Thermal modelling of a passively cooled inverter for wave power

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Abstract: Owing to very costly maintenance operations, the reliability of electrical systems for offshore renewable energy is a major issue to make electricity production economical. Therefore proper thermal management is essential in order to avoid the components from being damaged by excessive temperature increase. Both analytic and computational fluid dynamics (CFD) models were implemented to assess the temperature increase in the inverter installed in a submerged substation and during working conditions. It was shown that this inverter could transmit a total power of up to about 35 kW. This limit is dependent on a certain distance between the modules and a perfect thermal contact with the hull. The influence of several of such parameters as well as the efficiency of passive cooling were studied.

Nomenclature

\[ \Delta T \] temperature difference between the nitrogen and the seawater
\[ \lambda \] thermal conductivity
\[ \theta \] temperature increase
\[ A \] contact area between the IGBT and the heatsink
\[ A_i \] constants in the solution of the Bessel equation
\[ d \] duty cycle
\[ e \] thickness
\[ f \] switching frequency
\[ h \] convective coefficient
\[ l_0 \] modified Bessel function of the first kind
\[ K_0 \] modified Bessel function of the second kind
\[ Nu \] nusselts number
\[ P_{\text{loss}} \] dissipated power
\[ P_{\text{out}} \] output power
\[ R \] equivalent radius for the circular heat source
\[ r \] cylindrical coordinate
\[ R_{js} \] IGBT’s internal thermal resistance
\[ R_a \] Rayleigh number
\[ S \] heat source
\[ t \] characteristic time constant
\[ T_{\text{in}} \] temperature in the seawater
\[ T_j \] junction temperature
\[ V_{ce} \] voltage drop between collector and emitter
\[ V_{\text{DC}} \] voltage on the DC-bus
\[ x, y, z \] coordinates

1 Introduction

Although wave power is still a very immature sector, it could provide significant amount of electricity [1]. This source of energy is renewable and fairly predictable. A review of the various wave power technologies is presented in [1, 2].

One category of technologies is called point absorber. The research conducted at Uppsala university is focusing on this type of device. The concept developed at Uppsala University includes wave energy converters (WEC) and a submerged substation. The WEC comprises a buoy attached with a line to a linear generator placed on the seabed. The substation is used to connect the generators together and connect them to the electric grid onshore (see Fig. 1). A summary of the wave power activities conducted at Uppsala University can be found in [3].

In the substation, the output power from the WEC is rectified, connected to a common DC-bus, inverted, transformed before being transferred onshore. Two prototypes of marine substation with entirely passive cooling were built at Uppsala University and more detailed descriptions of these can be found in [4, 5]. A picture of the second prototype is shown in Fig. 2.

Owing to electrical losses, heat is dissipated by the components installed in the substation. Passive and sufficient cooling is a key aspect in order to ensure the reliability. High costs for offshore operation, especially on submerged devices, make cooling an essential issue to achieve economical viability. Earlier temperature studies [6, 7] have shown that the inverter is one of the most sensitive component with regards to overheating issues. The main characteristics for the inverters used for wave power at Uppsala University are therefore

- very high reliability requirements (submerged offshore device),
- special cooling conditions: sealed enclosure including various components and surrounded by seawater,
- entirely passive cooling system (e.g. no fans),
- have to manage a fluctuating input power.
For thermal management several approaches are possible, such as for instance analytic lumped parameter or CFD modelling. This method can be complementary, lumped parameter model being much more simple and less computationally consuming whereas full three-dimensional (3D) modelling can be more accurate [8]. In this paper, extensive thermal modelling is presented for this critical component. Analytic calculations as well as CFD modelling were performed in order to assess the relevance of such a passive cooling strategy. One purpose of this study is to determine whether the cooling strategy is sufficient or if extra cooling features, such as heat pipes, will have to be implemented. A review of common cooling solutions used for electronics can be found in [9]. From the results, a range of transmitted power for safe use was determined.

2 Modelling method

The studied inverter includes six dual-package IGBT modules mounted on a curved aluminium plate (see Fig. 3). The IGBTs are connected to different taps of the three-phase transformer and only three of them are operating simultaneously.

Two different approaches have been implemented in order to evaluate the possibility for passive cooling. The influence of several parameters was studied, such as gas temperature inside the substation, the surrounding water temperature, the thermal contact between heat-sink and hull and the distance between the IGBT modules.

The outer face of the hull is in contact with seawater. The inner face is in contact with the gas inside the substation. The properties of the surrounding water were set to be those of water with a salinity level of 3%, a typical value for places where such a substation could be installed [10]. The gas inside the substation is dry nitrogen, used in order to prevent condensation and fire. Nitrogen has also a slightly lower coefficient of thermal expansion compared with air [11].

2.1 Theory

2.1.1 Problem simplification: To estimate quickly and in a simple way the temperature in the inverter for a wide range of working conditions, an analytic solution was searched for a simplified geometry under certain assumptions.

First of all, the heat-sink and the hull were considered to be flat, instead of curved. The radius of the substation is much bigger than the dimension of the area in which most of the heat is exchanged.

The Biot number, \( h e / \lambda \), in the solid parts is on the order of \( 10^{-1} \) and the temperature can thus be considered to vary only in the plate directions. Thus, the problem is reduced to a two-dimensional problem. The heat equation can be written as in (1)
\[ \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} - m^2 \cdot \theta = \frac{S(x, y)}{\lambda e} \]  

where the temperature increase \( \theta \) is defined as the difference between the temperature of the surrounding seawater and the temperature field in the solid parts \( (\theta(x, y) = T(x, y) - T_\infty) \), the coefficient \( m \) is defined as \( \sqrt{h/\lambda e} \), \( e \) is the thickness of the plate, \( \lambda \) is the thermal conductivity and \( h \) is the total convective heat transfer coefficient.

The source term, \( S(x, y) \), can be written as a sum of three source terms, one for each IGBT module. Then, using the theorem of superposition, under the assumption that the coefficients \( m \) is uniform, the problem is reduced to three separate equations. The geometry is then further simplified, by assuming the module to be circular. The equation can be rearranged in cylindrical coordinates. It gives the Bessel equation as presented in (2)

\[ \frac{\partial^2 \theta_i}{\partial r^2} + \frac{1}{r} \frac{\partial \theta_i}{\partial r} - m^2 \cdot \theta_i = \frac{S_i(r)}{\lambda e} \quad i = 1, 2, 3 \]  

where, \( S_i \) is defined in two domains

\[ S_i(r) = \begin{cases} P_{\text{loss}}/(3A) & 0 < r < R \\ 0 & R < r \end{cases} \]  

where \( A_i \) is the contact area between the IGBT modules and the heat-sink and \( R \) is the radius of a circle with the same area. The solutions are in the form of: a sum of the Bessel coefficients, \( h \): the temperature can not become infinite at zero, it gives that only two coefficients are not equal to zero

\[ \theta_i(r) = \begin{cases} A_1 L_0(mr) + \frac{P}{3Ah} & 0 < r < R \\ A_4 K_0(mr) & R < r \end{cases} \]  

where \( A_1 \) and \( A_4 \) are constants that can be determined to ensure temperature continuity and heat flux continuity at \( r = R \). By superposition, we end up with the temperature in the solid domain as in (5)

\[ T(x, y) = T_\infty + \frac{1}{3} \sum_{i=1}^{3} \theta_i \left[ \sqrt{(x - x_i)^2 + (y - y_i)^2} \right] \]  

where \( y_i \) is the coordinate of the sources (\( x_i \) being defined equal to zero).

### 2.1.2 Convective heat transfer coefficients, \( h \): The Rayleigh number was calculated according to (6) [11]

\[ \text{Ra} = \frac{g \beta \Delta T L^3}{\nu \alpha} \]  

Empirical correlations was then used to determine the Nusselt number [12]. Finally the total convective coefficient \( h \) is calculated, as the sum of the convective coefficient on both sides of the plate, using (7)

\[ h = \frac{k N{\text{H2O}}_{\text{water}}}{L} + \frac{k N{\text{H2}}_{\text{nitrogen}}}{L} \]  

Since this coefficient is dependent on the temperature, the procedure was iterated. The coefficient was calculated for the mean temperature over the area in which 90% of the convective heat exchange takes place.

### 2.2 CFD model

A commercial finite element method-based CFD software was used to solve the coupled temperature and Navier-Stokes equations. It resulted in a fully determined field of temperatures and fluid flow around the modules.

Seawater was entering the domain outside the substation from the bottom boundary at the defined temperature \( T_\infty \). The other side of the hull is in contact with the ambient gas inside the substation. This gas, nitrogen, is also entering the domain from the bottom boundary at a temperature \( T_\infty + \Delta T \) (see Fig. 3). The maximum temperature, \( \max(\theta) \), increase in the solid domain can be extracted from both set of results.

A 3D and stationary study was performed using about 1.4 × 10^6 mesh elements. The mesh had five boundary layers in the gas domains and nine in the liquid domain. The results were shown to be mesh independent. The convective heat transfers at the fluid/solid interfaces were fully resolved in the model. The radiation was neglected because of low temperatures.

To help convergence for the iterative calculation, slip wall boundary conditions \((n \cdot u = 0)\) were implemented at the vertical boundaries around the fluid domains. These boundaries were tilted in the way that the horizontal cross-section area of the fluid domains was decreasing with the \( z \) coordinate. The slope was set so that these boundaries were following the physical streamlines. Only the top and bottom boundary were left open. The calculations were performed for an increasing dissipated power.

### 2.3 Junction temperature

With both of the approaches, the temperature inside the IGBT modules was not directly calculated. Yet, the temperature at the junction in the IGBT modules is the critical factor limiting the use of the inverter. The junction temperature was calculated using (8) (CFD model) and (9) (analytic model)

\[ T_j = \frac{P_{\text{loss}}}{3} R_{js} + \max(\theta) + T_\infty \]  

where \( R_{js} \) is the internal junction-to-sink thermal resistance of the IGBT, equal to 0.145 K/W [Fuji Electric Device Technology Co., 2MBI200U4H-120: IGBT module datasheet] (see Fig. 4).

In the regions close to the modules, the temperature on both sides of the solid domain (CFD model) differed significantly from each other and from the analytic results (see Section 3.1). For this reason, an additional term was added to calculate the junction temperature from the results obtained analytically. It represents the thermal resistance of a metal part of thickness \( e/2 \)

\[ T_j = \frac{P_{\text{loss}}}{3} \left( R_{js} + \frac{e/2}{\lambda A} \right) + \max(\theta) + T_\infty \]  

### 2.4 Maximal output power

Electrical losses in the transistors are of two types: switching losses and conduction losses. Both can be estimated with the data provided by the manufacturer. Conduction losses are
because of the voltage drop over the IGBTs and depend on the forward current, the junction temperature and the duty cycle. Switching losses depend on the forward current, the voltage on the DC-bus, the junction temperature and the switching frequency. The losses were assumed to be equally distributed between the three IGBTs, because of a balanced three-phase load

\[ P_{\text{loss}} = P_{\text{cond}}(I, d) + P_{\text{switch}}(I, f, V_{\text{DC}}) \] (10)

The absolute maximum junction temperature for safe use is \( T_{j,\text{max}} = 150^\circ\text{C} \) [Fuji Electric Device Technology Co., 2MBL200U4H-120: IGBT module datasheet]. The total dissipated power corresponding to such a junction temperature was determined with the results of both models.

Using (10), the maximal current per IGBT module was then estimated, with a working switching frequency \( f = 6 \) kHz, a DC-voltage \( V_{\text{DC}} = 150 \) V, (see Fig. 5) a duty cycle \( d = 0.64 \), \( T_{\infty} = 10^\circ\text{C} \), using (10). Although a reduced switching frequency could be used to reduce the losses, a relatively high value is usually chosen in order to limit the harmonics and thus losses in the filters [13]. The amplitude modulation ratio was set to 1. The dissipated power depends also on the junction temperature. This value was set to be 150°C, since it is the situation of interest here.

The maximal transmitted power was then calculated for the whole inverter, using (11) (see Fig. 5). The output voltage is set by the DC voltage on the DC-bus. The output power is varying with the current. The limit for this current was determined earlier

\[ P_{\text{out}} = \sqrt{3} \frac{(V_{\text{DC}} - V_{\text{ce}})/2}{\sqrt{2}} \hat{I} \] (11)

where \( V_{\text{ce}} \) is the voltage drop between collector and emitter.

### 3 Results

#### 3.1 Temperatures

An example of the results obtained with the CFD model can be seen in Figs. 6 and 7. For an aluminium heat-sink, the temperature increase is lower and more evenly distributed than for a steel heat-sink (see Fig. 6). We can observe convective flows oriented upward on both sides the plate (see Fig. 7).

Fig. 8 presents a comparison of the results obtained with both approaches. The temperature increase along the line on which the modules are placed is presented.

The heat transfer coefficient is considered uniformly distributed over each boundary in the analytic model. This is not the case in the CFD model and it explains also the differences between the two models (Fig. 9).

Of the total dissipated power, between 1 and 1.5% is transferred to the nitrogen inside the substation, depending on the amount of dissipated power. Similarly, the temperature of the gas inside the substation is not
influencing very much the junction temperature (see Fig. 10). This suggests that the inverter is well protected from a possible temperature increase caused by other components.

As mentioned in Section 2.2, the temperature distribution and the junction temperature were calculated for different dissipated power, which is directly correlated with the output power (see Section 2.4). As it can be seen in Fig. 9, the junction temperature increased almost linearly with an increasing power between 1 and 2 kW, until it reached its limit.

3.2 Transmitted power

The CFD model showed that the junction temperature reaches the limit of 150°C when the dissipated power increases above 1.82 kW. The analytic model showed a value of 1.86 kW. The maximal output power – under the typical working conditions for such a substation ($T_\infty = 10°$) and the design parameters chosen at Uppsala (130 mm between the modules) – was finally estimated, respectively, to 35 and to 34.5 kW, with the results from the analytic calculation and from the results of the CFD modelling. This corresponds to a 2% difference.

The influence of several parameters on this result was studied. As shown in the previous section, the results obtained with both approaches are in sufficiently good agreement, to be able to study this influence only with the analytic model. This was decided in order to avoid high computational costs. However, the effect of a poor thermal contact between the curved plate and the hull was simulated with the CFD model. The reason for this was that it involves steep gradient of temperature in the direction normal to the surface.

First of all, a varying seawater temperature, $T_\infty$, has an almost linear effect on the maximal transmitted power (see Fig. 11). The typical range of value for this parameter in Sweden is between 5° and 15°C. This temperature variation affects the maximal output power by ±2%, as compared with the reference value for $T_\infty = 10°C$.

The distance between the IGBT modules was also varied (see Fig. 12). The IGBT modules are currently at a distance of 130 mm from each other. The results showed that this spacing is reasonable, because it is a good trade-off between space saving and efficient cooling. Below this value, the thermal rating of the inverter started to drop dramatically.

A thin thermally resistive layer was also added between the curved plate and the hull (see Fig. 6). In that case, the...
temperature increases rapidly at the junctions. A one twentieth of a millimetre airgap causes a drop of the capacity to 30.5 kW. This illustrates the importance to achieve a contact good between the different parts when mounting the modules. Thermal grease was used in the prototype to avoid this issue.

4 Discussion

It was shown that around 1% of the total dissipated power is transferred to the nitrogen inside the substation. This result is of major importance for the future work and will be used to build a lumped-parameter network model for the whole substation. Although the heat transferred to the nitrogen represents only a small part of the total dissipated heat, it could lead to an accumulation of heat in the substation and affect other components, such as transformers.

In the regions close to the modules, the temperature on both sides of the solid domain differ significantly from each other. The Biot number, is indeed closer to 1 in this regions, because the solid domain becomes thicker.

As it can be seen in Fig. 8, the temperature increase from the analytic model remains well between the two curves from the CFD model (see Fig. 8) except for the module at the higher position. The convective flow is oriented upward and creates asymmetry – the higher module being warmer than the lower one. This effect in not taken into account in the analytic model.

The cooling was studied in a stationary state, as a worst-case scenario. The inverter could probably handle higher power during a shorter and limited period of time. A more computationally-costly transient analysis should be performed to determine these limits. However, a transient model would involve new parameters such as the mass and the heat capacity of each part. This could introduce more complexity and inaccuracy. A characteristic time constant, $t$ for the studied problem can be roughly estimated with (12).

$$ t = \frac{1}{P_{\text{loss}}} \iiint \rho C_p \theta $$ (12)

The limit evaluated in this paper has to be considered as an absolute maximum value and it is recommended to leave a safety margin.

An overall thermal resistance between the junctions and the surrounding seawater can be extracted from the results presented in this paper. The junction temperature increases by approximately 0.1 k/W of dissipated heat. This can be compared with the results from laboratory experiment presented in [7], where the thermal resistances are one order of magnitude higher. This illustrates that, as expected, the choice of a passive cooling strategy becomes relevant for a submerged device.

The special paint used to protect the hull of the substation from the corrosive seawater could also be subject to overheating. In the present study it was not of an issue, because the temperature at the outer face of the hull remains below the maximum temperature that the paint can withstand – namely 60°C according to the supplier [Technical characteristics can be found at www.tikkurila.se/industrifarger]. However, if significant improvements are made to limit the junction temperature, the temperature at the painted face could become a critical aspect.

To improve the cooling capacity, the modules could be aligned horizontally instead of vertically. Indeed, the lower modules were shown to heat up the highest one. Extra fins could also be built on the outer face of the hull. More advanced solution can also be implemented to improve the current design.

5 Conclusion

It was shown that analytic calculation and CFD modelling are in good agreement. In this regard, these methods can be considered to give a reasonable estimate of the maximal power output for the inverter installed in a subsea substation. In the current configuration, the thermal rating for a passively cooled inverter was shown to be approximately 35 kW.

The effect of the temperature of the gas inside the substation on this rating was shown to be very limited. On the contrary, the temperature of the surrounding water was greater. In typical Swedish condition, the influence of the seawater temperature is limited to ±2%.

Based on the results the following suggestions are made for the design of the inverter:

- the IGBT modules should be aligned horizontally in order to prevent thermal coupling by convection;
- the material chosen for the heat-sink is a key design parameter. Aluminium should be used instead of steel;
- the quality of the thermal contact between the heat-sink and the hull was shown to affect the results significantly. Thermal grease should be used and the inverter should be carefully mounted on the wall the substation;
- the distance between the semi-conductor modules can change the maximum power output by ±8%. 130 mm is considered to be reasonable.

In conclusion, it is realistic to envision a passive cooling strategy for inverter installed in the substation, even though some improvements may be needed to increase the maximal output power.
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7 References