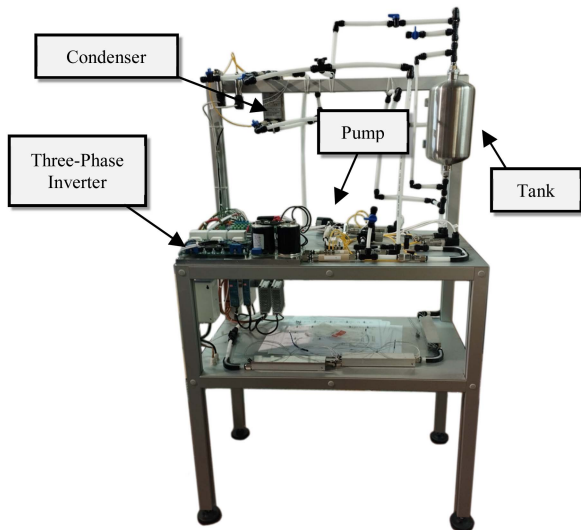


FIGURE 5. PTPC system prototype.

is then sent back toward the condenser to start a new cycle. The system can also be configured, so the operating layout of Fig. 4 is obtained. This configuration allows the separation between liquid and vapor inside the tank in order to send only vapor to the condenser. This double mode allows the characterization of the PTPC system in two different operating modes, if desired.

The final PTPC prototype is shown in Fig. 5. The system was positioned on a bench of steel profiles with a 50 × 50 mm section. Each of the bench tops has a surface area of 500 × 1000 mm. The total height, including the crossbar, is 1600 mm. The test bed is also designed to open the coolant circuit without losing the cooling fluid.

As mentioned earlier, to monitor the temperature and the pressure of the coolant in various sections of the circuit, negative temperature coefficient (NTC) sensors and flow rate transducers were positioned throughout the components. The sensors were installed in custom-designed sensor holders, as illustrated in Fig. 6.

The choice of the coolant strongly conditioned the materials used for the components of the hydraulic circuit. The properties of the coolant used can be seen in Table 2.

III. ELECTRICAL SYSTEM

The designed PTPC system will be used to cool down a three-phase-IGBT-based inverter with a field-oriented control

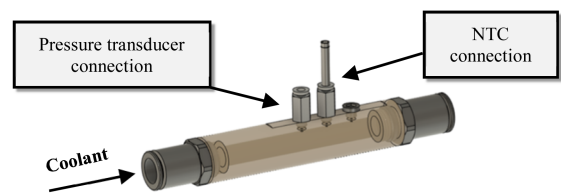


FIGURE 6. Custom-designed sensor holder.

TABLE 2. Properties of the Coolant Used

Boiling point at 1 atm	14.9 °C
Critical temperature	154.01 °C
Critical pressure	36.51 bar
Latent heat at boiling point	196,05 kJ/kg
Specific heat of the liquid at 25 °C	1,32 kJ/kgK
Global warming potential (GWP)	1030

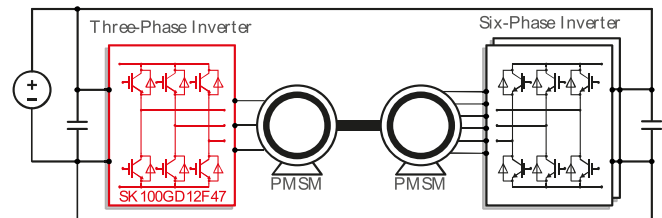


FIGURE 7. Schematic of the electrical system under test.

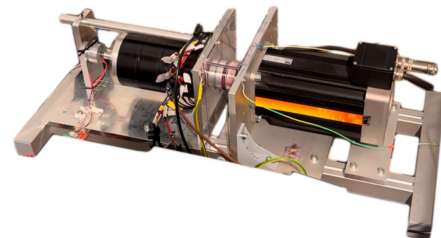


FIGURE 8. Electrical drive test bed. Left: the six-phase PMSM. Right: the three-phase PMSM.

connected to a PMSM having a rated current of 30 A, four pole pairs, a rated speed of 5000 r/min, and a rated power of 20 kW.

This machine is then coupled to the shaft of a six-phase PMSM controlled by a dedicated six-phase inverter and its control system, as shown in Fig. 7. In this manner, the PTPC system can be evaluated under practical circumstances. Both the three- and six-phase inverters are connected to the same dc power supply, being necessary for the latter only to supply the losses of the system. The test bed of the machines can be seen in Fig. 8.

The three-phase inverter is shown in Fig. 9, and it uses the IGBT power module SK100GD12F47 from Semikron Danfoss, rated 1200 V 100 A and coupled to a traditional industrial liquid-cooled heat sink (400 × 180 × 20 mm), as illustrated in detail in Fig. 10. The IGBT module junction

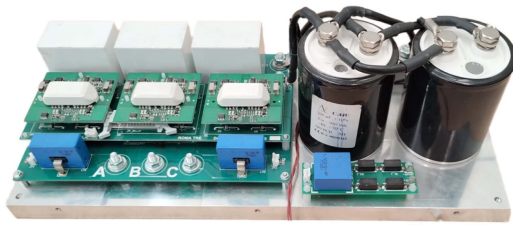


FIGURE 9. Three-phase IGBT inverter prototype.

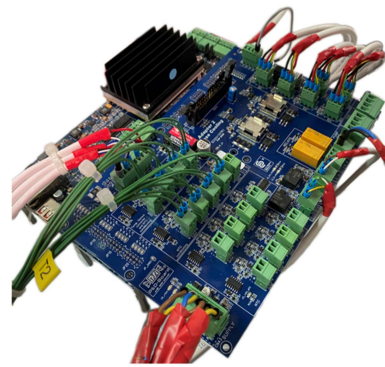


FIGURE 12. PED-Board controller and the dedicated adapter board developed.

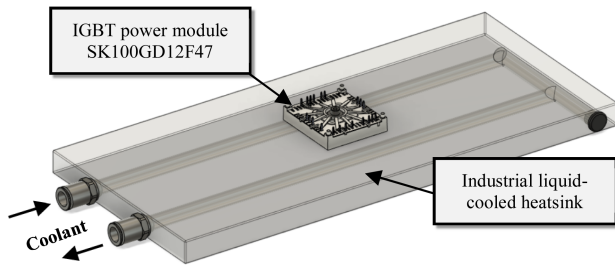


FIGURE 10. Design sketch of the industrial grade heat sink.

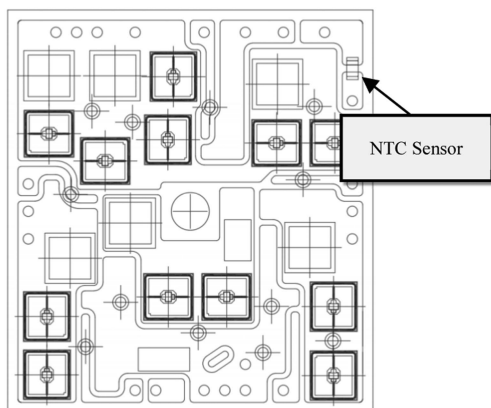


FIGURE 11. Position of the NTC sensor within the Semitop4 package of the SK100GD12F47 module.

temperature, which is available through an NTC sensor, is the variable of interest. The position of the inverter-embedded NTC sensor installed inside the SEMITOP4 package is reported in Fig. 11.

The Voltech PM3000A power meter is used to measure the dc-link power and the ac output power of the IGBT module, having, in this way, the losses that are managed by the PTPC system (i.e., the amount of heat to be extracted).

A. CONTROL SYSTEM

The complete control structure was implemented in the PED-Board industrial grade control platform that uses LabVIEW development environment. A suitable adapter board was designed and manufactured to properly acquire and control the variables of interest from the PTPC system and the electrical system described. This means that the control system is able to act not only on the PTPC system by regulating the pump

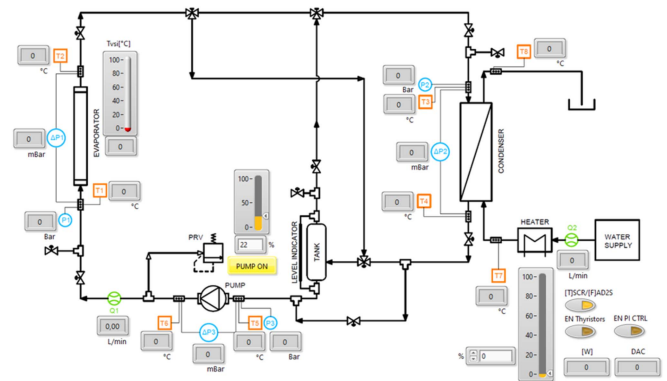


FIGURE 13. LabVIEW-based user interface for the two-phase system monitoring and control.

flow for instance, but it is also able to regulate the speed of the three-phase PMSM. The assembled PED-Board and the dedicated adapter board can be seen in Fig. 12.

To properly monitor and control the cooling system and collect data, a user interface was developed in LabVIEW, as shown in Fig. 13. All the variables present in Table 2 are presented next to its corresponding value.

IV. EXPERIMENTAL RESULTS

For all the experimental results, the measured losses on the three-phase inverter are 450 W (amount of heat to be extracted), and the measurement was accomplished by a Voltech PM3000A power meter. For all the following test results, the steady-state regime is considered achieved when the variation of temperature is smaller than 1 °C during a period of time of at least 30 s. The first experimental test consisted of turning ON the system and letting it go to the steady state with different flow rates ($Q1$) of the coolant with the temperature of the water on the secondary of the condenser at 20 °C and flow rate $Q2$ of 3.2 L/min. The junction temperature read from the IGBT module is called *inverter temperature* hereafter. The inverter temperature behavior for all the cases is presented in Fig. 14. The temperature difference (ΔT_{21}) between the output ($T2$) and the input ($T1$) of the heat sink is shown in Fig. 15 for all the cases.

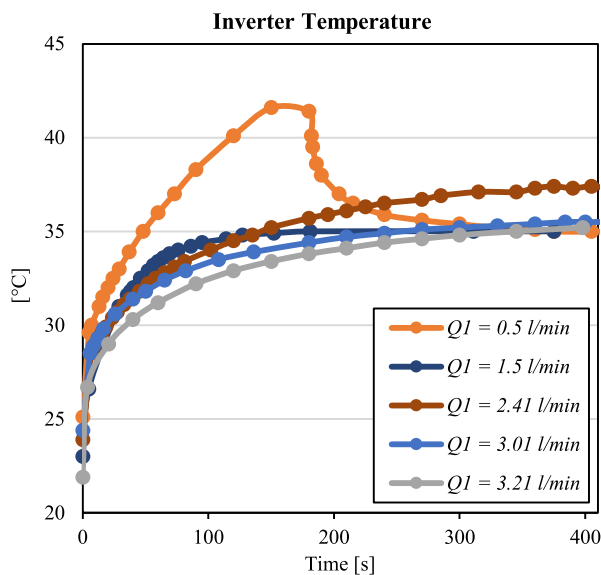


FIGURE 14. Inverter temperature behavior for different flow rates of the coolant ($Q1$) during turn ON to almost steady state with the temperature of the water on the secondary of the condenser at 20 °C.

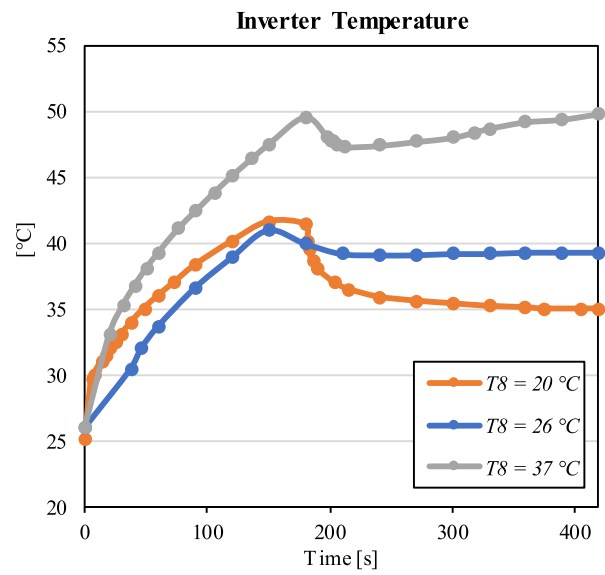


FIGURE 16. Inverter temperature behavior for the same flow rate of 0.5 L/min of the coolant ($Q1$) during turn ON to steady state with the different temperatures of the water on the secondary of the condenser.

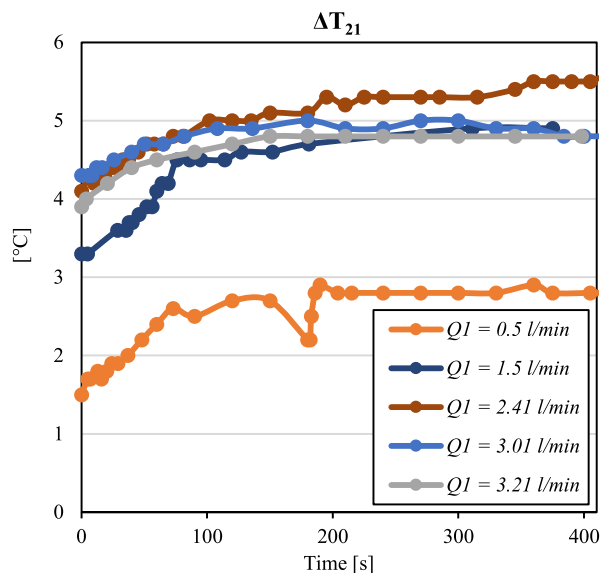


FIGURE 15. Difference of temperature behavior of the input and output of the heat sink for different flow rates of the coolant ($Q1$) during turn ON to steady state with the temperature of the water on the secondary of the condenser at 20 °C.

For $Q1 = 0.5$ L/min, the coolant barely flows in the circuit, resulting in an increase in the inverter temperature until the coolant enters the vapor phase, which makes the temperature decrease abruptly (near 180 s). ΔT_{21} is small, since the sensors of temperature measure the temperature of the coolant in the liquid phase. That is, the heat exchange is done in most part by the latent heat of vaporization. The flow rate of $Q1 = 1.5$ L/min presented itself as an adequate value for the system, since the heat exchange happens with the two-phase temperature, and the steady-state temperature is one of the lowest.

For $Q1 = 2.41$ L/min, the steady-state inverter temperature increases since the system is exchanging heat mostly through the liquid phase of the coolant. For this value of flow rate of the coolant, the PTPC system behaves as a liquid-cooled system, which can be seen by the decrease in the steady-state inverter temperature as $Q1$ increases to 3.01 and 3.21 L/min.

The following test is to demonstrate the influence of the temperature of the water of the secondary circuit on the primary circuit. To regulate the temperature of the secondary circuit, the thyristor control of the resistors is activated and regulated together with the flow rate $Q2$ to achieve different operating temperatures.

Fig. 16 presents the inverter temperature during the turn ON up to the steady state for the flow rate of 0.5 L/min of the coolant ($Q1$) for different temperatures $T8$ on the secondary circuit. It is clear that the higher the temperature on the secondary circuit, the higher the temperature on the primary circuit. Besides the increase in temperature, the pressurization of the primary also changes accordingly, going, respectively, from 1.2 bar to 1.6 bar and 2.1 bar for $T8 = 20$ °C, 26 °C, and 37 °C.

The next test is done to observe the effect in the inverter temperature as a consequence of the change in the coolant flow rate $Q1$. Starting from a steady-state operating point, the flow rate is reduced in steps, as presented in Fig. 17. The temperature on the secondary circuit $T8$ is 20 °C. A reduction of the coolant flow rate from 3 to 2.6 L/min causes an increase in temperature, since the system is operating mostly in the liquid phase, as also observed in the first test presented in Fig. 14.

Nevertheless, when reducing the flow rate from 2.6 to 2.1 L/min, the inverter temperature drastically reduces, clearly indicating the two-phase operation.

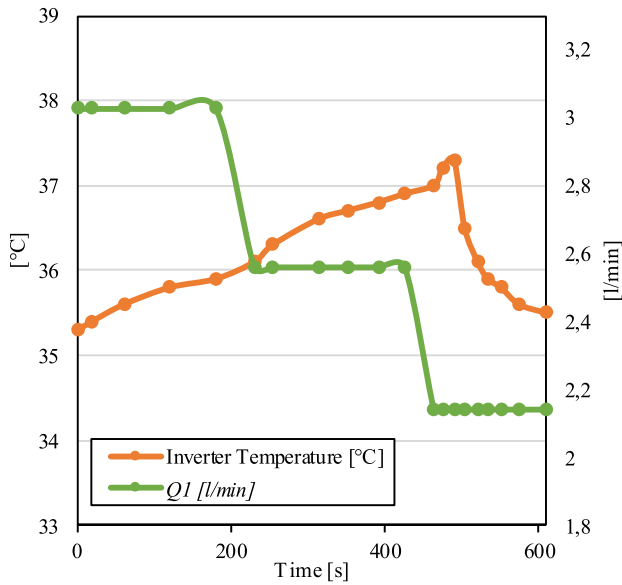


FIGURE 17. Inverter temperature behavior in response to different coolant flow rates with the temperature of the water on the secondary of the condenser at 20 °C.

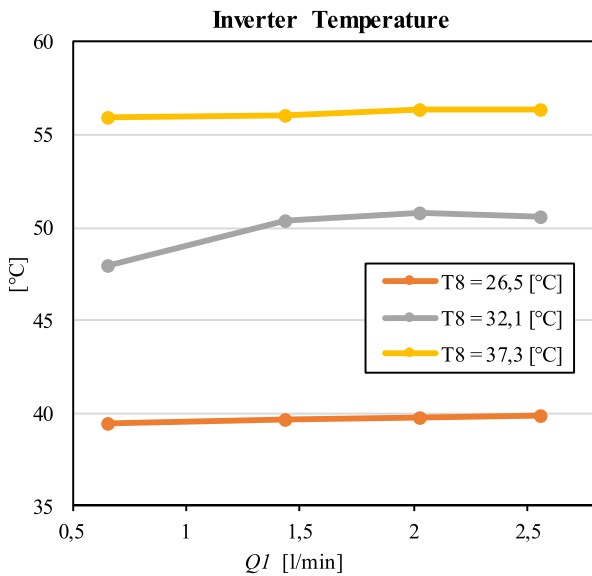


FIGURE 18. Inverter temperature in the steady state in response to different coolant flow rates and different temperatures of the water T_8 on the secondary of the condenser.

Following the idea of the previous test, the inverter temperature in the steady state for the same operating point is observed for different temperatures T_8 and different coolant flow rates Q_I . The results are presented in Fig. 18. The main conclusion of this test is that similar inverter temperatures can be achieved for low and high values of the coolant flow rate. That means, for small values of coolant flow rates, the system operates in the two-phase region; on the other hand, for high flow rates, the system operates mostly with the liquid

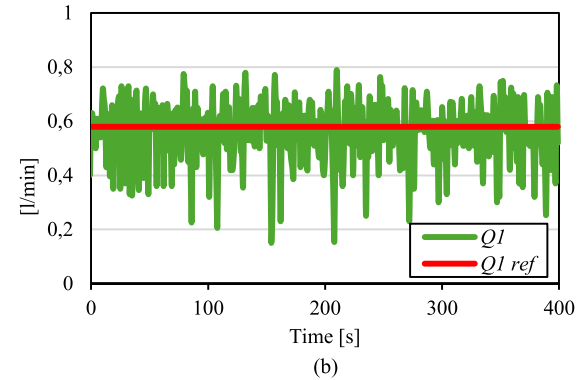
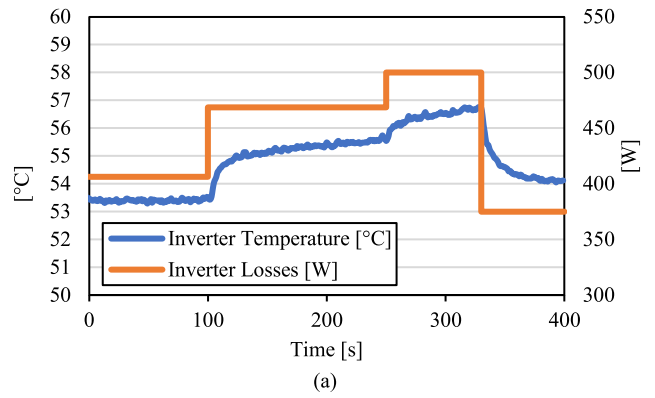


FIGURE 19. Inverter temperature and Q_I measurement during inverter loss steps (amount of heat to be extracted) with the temperature of the water on the secondary of the condenser at 30 °C.

phase of the coolant, being necessary to increase the flow rate to achieve low inverter temperature, such as a traditional liquid-cooled system. As a result, it illustrates one of the main advantages of working in the two-phase region: low inverter temperatures with low coolant flow rates.

In Fig. 19(a), inverter loss steps (amount of heat to be extracted) were given for a fixed value of Q_I equal to 06 L/min [in Fig. 19(b)], so the inverter temperature could be observed. This represents the system at an even more realistic operation. It is important to note that since the TPC is happening, the measurement of Q_I has oscillations around the chosen reference (Q_I ref). This is due to the formation of bubbles that interfere in the flow rate measurement system. Small temperature changes were observed for significant load steps, showing again the effectiveness of the proposed PTPC system.

Finally, in Fig. 20, the system was tested in a long time period for different inverter losses and different flow rates Q_I . Fig. 20(a) presents the inverter temperature and the inverter loss steps, while Fig. 20(b) presents the secondary temperature T_8 and the fixed flow rates Q_I . It is important to note that T_8 reaches circa 50 °C, which can be considered an extreme case scenario for the system. Nevertheless, the inverter temperature remained in an acceptable operating range even in extreme operating points.

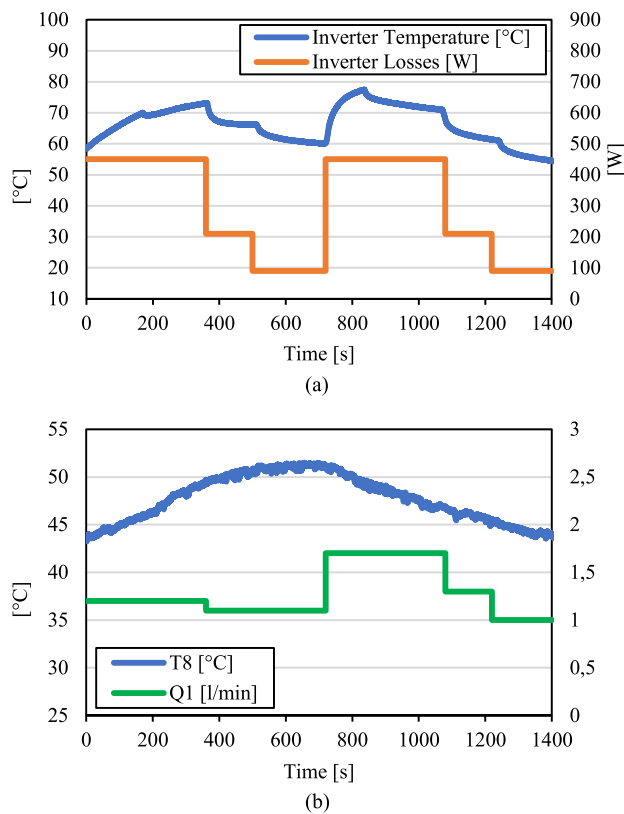


FIGURE 20. Inverter temperature and secondary temperature (T_8) in an extended test for different steps on the inverter losses and flow rates Q_1 .

V. CONCLUSION

A PTPC system for cooling a 1200-V 100-A IGBT power module of an inverter controlling a PMSM is proposed and tested extensively. The hydraulic and electrical systems are presented in detail. The experimental results showed that the proposed PTPC system can be used with a traditional liquid-cooled heat sink and still obtain great results in cooling the IGBT module.

It was possible to observe that for very low flow rates of the coolant, the vapor phase dominates the heat exchange, while the increase in the flow rate shows that the system goes toward two-phase and after that to the liquid phase. Low flow rates of the coolant on the primary circuit (during two-phase operation) obtained similar or even lower temperatures of operation for the IGBT module when compared with high flow rates in which the system operated mainly with the liquid phase. This behavior demonstrates one of the main advantages to working in two-phase, that is, low operating temperatures with low coolant flow rates.

The temperature of the water on the secondary circuit of the system and consequently the temperature of the condenser also demonstrated great influence in the operating point on the primary circuit side. The higher the temperature on the secondary side, the higher the steady-state temperature of the inverter on the primary side, also directly impacting on the pressurization of the primary circuit.

From the load steps, it could be observed that even for significant changes on the amount of heat to be extracted, the inverter temperature had small changes in its operating value, showing again one great advantage of the proposed system.

Thanks to the phase change of the coolant, the operating temperature of the equipment under test, in this case the IGBT module, achieves low temperatures using low flow rates of the coolant, which does not happen when using a traditional water-based cooling system. The PTPC works with very low flow rate to extract the same amount of heat. With respect to water cooling, the flow rates are less than one-tenth thanks to the fluid evaporation. Pipe diameter and pumping power are lower than common water-based cooling apparatus, whereas both water cooling and PTPC need a reservoir tank to store the fluids. This results in a smaller size of the overall PTPC system with respect to common water cooling.

One of the main drawbacks of using this type of technology is the challenge to design a control system, which would be responsible for controlling the inverter temperature to its lowest value possible in any possible situation. Due to the high nonlinearity of the cooling system, it is quite challenging to design a control system that considers only one control variable, since this type of system could be controlled by changing, for instance, the flow rate of the primary circuit, the flow rate of the secondary circuit, or the pressurization. Besides the fact that a change in one of these variables can imply a change in another, as seen when the temperature of the water on the secondary circuit directly impacts the pressurization of the primary circuit (besides changing the inverter temperature). The focus of this article was to present the main characteristics and relationships of the system's variables, so a more in-depth comparison of the performance of the system using water cooling and using the proposed two-phase system will be made in the future for larger systems along with the proposal of a control system.

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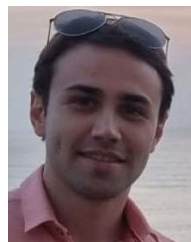
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