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Reliability analysis of liquid cooling systems' mechanical components for 3 MVA power converter

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Nomenclature

λ – failure rate, times/year; μ – repair rate, times/year; *A* - availability; *UA* – unavailability; *MTTR* – Mean Time To Repair; *MDT* – Mean Down Time; *MTBF* – Mean Time Before Failure; *R* – reliability; *t* – time; *k* – number of failed components; *m* –number of operate components; *n* – total number of components.
Subscripts: *i*- component, *s* – subsystem/system.

1. Introduction

Several countries have set reduction targets for carbon dioxide emissions. To reach the goal the annual drop of emissions should be several percents over coming four or five decades. Better fuel efficiency in vehicles along with better hybrid technology, energy reuse systems, alternative energy resourses, such as wind and solar plants, will reduce emisions and therefore these technologies are evolving rapidly. The wind turbine price is only haft of the total wind turbine installation price, and therefore turbine power is expected to increase further [1]. Generators, mechanical constructions and electrical converters become more powerful, such as direct-drive train, high power and voltage permanent magnets based generators, medium voltage converters and ect. Rapid growth of power will affect the mechanical structure, cooling capacity and also the cooling technology. If traditional water cooling devices are used with high power converters the mechanical size of cooling devices will grow heavily. Therefore other than traditional methods for cooling should be researched for future installations. For example, two-phase cooling will provide promising potentional for future solutions. New kinds of cooling solutions with reduced size, higher reliability and improved operation life are developed by producers and researchers to cool the power electronic modules in industrial and commercial applications [2-6].

High powers of medium voltage converters assosiate high heat losses, which should be removed by an efficient cooling system. Traditional air cooling system based on heat sink is not applicable in the case of medium voltage converters as it can not remove the generated heat losses with small dimensions [7]. The air based cooling systems dissipate the heat flux up to 500 kW/m^2 [8]. In high power application, only closed single- and two-phase cooling systems are applicable, but these systems complicate the converter design and require auxiliary equiments to provide their reliable operation. The reliability issue becomes essentional and therefore material selection, coolant treatment system should be considered during the design stage [9]. The designed cooling system should have an ability to keep the temperature of Insulated Gate Bipolar Transistors (IGBT) and diode chips in temperature lower than 125°C at all operation conditions, since this improves long term reliability [8].

The main frame of reference of this study consists in developments of the best cooling solution for a 3 MVA medium voltage three-level three-phase NPC converter from thermal, mechanical and reliability points of view. The designed cooling solution should have simple mechanical structure, available constituted components, fast and easy serviceability for all technicients, including people without deep technical knowledge. Cooling systems based on one-phase liquid cold plates, heat pipes & water pool and two-phase cold plates are presented and investigated in this paper. The purpose is to develop the cooling solutions that should be capable of providing the required cooling and treatment of the main working liquid in conditions of ambient temperature up to +35°C. Each of the presented systems is discussed and compared by thermal and reliability analysis.

The thermal behaviour of the studied conveter power module with peak power is simulated by 3D FEM commercial software Comsol. The aim of these numerical simulations are to predict the thermal behavior of power module with the integrated cooling system and compare three different cooling solutions - single-phase cold plate, heat pipes inserted in direct bond copper & water pool and two-phase cold plate. The reliability analysis of the cooling systems is performed only on the mechanical equipments itself and it does not take into account the reliability of the electrical power and control system.

2. Description of a studied converter

2.1. A studied converter

The studied object is a 3 MVA medium voltage three-level three-phase Neutral Point Clamped (NPC) converter. Onshore and offshore wind farms should offer possible application fields of such converter. The rated current and voltage are 650 A and 3000 V. The converter consists of a DC-AC rectifier, a DC - link and a DC-AC NPC inverter. The NPC inverter consists of 12 Insulated Gate Bipolar Transistors and 6 Diodes modules. The rectifier includes 6 Diode modules and DC link – 4 film capacitors with rated voltage of 2400 V.

In the designed converter the main heat sources are associated with the inverter and rectifier. The fast IGBT and diode power switches generate a lot of heat. The cooling system of power converter should provide adequate cooling in mode of continuous power and peak power. Table 1 lists the heat sources in the studied converter in conditions of peak power and maximum frequency 1 kHz.

The heat flux distribution of the converter power module is non-uniform with hot-spots under the power modules. Hot-spots are several times greater than average base heat flux. For example, the average base heat flux of inverter IGBT is 400 kW/m^2, but the local heat flux exceeds 1500 kW/m^2 in position of IGBT and diode chips (Fig. 1).

Table 1

Heat losses in the studied inverter

Heat Source	
Inverter Module - IGBT - Diode	 2450 W 1430 W
Rectifier Module - Diode	 700 W
DC Link - Capacitor	 270 W

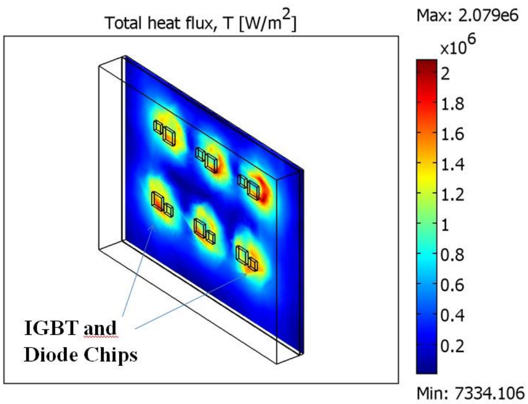


Fig. 1 Heat fluxes within the simulated IGBT module

2.2. Description of simulated power model

From thermal point of view the critical converter component is the inverter IGBT module (Table 1), so only it was chosen for simulation with the integrated cooling systems to assess the cooling solutions' effects. The heat losses within the simulated IGBT inverter module is separated between IGBT (80%) and Diode (20%) chips. Fig. 2 presents the simulated model of the inverter IGBT module.

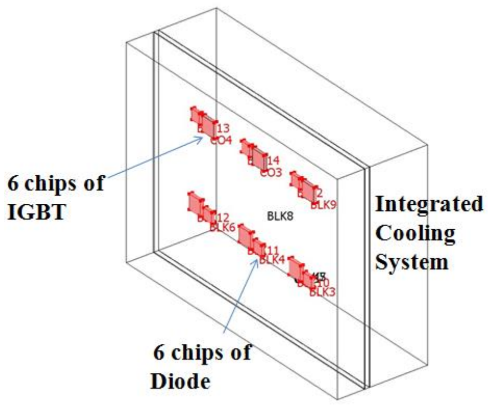


Fig. 2 Simulated IGBT model with integrated cooling system

The power module contains a total of 12 chips, with 6 of them being IGBT chips and 6 being diode chips. Diode and IGBT chips are soldered on the substrate tile and to a direct bond copper (DBC) substrate. The cooling module is directly mounted on the substrate through layer of thermal grease to avoid air spots and therefore reduce the thermal contact resistance [5, 7]. This design does not include a copper base plate between the cooling element and the power module, as it is heavy and expensive element [10]. By this design the additional thermal resistance of the copper base plate and solder layer (0.0006 K/W) is avoided, that allows reducing additional thermal stresses and therefore achieving higher reliability [7, 10]. All chips are immerged in the silicone die, so the main cooling heat transfer mechanism is conduction through substrate, base plate and grease to the integrated cooling system. Table 2 provides the geometrical data of the simulated IGBT module.

Table 2

Geometrical data of the power module studied [5]

Parameter	Quantity
Dimensions of IGBT Chip	10 mm × 10 mm × 2mm
Dimensions of Diode Chip	7 mm × 7 mm × 2mm
Thickness of Solder	1 mm
Thickness of DBS	3 mm
Thickness of Thermal Grease	0.04 mm
Dimensions of Power Module	140 mm × 190 mm × 45mm

The thermal resistance of each interface layer between the chip die and the cooling module is defined by the layer material conductivity and its thickness. The power module represents a device with many poor thermal conductivity interfaces. The thermal conductivity of the materials constituting the power module parts are listed in Table 3 and all of them are included in the thermal model to examine carefully the abilities of the designed cooling systems.

Table 3

Thermal conductivities of materials used in power module [5, 11]

Model Component	Thermal Conductivity, W/Km
Chip	150
Air at 80˚C	0.03
Silicone Die	150
DBC Substrate	170
Thermal Grease	1
Heat Pipe	100000

2.3. Reliability date of the cooling system components

Reliability considerations play an important part in design and comparison of the converter cooling systems. The proper operated cooling system ensures long operation time of the power module critical components. The presented cooling systems consist of several repairable components with constant failure and repair rates, so reliability evaluations include the repair effects (mean down time). The reliability analyses are executed using the main reliability metrics, such as *MTBF*, *MDT*, *MTTF*, failure rate, reliability and availability. Two types of repairable system are used - series system with n components and parallel m/n system (identical components – active redundancy) [12]. The following equations allow calculating the total system unavailability, repair rate and failure rate for series system:

$$UA_s(\infty) \approx \sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}; \tag{1}$$

$$\mu_s(\infty) \approx \frac{\sum_{i=1}^{n} \lambda_i}{\sum_{i=1}^{n} \frac{\lambda_i}{\mu_i}}; \tag{2}$$

$$\lambda_s(\infty) \approx \sum_{i=1}^{n} \lambda_i . \tag{3}$$

The total system unavailability, repair rate and failure rate for parallel m/n system with identical components are calculated by the next equations [12]:

$$UA_s(\infty) \approx \sum_{k=1}^{m-1} C_n^k \left(\frac{\lambda_i}{\mu_i} \right)^{n-k}; \tag{4}$$

$$\mu_s(\infty) \approx \frac{(n-m+1)\mu_i\, C_n^{m-1}\, \mu_i^{m-1}\, \lambda_i^{n-m+1}}{\sum_{i=0}^{m-1} C_n^k\, \mu_i^k\, \lambda_i^{n-k}}; \tag{5}$$

$$\lambda_s(\infty) \approx \frac{m\lambda_i\, C_n^m\, \mu_i^m\, \lambda_i^{n-m}}{\sum_{k=m}^{n} C_n^k\, \mu_i^k\, \lambda_i^{n-k}}. \tag{6}$$

The total system *MTTR*, *MDT* and *MTBF* for series and parallel m/n system are calculated by the following equations [12]:

$$MTTR_s = \frac{1}{\lambda_s}; \tag{7}$$

$$MDT_s = \frac{1}{\mu_s}; \tag{8}$$

$$MTBF_s = MTTR_s + MDT_s . \tag{9}$$

The repairable system is characterized by two main reliability measures – reliability and availability, which can be defined by the next equations [12, 13]:

$$R(t) = e^{-\lambda t} \tag{10}$$

$$A_s = 1 - UA_s \tag{11}$$

The literature values of failure rates and mean down times of the cooling systems' components are collected in Table 4.

3. Design of liquid cooling system

Three different cooling solutions are studied and compared further. The simplified thermal models of the IGBT with the integrated cooling system are simulated with the commercial software Comsol. The reliability metrics of the cooling systems are calculated by Eqs. (1)-(11) by values presented in Table 4.

Table 4

Reliability parameters of the cooling system components [13-17]

Component	Failure Rate, per year	Mean Down Time, man-hours
Single Phase Cold Plate	5×10^{-2}	8
Two Phase Cold Plate	-	-
Heat Pipe at 60˚C	6×10^{-2}	0.5
Pump/Fan	8.64×10^{-2}	5.6
Refrigerant Pump	1.7×10^{-2}	5.6
Water Filter	4.32×10^{-1}	4
Water-Vapor Separator	2.1×10^{-2}	4
Refrigerated Tank	1×10^{-5}	24
Water Tank	3×10^{-4}	24
Heat Exchanger	8.64×10^{-3}	10

3.1. Cooling system based on cold plates

The single phase liquid cold plate is common compact cooling system for power modules with heat losses up 1500 kW/m^2 [13]. The conventional cold plate presents tubing device with liquid inside as a coolant. The modern cold plate contains many corrugated channels such a design allows providing a greater heat transfer area with the cooling medium [3].

The inverter IGBT module is cooled by single phase convection through a cold plate in the simulated model. The cold plate is pressed onto the power module through a layer of the thermal grease to remove the air resistance. The constant temperature of the cold plate (55°C) was defined as boundary condition. The commercially available cold plate was chosen for simulation purposes with dimensions 280 mm × 200 mm and thermal resistivity 0.003°C/W [18]. The mass flow rate and pressure losses through a cold plate are 0.128 kg/s and 0.5 bar correspondingly. Fig. 3 presents the temperature distribution in the cross-section of the simulated model. Hence, the single phase liquid cold plate and coolant with inlet temperature 45-50ºC coolant allows keeping temperature of IGBT and diode chip under 100ºC.

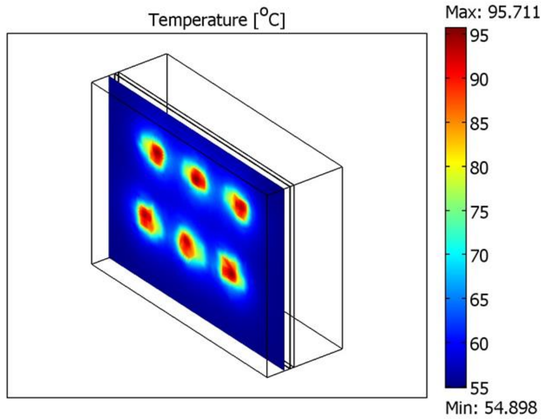


Fig. 3 Temperature distribution within the simulated power model

To assess the total cooling system of the medium voltage converter the auxiliary equipments were chosen. For cooling and treatment purposes of main liquid - the auxiliary elements are considered, such as water pump of the primary cooling loop, heat-exchanger, water tank, filter and fan/pump of the secondary cooling loop (Fig. 4). The corrosion issue and special treated system should be considered in water based cooling system to provide safe and reliable operation of the single-phase cold plate. The main coolant is cooled by ambient air/water with temperature up to 35°C.

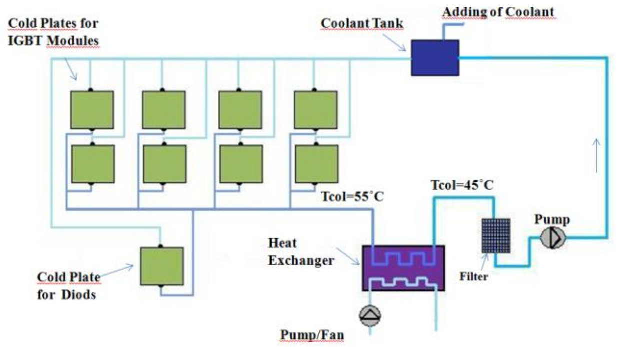


Fig. 4 Scheme of cooling system based on single-phase cold plates

The reliability of the presented cooling system is defined by the reliability measures of the components presented in Table 4. The system of the cold plates is defined as parallel m/n system, so Eq. (4)-(11) were adopted to calculate their total reliability. The auxiliary components, such as filter, pump, coolant tank and heat exchanger unit (pump/fan and heat exchanger) is considered as series connected with the cold plates' system. Table 5 lists the main reliability measures of the parallel-connected cold plates, the series-connected auxiliary components and total cooling system.

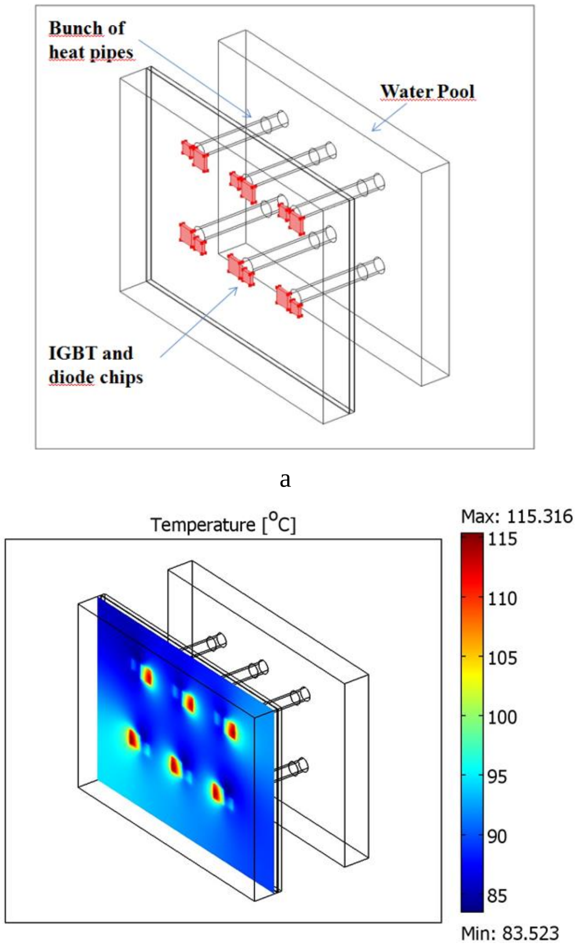
Table 5
Reliability parameters of cooling system based on cold plates

Parameter	System of heat pipes & water pools	Auxiliary Components	Total System
Failure Rate, per year	0.4	0.62	1.02
MTTF, years	2.5	1.6	0.97
MDT, man-hours	8	4.6	6
MTBF, years	2.5	1.60	0.98
Availability	≈ 0.9996	≈ 0.9997	≈ 0.9993
Unavailability	3.70×10^{-4}	3.32×10^{-4}	7.03×10^{-4}

The above table shows that the total cooling system based on cold plates requires service each year during 6 hours mainly because of filter cartridge change.

3.2. Cooling system based on heat pipes and liquid pool

The second cooling solution is using of thermal bridge (heat pipes) and water pool in order to spread the generated losses from a concentrated heat source. Heat pipe is a device with very high capability to transfer heat between two points with a minimal temperature difference. The operation of a heat pipe is based on a phase shift of passive circulating coolant along three sections of pipe: evaporator, adiabatic section and condenser [2]. The heat pipes are embedded in the water pool at one side and attached to the power module at another (Fig. 5). Thus, the thermally conductive heat pipes absorb the generated heat from the power modules and dissipate it on the other side to the water. The six bunches with 3 heat pipes per each were considered, as the heat capacity of a heat pipe with diameter 8 mm and length 100 mm is up to 130 W in conditions of 60-80°C temperature difference [19]. The computational model of IGBT module with attached heat pipes & water pool is created to describe the feasibility of this cooling solution.



b

Fig. 5 Simulated IGBT model with cooling system based on heat pipes & water pool (a) and temperature distribution within model (b)

As seen in Fig. 4 the heat dissipation system assures cooling of the power module chips up to 115°C. Hence, the heat pipes & water pool is possible solution for cooling of IGBT module. The auxiliary equipments of the studied cooling system include water pump of the primary cooling loop, heat-exchanger, fan/pump of the secondary cooling loop and filter (Fig. 6).

The reliability of the presented cooling system is defined by reliability measures of the components presented in Table 4. Table 6 lists the main reliability measures of the cooling system based on heat pipes & water pools. The systems of the heat pipes' bunches and water pools are defined as parallel m/n systems and Eqs. (4)-(11) were adopted to calculate their total reliability. The auxiliary components, such as filter, pump, coolant tank and heat exchanger unit (pump/fan and heat exchanger) are considered as series connected with the main system of heat pipes and water pools. Table 6 lists the main reliability measures of the heat pipes & water pools system, the series-connected auxiliary components and total cooling system.

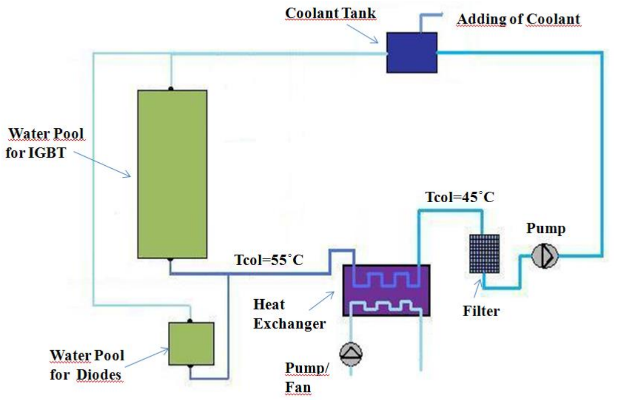


Fig. 6 Scheme of cooling system based on heat pipes and water pool

Table 6

Reliability parameters of cooling system based on heat pipes & water pool

Parameter	System of heat pipes & water pools	Auxiliary Components	Total System
Failure Rate, per year	17	0.62	17.9
MTTF, years	0.06	1.60	0.06
MDT, man-hours	0.13	4.6	0.3
MTBF, years	0.06	1.6	0.06
Availability	≈ 0.9997	≈ 0.9997	≈ 0.9994
Unavailability	2.60×10^{-4}	3.32×10^{-4}	5.92×10^{-4}

3.3. Cooling based on two-phase devices

The two-phase cooling systems are developed by several producers, such as EPFL in Lausanne, USDOE Oak Ridge National Laboratory, Parker Hannifin, Raytheon Company, Thermal Form & Function Inc., as this technology is capable to provide the cooling of the power modules with heat losses up to 9000 kW/m^2 [8, 20]. Two-phase cold plates are developed to cool down high - power electronics modules in order to reduce the size of the cooling system. The two-phase cooling system differs from the single-phase cooling system by lower mass flow rate, higher heat capacity and ability to cooling the power device in the conditions of high ambient temperatures (> 35-40°C) [21, 22]. The disadvantages of the two-phase cooling systems are related with difficulties to control the evaporation and heat - transfer processes [21].

The basic element of the two-phase cooling system is evaporative or two-phase cold plate, where heat is transferred to the system by the power device being cooled. This vapor is further carried through the condenser, liquid-vapor separator and goes out as liquid. The liquid refrigerant is pumped by special pump to the microevaporators.

In two-phase cooling systems for high performance electronic application different refrigerants are used, such as R-134a, R-1234ze, R-236fa and R-245fa. Water is not used usually in two-phase cooling systems, as boiling water flow is difficult to control because of large difference between vapor and liquid densities [8]. For the designed two-phase cooling system of power converter refrigerant R-134a was considered as it has appropriate heat transfer properties at saturation temperature 30°C (Table 7). The refrigerant R-1234ze has similar thermal properties and significantly lower greenhouse effect, so it is produced now as a substitute for R-134.

Table 7

R-134a and R-1234ze saturation properties at 30°C [8]

Parameter	R-134a	R-1234ze
Pressure	7.7 bar	5.78 bar
Liquid density	1187.5 kg/m^3	1146.3 kg/m^3
Vapor density	37.54 kg/m^3	30.56 kg/m^3
Latent heat	173.1 kJ/kg	162.9 kJ/kg
Liquid Viscosity	183 μPas	188 μPas
Vapor Viscosity	13 μPas	12.5 μPas

The most of refrigerants are non-toxic and compatible with a wide range of rubbers, polymers, tubing and insulating materials. In case of leaks, these coolants evaporate at room temperature and cause no damage to electronics [23].

It is impossible to find the two-phase cold plate in commercial, so the experimental results presented in dissertation of E. Costa-Patry [8] are used to assess the two-phase cooling system from thermal point of view. For power module with non-uniform heat flux 1200:700 kW/m^2 the heat capacity of microevaporator should be about 470 kg/m^{2}s to keep temperatures of the base plate in range of 50-63°C. The pressure losses along a single two-phase cold plate are about 0.3 bars. Fig. 7 presents the temperature distribution within IGBT with imposed heat losses and constant temperature of the cold plate 60°C.

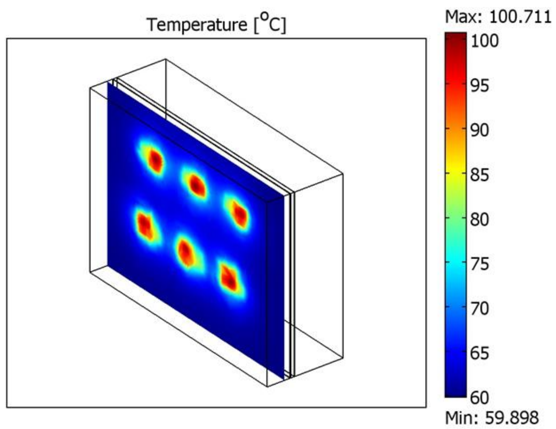


Fig. 7 Temperature distribution within the simulated power model

For operation of the two-phase cooling system the following equipments are necessary – microevaporator or two-phase cold plate, heat exchanger (condenser), liquid-vapor separator, refrigerant tank, refrigerant pump, pump/fan of the secondary cooling loop [8]. The scheme of the cooling system based on the two-phase cold plates is presented on Fig. 8.

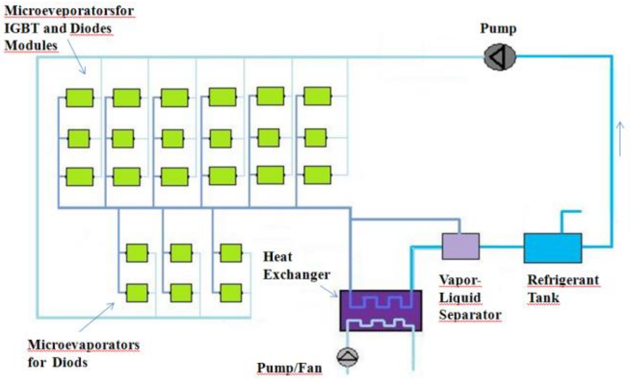


Fig. 8 Scheme of cooling system based on two-phase cold plates

The reliability of the presented cooling system is difficult to assess, as the reliability measures of the microevaporators is unknown. Many authors announce higher reliability of two-phase cold plate compared with single-phase cold plate [21-23]. The refrigerants as coolants are significantly less corrosive and aggressive and therefore two-phase cold plates should be more resistant to the worst problems of any heat-exchange equipments – fouling and corrosion [13]. Also, refrigerants are safe in the event of leak. The two-phase cold plates are characterized nearly isothermal working conditions because of the latent heat absorption. The disadvantages of these systems are prone to pressure uncertainties, dry-out and critical heat flux overshoot, which can cause overheating and failure [21]. Thus, the isothermal microevaporators provide less thermal stresses and therefore greater reliability in the whole setup under the precise operation control. Table 8 presents the reliability metrics of the auxiliary equipments (besides the microevaporators), such as heat exchanger (condenser), liquid-vapor separator, refrigerant tank, refrigerant pump, water pump/air fan.

Table 8

Reliability parameters of cooling system based on two-phase cold plates

Parameter	Parallel-Connected Two-Phase Cold Plates	Auxiliary Components	Total System
Failure Rate, per year	-	0.15	-
MTTF, years	-	7.06	-
MDT, man-hours	-	5.6	-
MTBF, years	-	7.06	-
Availability	-	≈ 0.9999	-
Unavailability	-	$9.23 \cdot 10^{-5}$	-

4. Conclusions

Three different cooling solutions for a 3 MVA medium voltage three-level three-phase NPC converter were presented and studied. The cooling systems based single-phase cold plates, heat pipes & water pools and two-phase cold plates allow the power module to be run to full and peak powers while keeping the IGBT junction temperatures up 125ºC. However, the use of single-phase and two-phase cold plates provide the lowest temperature of the power module chips (95ºC - 100ºC) compared with the cooling system based on heat pipes and water pools (115ºC).

From reliability point of view the using of single-phase cold plates and heat pipes & water pools ensure the system availability – 0.9993 and 0.9994 correspondingly. But more frequent service (each 25 days) should be provided in case of the cooling system based on heat pipes & water pools compared with the cooling system based on single-phase cold plates (each year). The frequent service is caused by the bulk of the attached heat pipes. It is difficult to reduce the heat pipes number as more powerful heat pipes have bigger length and it causes bigger cooling system dimensions. The reliability of the two-phase cold plates is impossible to calculate, as no values of failure rate and mean down time are available. However, many researchers concluded that the two-phase cold plates associate less potential failure because of noncorrosive fluids, but they are problematic to control [18, 21-24]. The auxiliary components' availabilities have equal values (0.9997) for the cooling systems based on single-phase cold plates and heat pipes & water pools. In case of the two-phase cold plates the auxiliary components' availability is 0.9999, as refrigerants are less corrosive compared with water and therefore components have higher lifetime.

It can be concluded that the cooling system based on the single-phase cold plates is the best solution for a medium voltage converter as this technology is well-studied, good controlled and provides adequate temperature of the power converter critical components. The single-phase cold plates and auxiliary components for their operation are available on the market and they can be easy changed. But it is applicable only in conditions of ambient temperatures up to + 35ºC. The two-phase cooling system becomes the promising solution for critical components of medium voltage converters, such as IGBT, in hot regions with ambient temperatures higher + 35ºC. This technology has ability to remove large amounts of heat that is generated in power electronic devices.

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3 MVA GALIOS KONVERTERIO AUŠINIMO SISTEMOS SU SKYSČIU MECHANINIŲ KOMPONENTŲ PATIKIMUMO ANALIZĖ

R e z i u m ė

Sparčiai tobulėjant vėjo elektrinių galios generatoriams galios konventerių gamintojai yra priversti ieškoti būdų, kaip maksimizuoti nominaliąją galią ir ją naudingai konvertuoti. Projektuojami vidutinės įtampos konverterių, kurių projektinė galia yra 3 MVA, aušinimo tirpalai. Jie įvertinami terminiu ir patikimumo atžvilgiais. Siekiant pagerinti didelės galios įrenginių svorio, tūrio ir patikimumo rodiklius, aušinimas tampa ribojančiu veiksniu. Galios modulio šiluminis modeliavimas atliekamas naudojant 3D BEM, o aušinimo sistemos įrenginių analitinė patikimumo analizė panaudota palyginti aušinimo sistemoms, sudarytoms iš vienos fazės aušinimo plokštelių, šilumos vamzdynų su vandens baseinais ir dviejų fazių aušinimo plokštelių.

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RELIABILITY ANALYSIS OF LIQUID COOLING SYSTEMS' MECHANICAL COMPONENTS FOR 3 MVA POWER CONVERTER

S u m m a r y

The rapid development of powerful generators for wind power plants leads producers of power converters search ways to maximize the nominal power and availability of their converter units. The cooling solutions of a medium voltage converter with rated power of 3MVA are designed and assessed here from thermal and reliability points of view. Cooling becomes the limiting factor in meeting the weight, volume and reliability objectives of high power devices. The 3D FEM thermal modeling of the power module and analytical reliability analysis on the cooling systems' equipments are used to compare the cooling systems based on single-phase cold plates, heat pipes with water pools and two-phase cold plates.

Keywords: converter, cooling system, reliability analysis.

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