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Battery Energy Storage System

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Abstract

The ability to store electrical energy adds several interesting features to a ships distribution network, as silent power, peak shaving and a ride through in case of generator failure. Modern intrinsically safe Li-ion batteries bring these within reach. For this modern lithium battery applications thermal management is vital in achieving a good trade off between maximum lifetime and optimal performance. This article addresses part of the thermal design of a battery storage system, based on commercially available lithium battery technology. During the design process the model assisted in assessment of design choices by checking that battery temperature rise would remain within acceptable levels. The final design is based on eight modules in parallel called PowerBlocks, where each module consists of thirty lithium batteries in series (30x12.8V = 384V; 130Ah) and a three phase converter. The complete battery storage system was modeled thermally, where validation of the model was done in the laboratory. Based on the experimental results from the validation a safe operating area was defined, which marks the thermal boundaries of the system. This study's conclusions indicate that commercially available lithium battery technology can, with good thermal management, be applied to improve the performance of power distribution systems in maritime applications.

Keywords: lithium battery, boat, energy storage, thermal management, converter

1 Introduction

Energy storage in batteries as part of the electrical distribution system aboard ships serves three main purposes. Firstly it can offer silent power when running alone. Secondly it enables peak shaving, load-sharing and temporary increase of the maximum power of the whole system when running along with the generators. Finally it offers UPS functionality (ride through) and emergency power at generator failure. Silent power means zero-emission and no noise. This is comfortable on the one hand, but can also be necessary due to legal regulations in certain areas. Peak-shaving and load-sharing can increase the overall efficiency of the power system because starting an extra generator can be postponed or avoided. As a consequence energy storage allows for lower fuel consumption and less wear of the generators. The described advantages have driven the decision to equip a sailing yacht (Ethereal) with a battery storage system.

Up to recently batteries were not considered for these kinds of applications because of the amount of energy that could be stored per unit volume or mass, poor efficiency, the limited lifetime and safety issues. New developments of (Li-ion-)

battery technology have overcome these limitations. Manufacturers have been able to make the Li-ion technology intrinsically safe, i.e. safe even in case of failure of the battery management system. Especially the convincing experiment to drill a nail into a battery without introducing a dangerous situation makes this technology eligible for large scale applications in electrical networks.

The main challenge for implementation of a battery storage system, based on lithium technology, aboard Ethereal is the thermal management. Lithium batteries are sensitive to strong ageing when a certain temperature level inside the battery is exceeded. It is therefore important to respect this maximum value in order to achieve a good trade off between maximum lifetime and optimal performance. Points of departure for this trade off are the design criteria which are based upon Caribbean conditions.
The storage system is connected to the distribution system of the ship according to Fig. 1.

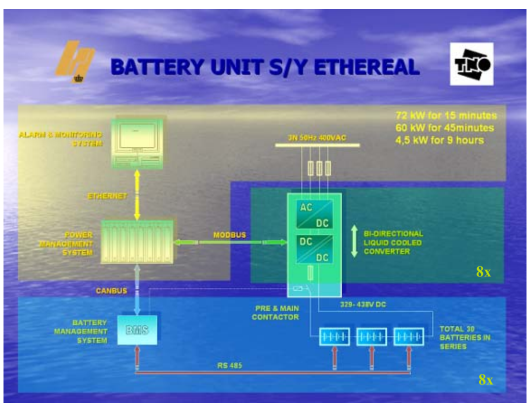

Figure1: Electrical overview battery system Ethereal

Eight storage modules (called PowerBlocks) connected in parallel, power the boat next to generator sets with a total power of 840kW. Each Powerblock consists of 30 batteries in series (total voltage: 30x12.8V=384V; 130Ah), and a converter to connect the batteries to the 50Hz grid (see Fig. 1). The batteries have their own battery management system and the Powerblock is equipped with control electronics that makes the system appear to the outside world as a transparent load/generator. In this paper a model for the battery storage system is presented which was used to asses design choices for worst case operating conditions (Caribbean). The model is validated, with an experimental set-up arranged in the same way as in the ultimate situation aboard. With the experimental data resulting from the validation a safe operating area is defined, which marks the thermal boundaries for an arbitrary amount of continuous delivered power.
The paper is organized as follows. In order to be able to asses the design choices a thermal model was derived in paragraph 2. The model is validated by means of experiments; the results of the validation are presented in paragraph 3 and 4. In paragraph 5 the safe operating area is presented. A performance discussion concludes this paper.

2 Thermal design and model

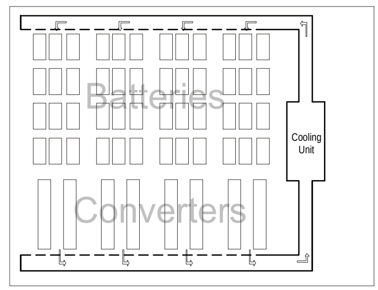

Figure2: Cooling of all Power Blocks

The system is cooled by a closed circuit of cooling air; see Fig 2. The air flows through the battery part, next through the converters, after that through a cooling unit and again into the battery part. In this closed loop the cooling unit allows for heat removal to the outside world. This unit can be used to control the temperature of the air when it enters the battery part. The second way of heat removal out of the system is via a coldplate. See the more detailed view of one Powerblock in fig. 3. The air entering the battery part is heated due to the ohmic losses of the batteries. Next the air is forced through the magnetics, inside the converter. This increases the air temperature further. Finally the air reaches the heat sink (HS). The HS is mounted on a cold plate. It operates in reverse direction transferring heat from the air to the cold plate (CP). The water that is pumped through the cold plate, conveys heat to the outside world. The temperature difference between the water and the air determines the amount of heat that is removed in this way. On the other side of the CP the IGBT’s are mounted. The heat generated by the IGBT’s is completely removed by the CP, without heating the air.

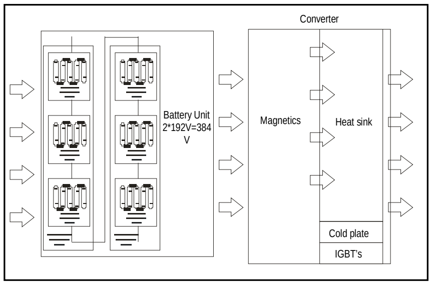

Figure3: Cooling of one Power Block

The cooling unit is only brought into action if the CP's of the powerblocks are not able to keep the internal battery temperature below its maximum allowable temperature equal to 55 ºC.

The thermal model is based on those of its main components; a model of the battery and a model of the converter. These two models are glued together by modelling the forced cooling air which connects them thermally.

2.1 Battery model

The battery model is based upon a first order *RC*-circuit with a current source accounting for the generated heat and a voltage source accounting for the ambient temperature. A sketch of this model is depicted in Fig. 4.

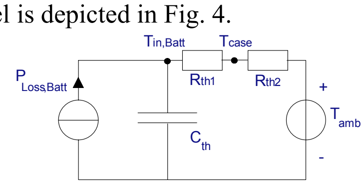

Figure4: Battery thermal model

The power loss inside the battery in Fig. 4 can be represented by the following equation:

$$P_{loss,Batt} = R_{\Omega} I^2 \qquad (1)$$

Each PowerBlock has a number of N_{batt} = 30 batteries, forming one battery-unit. In the modelling they are supposed to behave all in the same way, so only one battery needs to be simulated. Afterwards the heat flux is multiplied by a factor N_{batt} to get this quantity at the level of the battery-unit.

2.2 Converter model

In Fig. 5 the thermal model of the converter is depicted, like the battery model also in the form of its electrical analogon. Special attention is drawn to the controlled sources. The components in the air flow heat up the air. The ratio between the power that is transferred to the passing air and its temperature rise can formally be interpreted as a transimpedance. The same applies to the heating of the waterflow in the CP. The transimpedance of flowing air and flowing water are represented by:

$$R_{th,air} = \frac{\Delta T}{P} = \frac{1}{C_w D_{air} f_{air}} \qquad (2)$$

$$R_{th,water} = \frac{\Delta T}{P} = \frac{1}{S_w f_{water}} \qquad (3)$$

Where f_{air} is the air flow in dm^3/s, D_{air} is the density of air in kg/m^3, C_w is the specific heat of air at constant pressure in $Jkg^{-1}K^{-1}$, S_w is the specific heat of water in $Jkg^{-1}K^{-1}$ and f_{water} is the water flow in dm^3/s.

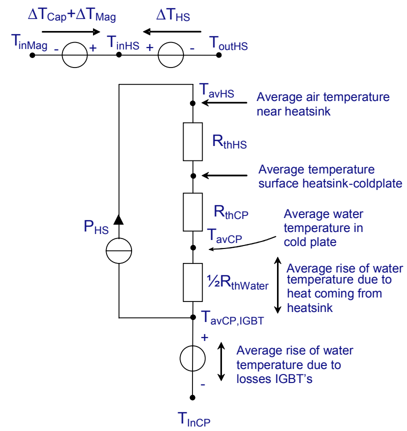

Figure5: Converter thermal model

All of the heat from the capacitors and magnetics has to be removed by the air, so these components heat the air by:

$$\Delta T_{Cap} = R_{th,air} P_{Cap} \qquad (4)$$

$$\Delta T_{Mag} = R_{th,air} P_{Mag} \qquad (5)$$

Likewise all of the heat of the IGBT's has to removed by the water, so this heats the water by:

$$\Delta T_{IGBT} = R_{th,water} P_{IGBT} \qquad (6)$$

The heat that is removed via the HS and the CP depends on the difference between average air temperature and average water temperature. This heat flow P_{HS} is depicted as a current source that sustains the "voltage" between T_{avHS} and $T_{avCP,IGBT}$. This heat flow cools down the air by:

$$\Delta T_{HS} = R_{th,air} P_{HS} \qquad (7)$$

Where P_{HS} is defined by:

$$P_{HS} = \frac{T_{avHS} - \left(T_{inCP} + \frac{1}{2}\Delta T_{IGBT}\right)}{R_{thHS} + R_{thCP} + \frac{1}{2}R_{th,water}} = \frac{T_{avHS} - T_{avCP,IGBT}}{R_{thHS} + R_{thCP} + \frac{1}{2}R_{th,water}} \qquad (8)$$

The inlet air temperature of the battery compartment is the only variable which is controlled, i.e. limited by the cooling unit in such a way that the internal battery temperature never exceeds 55 ºC. The inlet water temperature is fixed.

2.3 Model implementation and computational aspects.

The preceding results allow us to define the different parts of the system: 1.) Converter, 2.) Battery-unit 3.) Chiller unit as well as 4.) the facility on the test site to let in or let out external air as sources or sinks of heat. Each of these parts either supply or retrieve heat depending (amongst others) on the internal air temperature. The different heat fluxes are modeled as “current sources” and connected to the thermal capacity of the internal air (see Fig. 6). The “voltage” over this thermal capacitor is the temperature of the internal air. So for each point of time either the sum of the power sources amounts to zero (in that case the temperature is constant as a function of time) or the sum is unequal to zero (in that case the temperature rises or falls as a function of time). The relation is as follows. Suppose the time step is Δt and the net power of all the sources is P_{sum}. Let the temperature difference between last calculated step and the next step be:

$$\Delta T = T_{i+1} - T_i \qquad (9)$$

then the amount of heat that has to be stored in the thermal capacity of the internal air to realise this temperature difference is:

$$W = \Delta T C_{th} \qquad (10)$$

This heat has to be equal to:

$$W = P_{sum} \Delta t \qquad (11)$$

This simple system description allows for an implementation in Excel. This programme was chosen as a platform because of its general availability, notwithstanding its severe limitations as a simulation tool.

Aboard the Ethereal a total of eight PowerBlocks are present. The converters have their own set of batteries electrically as well as their own cooling within their own housing. But the thermal properties of the batteries are shared by all the converters. Heat generated by the batteries and the converter of one Powerblock will be spread over all the batteries and contribute to the input temperature of all the other converters. The model of the total system is the addition of the models of eight Powerblocks, only that they share one common thermal capacity. The procedure to calculate iteratively the temperature as a function of time is as follows. Given the temperature at t the temperature at $t+\Delta t$ is found by making an initial guess for T. For this guess the sum P_{residu} of all current sources as well as the current taken by the capacitor (as depicted in Fig. 6) is calculated for all of the Powerblocks. If P_{residu} is lower than a small number, the guess is taken as the value of T for $t+\Delta t$. Otherwise a new estimate is made:

$$T_{new} = T_{old} + \alpha P_{residu} \qquad (12)$$

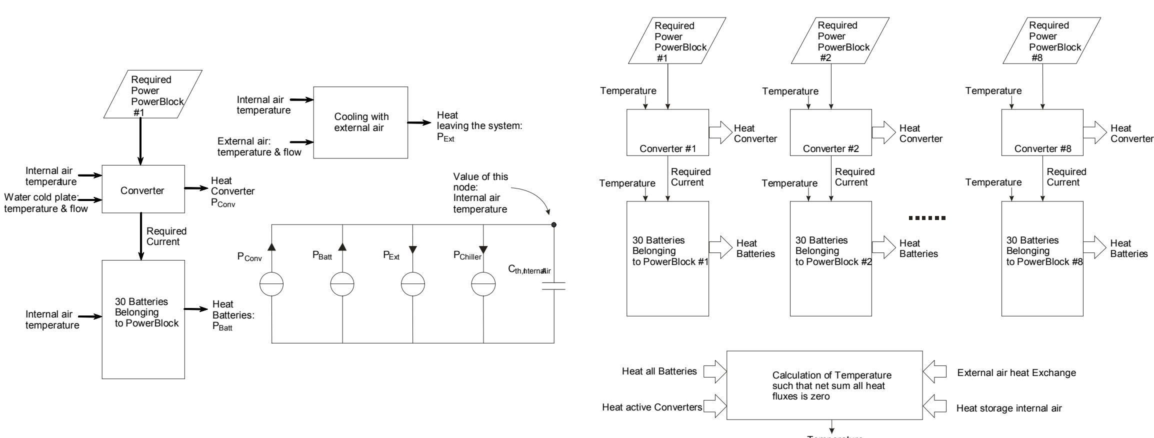

Figure6: Thermal model of one PowerBlock and overall thermal model

For this new estimate the value of P_{residu} is calculated and the process just described starts all over again. The value of α has to be chosen keenly. If it is too high, the iterative process won't converge. If it is too low, the iteration will converge only very slowly. The optimum can be found partly by looking at the partial derivatives with respect of this temperature of all the power sources and sinks in the system and partly experimentally.

3 Battery characterization

As mentioned before the lithium-ion battery that was used can thermally be represented by a simple first order RC-circuit. The parameters R_{th}, C_{th} and R_{Ω} have to be determined experimentally to be able to use the model. Two types of experiments were carried out, one to determine heat properties and one to determine loss properties:

1. R_{th}, C_{th} experiment with forced cooling
2. R_{Ω} Internal resistance experiment

Ad.1: For the forced cooling experiments the battery was put into a duct as depicted in Fig 7.

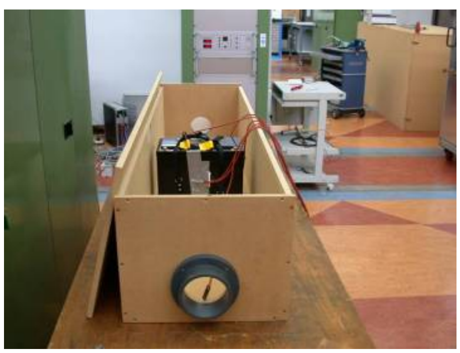

Figure7: Battery testing with forced air flow

The duct can be closed and connected to a few fans that generate a variable airflow. This airflow is increased step by step and at each value an experiment as described below is carried out. The battery is discharged with a current of 115A during some 70 minutes. After that a cooling period of 3 hours starts. Then the battery is charged with 65A during 2 hours after which the battery is cooled down again during 10 hours. The measurement results at an air velocity of 0.5m/s are given in Fig 8. In the figure the start and end points of the discharge and charge phases are indicated by (t#,T#). The parameters of the thermal model can be calculated on the basis of end values and average values as follows. Define average temperature and temperature differences for charge and discharge phases:

$$T_{av1} = \tfrac{1}{2}\left(T_{11} + T_{12}\right) \quad (13)$$

$$T_{av2} = \tfrac{1}{2}\left(T_{21} + T_{22}\right) \quad (14)$$

$$\Delta T_1 = T_{12} - T_{11} \quad (15)$$

$$\Delta T_2 = T_{22} - T_{21} \quad (16)$$

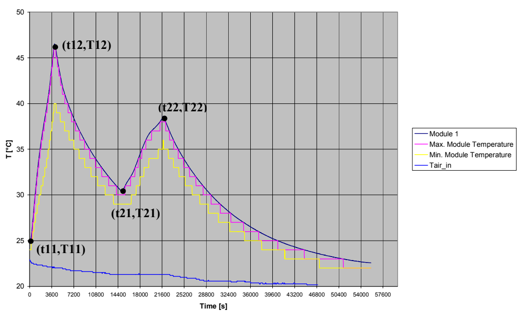

Figure8: Internal and ambient temperature of battery at 0.5m/s air velocity

As the average ambient temperature during discharging and charging differs slightly, it makes sense to define them both: ambient temperature during discharging is T_{amb1}; ambient temperature during charging is T_{amb2}. If the ambient temperature can be considered constant during charging, discharging and during both cooling down phases, the power equilibrium during discharging and charging holds true:

$$I_1^{\,2} \cdot R_{\Omega} - G_{th} \cdot (T_{av1} - T_{amb1}) = C_{th} \cdot \frac{\Delta T_1}{\Delta t_1} \quad (17)$$

$$I_2^{\,2} \cdot R - G_{th} \cdot (T_{av2} - T_{amb2}) = C_{th} \cdot \frac{\Delta T_2}{\Delta t_2} \quad (18)$$

Where:

$$G_{th} = \frac{1}{R_{th}} = \frac{1}{R_{th1} + R_{th2}} \quad (19)$$

It follows that:

$$G_{th} = \frac{W_1 \cdot \Delta T_2 - W_2 \cdot \Delta T_1}{\Delta T_A \cdot \Delta t_1 \cdot \Delta T_2 - \Delta T_B \cdot \Delta t_2 \cdot \Delta T_1} \quad (20)$$

$$C_{th} = \frac{W_2 \cdot \Delta T_A \cdot \Delta_{t1} - W_1 \cdot \Delta T_B \cdot \Delta t_2}{\Delta T_2 \cdot \Delta T_A \cdot \Delta t_1 - \Delta T_1 \cdot \Delta T_B \cdot \Delta t_2} \quad (21)$$

Where:

$$\Delta T_A = T_{av1} - T_{amb1} \quad (22)$$

$$\Delta T_B = T_{av2} - T_{amb2} \quad (23)$$

$$W_1 = P_1\Delta t_1 = I_1^2 R_\Omega \Delta t_1 \quad (24)$$

$$W_2 = P_2\Delta t_2 = I_2^2 R_\Omega \Delta t_2 \quad (25)$$

The values that have been calculated in this way are depicted in Fig. 9.

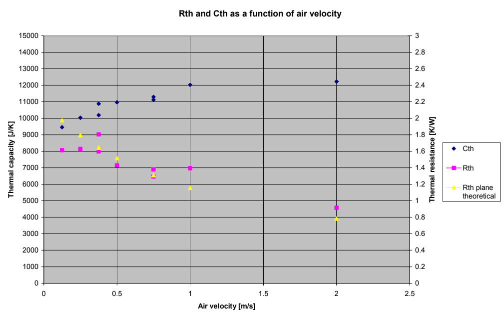

Figure9: Thermal resistance and capacity calculated from charge and discharge phases

Values for the thermal capacitance C_{th}=*11 kJ/K* and the thermal resistance R_{th}=*1.4 K/W* seem to be a reasonable choice for calculating purposes. Of course only *Rth* is dependent on the air velocity and *Cth* should be constant for all experiments. As a reference, thermal resistance values of some forced cooled plane is added. These values have been obtained from an empirical formula in literature giving the cooling of a large plane as a function of air velocity [1]:

$$P_{conv} = (4.54 + 4.1 \cdot v_{air})\Delta T \ \ [W/m^2] \quad (26)$$

This gives some extra confidence that the calculated *Rth* and *Cth* are realistic.

Ad. 2: The internal resistance of the battery can be determined by means of current excitations. Measuring the voltage jumps immediately after the current excitation, with respect to the average voltage at an arbitrary SOC, a good estimate for the internal resistance of the battery is obtained.

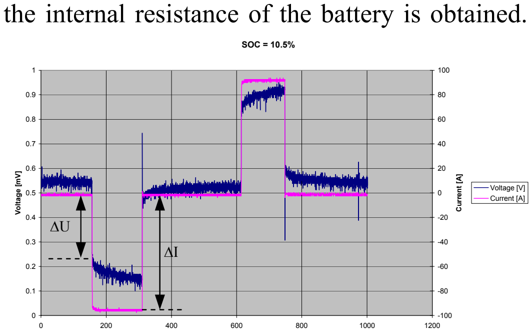

Figure10: Battery voltage and current used to calculate internal resistance

The experiment was carried out at different SOC values. In Fig. 10 the measurement results are depicted for 10.5% SOC. The resistance is equal to the 'instantaneous' voltage step (exponential voltage built up or decay in Fig. 10 due to relaxation processes is not included in the calculation) divided by the current excitation:

$$R_\Omega = \Delta U / \Delta I$$

In Table 1 several internal resistances were calculated at SOC's ranging form 10% to 50%. It can be seen that the internal resistance is quite stable varying between 3.5 mΩ..3.75 mΩ.

Table1: Battery internal resistance for different SOC's

SOC (%)	Calculated R_Ω (mΩ)
10.5	3.56
18.3	3.56
31.6	3.48
45.7	3.75

4 PowerBlock experiments

In this paragraph, experimental results with one PowerBlock (out of eight) are presented. The experiments were conducted with an experimental set-up in which construction features and operating conditions aboard Ethereal can be approached. Aim of the experiments was 1.) to validate the thermal modeling in a mode of operation that was much the same as to be expected in the ultimate application and 2.) to evince system behaviour of one Powerblock.. That is to say, that even in case of poor modeling, the experiments would still bring to light the abilities of the Powerblock to perform. The Powerblock is designed to deliver power up to some 60kW. In the lower power range (up to appr. 25kW) in a continuous mode, at higher power levels intermittently. In order to obtain a comprehensie picture of thermally transient and steady state mode operation over the whole power range six basic experiments were defined where the Powerblock worked for a prolonged time at a fixed level of processed power. The experiments were: running at 10kW, 20kW, … , 60kW for some 8 to 12 hours. The duration was long enough to reach stable end temperatures. Caribbean circumstances were emulated by chosing the right ambient conditions and making use of test site options. Of course a battery system can not work very long in one mode of operation, being it either delivery or storage power. So the experiments were set up as repetition of 20 minute-cycles. Within each cycle the battery was charged for 10 minutes and discharged for 10 minutes. In this way it was possible to run the long-term experiments at any power level. In Fig. 11 a sketch of the experimental set-up is presented and in Fig. 12 a photo is displayed. The set-up possesses different options to control the experimental environment and operation of the Powerblock:

- recirculation of air (emulating a fully closed circuit air cooling system)
- no recirculation of air (removal of tube, usage of climate controlled container air, emulating the functionality of the chiller or even letting in or out external air)
- waiting times converter (emulating the intermittent operation at higher power levels)

Next to the different options in the set-up there are parameters which can be controlled:

- Temperature and flow of air
- Temperature and flow of water

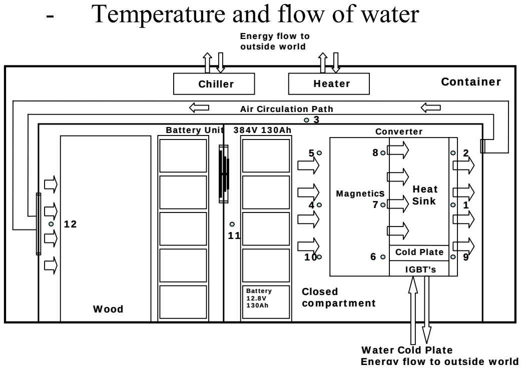

Figure11: Experimental set-up for testing PowerBlock

The numbers in the sketch correspond to the physical location of temperature measurement devices. The battery temperatures were measured with the onboard temperature sensors which among others measure the internal battery temperature (< 55ºC).

Figure12: Impression set-up for testing PowerBlock

Two main objectives were pursued: 1.) to assess the losses in converter and batteries and 2.) to assess the thermal behavior (i.e. the temperature response of batteries and converter). They are both considered in detail next.

4.1 Electrical analysis measurement data: losses in batteries and converter

The electrical circuit of the Powerblock during the experiments is depicted in Fig. 13. The following relation holds true:

$$P_{toBatt} + P_{toGrid} + P_{LossConverter} = 0 \qquad (27)$$

Two different kinds of experiments were carried out:

1. zero average power consumption from the grid ('net no work to grid mode')
2. zero average energy storage in the batteries ('net no storage to battery mode')

Both of these experiments were run at 10kW, 20kW, … 60kW at 20 minutes cycles.

Ad.1: The converter plus batteries can be run in a mode where there is over a prolonged time net no intake or output of power from the grid. For instance by running for a long time, a cycle of taking 20 kW from the grid during 10 minutes, and supplying 20kW to the grid during 10 minutes.

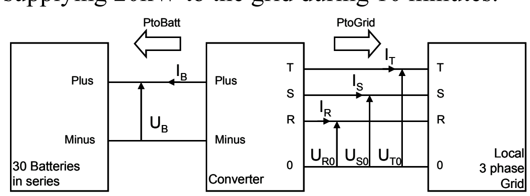

Figure13: Basic circuit for testing batteries and converter

In this case $\overline{P}_{toGrid} = 0$ so:

$$\overline{P}_{LossConverter} = -\overline{P}_{toBatt} \qquad (28)$$

This of course gives rise to a gradually discharging of the batteries, all the losses of the system have to be made good for by the batteries. It is the initial energy minus the final energy stored in the batteries divided by the time the experiment lasts. So it comes down to the difference in initial and final SOC. This number can be assessed fairly precisely. By measuring the battery voltage and current, another power exchange number is obtained. This power can be integrated mathematically and represents as well the total energy that is dissipated in the converter.

Ad.2: Similar to *Ad.1*, the converter and the batteries can be run in a mode where there is over a prolonged time no net storage or retrieval of energy from the batteries. This is done by running a slightly modified cycle as follows. The batteries start at a SOC of for instance 85%. Then 20kW is taken from the grid during 10 minutes. Next 20 kW is supplied to the grid until again the SOC of 85% is reached, and the cycle is started over again.

$$P_{toBatt} = P_{BattStorage} + P_{BattLoss} \qquad (29)$$

In this case $\overline{P}_{BattStorage} = 0$ so:

$$\overline{P}_{LossConverter} + \overline{P}_{BattLoss} = -\overline{P}_{toGrid} \qquad (30)$$

All the losses in the system have now to be made good for by the average net intake of power from the grid. This number is again obtained by mathematically integrating the power from the grid and dividing it by the time the experiment lasts (slope of the trend line when fitted to the calculated energy).

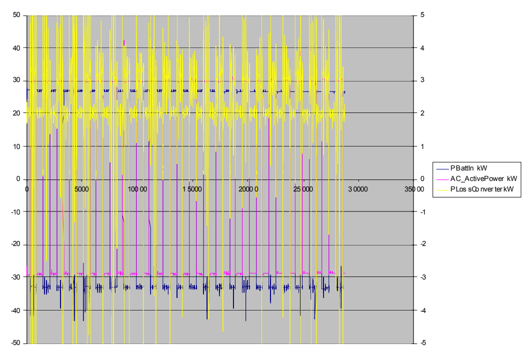

Figure14: Power measurement data as a function of time for "net no work to grid mode" @ 30kW

As an example of the power measurement, data for the 30kW operation point is depicted in Fig 14 for the net no work to the grid mode. The graph comprises the power flow into the batteries *P_BattIn*, powerflow to the grid *AC_ActivePower* and the converter losses *PLossConverter*, where *PLossConverter* can be calculated as follows:

$$\overline{P}_{LossConverter} = -\overline{P}_{BattLoss} - \overline{P}_{toGrid} \qquad (31)$$

The averaging is done by first integrating and then letting Excel calculate the slope of the integrated graph, see figure 15. The target "net no power to the grid" is not perfectly realized, but can be easily corrected for. Due to the storage nature of the battery, its losses cannot directly be obtained from the battery absorbed or delivered power.

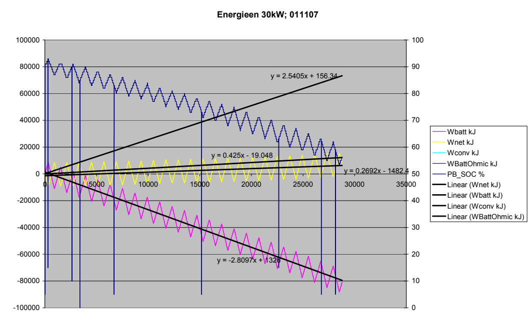

Figure15: Energy flow in the Power Block system for " net no work to grid mode" @ 30 kW

An estimate however can be determined with the internal resistance R_Ω via "*net no storage to battery mode*" (described in the next paragraph). This estimate is used to calculate *WBattOhmic* in Fig. 15. For the "*net no storage to battery mode*" the integrated data are presented in figure 16.

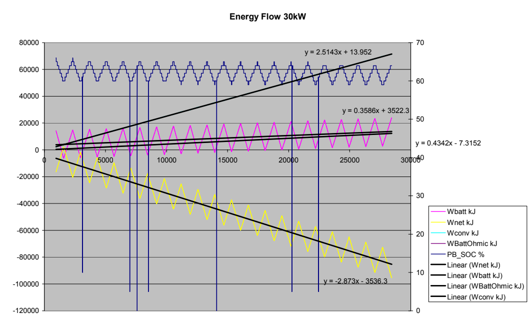

Figure16: Energy flow in the Power Block system for "net no storage to battery mode" @30kW

Characteristic for this operational mode is that the total losses in the system, battery loss and converter loss, are supplied by the grid. This means that the difference between the energy supplied by the grid and the energy dissipated by the batteries represents the amount of energy dissipated inside the converter. The net work that is done by the battery are losses dissipated inside the battery, this result is represented by "*Wbatt*". The slope of the trend line for "*Wbatt*" in Fig. 16 therefore gives the amount of average battery loss. This power loss can also be calculated as follows:

$$P_{loss,Batt} = 30 I^2 R_\Omega \qquad (32)$$

Substitution of 2.5 mΩ in (32) and integration of P_{loss} gives quite a good fit between *WBatt* and *WbattOhmic* in Fig. 16. The losses for the remaining operating points are calculated in a similar fashion. Together these results give loss as function of operating point (depicted in Fig. 17).

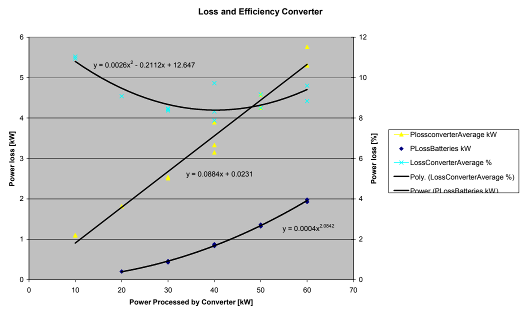

Figure17: Converter power loss, efficiency and battery power loss

4.2 Thermal analysis measurement data: heat fluxes

The next step in the analysis of the experimental data is the temperature measurement results. These results together with the power measurement results make analysis of the heat fluxes in the system possible (see Fig. 18). It gives insight in the way heat is removed to the outside world. An example of monitored temperatures is depicted in Fig. 19 for the 30kW operating point (these temperatures, among others correspond with measurement points 3, 11 and 12 in Fig. 11).

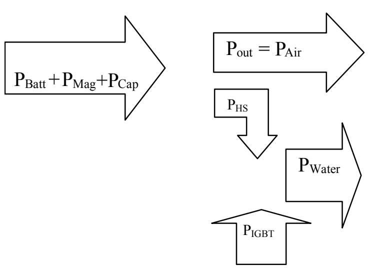

Figure18: Heat fluxes in the PowerBlock

With the temperature data in Fig. 19 calculations can be performed. In (8) for example an equation for P_{HS} was presented. However for the purpose of analysis (33) is derived:

$$P_{HS} = \frac{T_{in,HS} - T_{in,CP}}{R_{th,HSCP}} - \frac{(\Delta T_{HS} + \Delta T_{CP})}{2 \cdot R_{th,HSCP}} \quad (33)$$

Calculation of (33) as a function of $T_{in,HS}$-$T_{in,CP}$ = ΔT resulted in Fig. 20. The yellow triangles in Fig. 20 represent the relation between P_{HS} and ΔT for nine different experiments. Additionally P_{HS} is calculated without the minus term, neglecting the loss dependent part (ΔT_{HS}+ΔT_{CP}). The graph shows that P_{HS} is mainly dependent (≈ 80%) on ΔT. The loss dependent term is relatively small, approaching a constant value for varying experimental conditions.

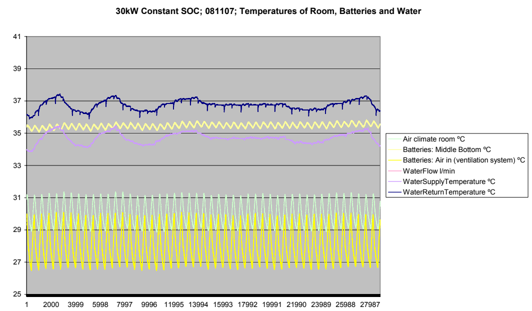

Figure19: Batteries, water and room temperatures @ 30kW operating point

This means that for a fixed water temperature of 30 ºC the heat flux through the CP can mainly be controlled by the inlet air temperature of the battery compartment (i.e. controllable cooling air $T_{in,Air}$):

$$T_{in,HS} = T_{in,Air} + \Delta T_{Batt} + \Delta T_{Mag} + \Delta T_{Cap} \quad (34)$$

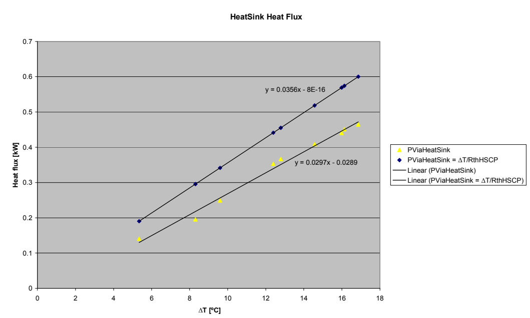

Figure20: Converter power loss, efficiency and battery power loss

It is interesting to see that with eight CP's at ΔT = 12.5 ºC, a total of 2.8kW heat can be conveyed to the sea. This is equal to the total power loss of one PowerBlock running at app. 28kW continuously (nominal power).

4.3 Model validation and parameterization

In this paragraph the thermal model is validated. Validation gives rise to a consolidated set of battery parameters valid for the case that thirty batteries are placed together. The validated model can also be used to generate temperature predictions for varying system parameters. This is especially interesting for the battery system, being the weakest thermal link in the system. The following starting points for this validation process were chosen:

- validation at 30 kW operating point, close to the nominal operating point of the system and sufficient measured amplitudes for accurate results
- temperature rise of worst case battery (out of thirty batteries in total) in order to get a worst case estimate

A number of subsequent iterative strokes, with different thermal battery parameters (R_{th}, C_{th}, and R_{Ω}), resulted in the simulation result displayed in Fig. 21. The yellow line in Fig 21. was generated by the PowerBlock model, the blue line is the measured temperature of battery module number 6 and the magenta line represents module 15.

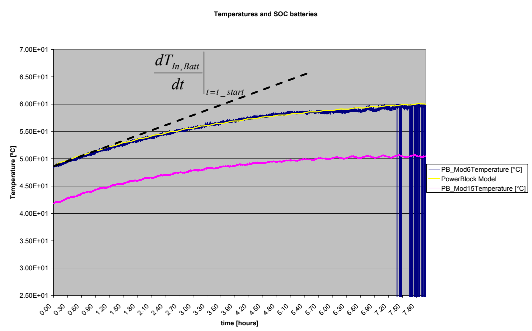

Figure21: Battery internal cell temperature for module 6, module 15 and prediction by model @ 30 kW

The parameters which were chosen can be summarized as follows:

- $R_{th} = 1.35$ K/W
- $C_{th} = 9.75$ kJ/K
- $R_{\Omega} = 2.65$ mΩ

Form these parameters the thermal time constant can be determined:

$$\tau_{th} = R_{th} C_{th} = 13200 s \tag{35}$$

The validation process has provided a consolidated worst case set of battery parameters. These parameters more or less agree with the result in paragraph 3. The set derived in this paragraph is used for the derivation of the safe operating area in the next paragraph.

5 Safe operating Area (SOA)

The battery is the limiting component in the system because of its low maximum internal temperature as well as its SOC constraints. Starting point is therefore the battery thermal model in Fig. 4, for which the following ODE can be derived:

$$\frac{dT_{In,Batt}(t)}{dt} = \frac{T_{amb} - T_{In,Batt}(t)}{\tau_{th}} + D\frac{P_{Loss,Batt}}{C_{th}} \tag{36}$$

Where D = duty cycle of the Powerblock. If the Powerblock is switched off, D=0, then only the heating or cooling down by surrounding air results:

$$\frac{dT_{In,Batt}(t)}{dt} = \frac{T_{amb} - T_{In,Batt}(t)}{\tau_{th}} \tag{37}$$

If the battery starts working at $T_{In,Batt} = T_{Amb}$, only the heating due to internal losses manifests itself:

$$\frac{dT_{In,Batt}(t)}{dt} = D\frac{P_{Loss,Batt}}{C_{th}} \tag{38}$$

The general behaviour of the battery is the superposition of both phenomena. With the initial internal battery temperature T_{Init} as the initial condition of the system a solution for the ODE can be found:

$$T_{In,Batt}(t) = \left(\Delta T_{loss} - \Delta T_{Init}\right)\cdot\left(1 - e^{-t/\tau_{th}}\right) + T_{in,BattInit} \tag{39}$$

Where:

$$\Delta T_{Init} = T_{in,BattInit} - T_{amb} \tag{40}$$

$$\Delta T_{loss} = D P_{loss,Batt} R_{th} \tag{41}$$

For this general solution different operational conditions can be considered which can be summarized as follows:

1. $T_{in,BattInit} = T_{ambient}$
2. $T_{in,BattInit} \neq T_{ambient}$
3. intermittent D < 1 (D = duty cycle)
4. $P_{loss} = 0$

5.1 Derivation of the SOA diagram

The SOA (Safe Operating Area) is basically the time during which the system can deliver or absorb a certain amount of power. This is the solution of (39) based upon the requirement $T_{In,Batt} \le T_{Max}$ under all circumstances. In order to show this an example with the following assumed operational conditions is given:

- ambient temperature ≈ 32.5ºC
- $T_{in,BattInit} = T_{ambient}$
- D = 1 (duty cycle)

The calculation result for (39) with the $T_{In,Batt} \le T_{Max}$ requirement is depicted in Fig. 22 for several operating points (i.e. delivered continuous delivered power).

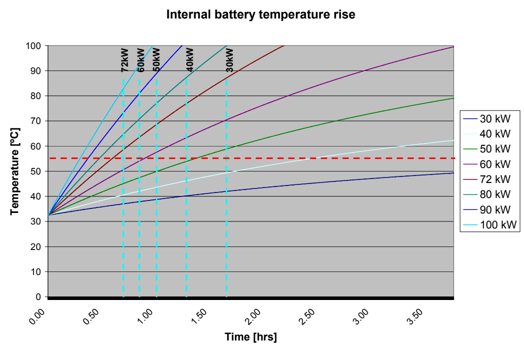

Figure22: Battery Internal Cell Temperature @ 32.5 ºC ambient temperature

The red dashed line in Fig. 22 represents the maximum allowable internal battery temperature ($T_{In,BattMax}$ = 55ºC), whereas the cyan dashed line with accompanying amount of delivered power P in kW represents the point in time for which the batteries are fully discharged. From the temperature rise depicted in Fig. 22 it is quite straight forward to obtain the SOA diagram. This diagram is namely based on the intersections of the exponential lines corresponding to an arbitrary amount of delivered power P and the temperature limit. Analytically the equation behind the SOA diagram, for the general case, can be derived by substitution of:

$$P_{loss,Batt} = I^2 R_\Omega = (P/U)^2 R_\Omega \qquad (42)$$

in (41), $T_{In,Batt} = T_{In,BattMax}$ in (39) and isolation of P from (39). The following result can then be obtained:

$$P = \frac{U}{\sqrt{k}} \sqrt{\Delta T_{Max}\left(1 - e^{-t/\tau}\right)^{-1} + \Delta T_{Init}} \qquad (43)$$

Where:

$$\Delta T_{Max} = T_{In,BattMax} - T_{amb} \qquad (44)$$

$$k = D \cdot R_\Omega R_{th,Batt} \qquad (45)$$

Making the same assumptions as in Fig. 22 one arrives at the SOA diagram depicted in Fig. 23. To get a better understanding of the graph in Fig. 23 the following example is given: if the captain of Ethereal would for example request 60kW, one needs to start on the y-axis at the 60 kW point in Fig. 23 and follow the 60 kW line to the right. When moving in the right direction we first pass the purple line related to an ambient temperature of 50 ºC. This means that, with an ambient temperature of 50 ºC, the PowerBlock is able to supply 60 kW for approximately 788 seconds (≈ 0.2 hours) before reaching thermal boundaries.

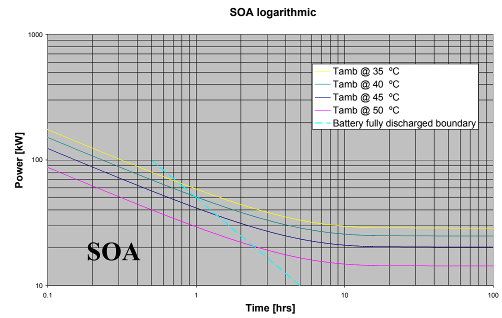

Figure23: SOA diagram (logarithmic scale)

Moving further to the right we pass the blue solid line related to an ambient temperature of 45 ºC. This means that the battery is able to supply 60 kW for approximately 1624 seconds without reaching critical internal battery temperatures. Subsequently for ambient temperatures of 45 ºC and 50 ºC the battery can successively supply 60 kW for 2536 and 3480 seconds. In the latter case however we passed the cyan dashed line which represents the "fully discharged" boundary. This means that before the battery will reach its thermal boundary all its energy has been depleted. When the PowerBlock is used for continuous power supply, it will never reach the area on the right side of the dashed cyan line, accept when the system is used in peak shave or load sharing mode and storage of energy is also part of the cycle.

5.2 Thermal range prediction

An alternative approach for analysis of (39) is isolation of time t instead of P:

$$t = \tau_{th} \cdot \ln\left\{\frac{\Delta T_{loss} - \Delta T_{Init}}{\Delta T_{loss} - \Delta T_{Max}}\right\} \qquad (46)$$

In this way the thermal margin for the batteries at continuous delivered power can be calculated for different operational conditions. It can be used for thermal range prediction. In Table 1 this calculation is executed with the following operational conditions:

- ambient temperature = 32.5ºC
- $T_{in,BattInit} = T_{ambient}$
- eight PowerBlocks D = 1/8
- one PowerBlock D = 1

Table2: Thermal margin for typical Ethereal missions for continuous delivered power

Mission	**Average**				**Peak**			
	Power [kW]	**SOC = 0% [hrs.]**	**$T_{In,Batt}$= 55ºC**		**Power [kW]**	**SOC = 0% [hrs.]**	**$T_{In,Batt}$ = 55ºC**	
			D = ⅛ [hrs.]	**D = 1 [hrs.]**			**D = ⅛ [hrs.]**	**D = 1 [hrs.]**
Sail quiet ship	87	4.59	6.26	0.39	240 (<5 min)	1.66	0.41	0.05
El. Troll quiet ship	285	1.40	0.29	NA	720	0.55	0.044	NA
Anchor quiet ship	29	13.77	∞	9.32	33	12.10	∞	4.55
Go Home mode	14	28.52	∞	∞	16	24.96	∞	∞

It can be seen in Table 2 that mission ‘Go Home mode’ does not have a thermal boundary for both average and peak power (energy supply is limited by Ah). For ‘Anchor quiet ship’there is a thermal boundary if one PowerBlock has to do all the work, in intermittent mode energy supply is limited by Ah’s. Mission ‘Sail quiet ship’ is limited by Ah’s in intermittent mode for average power. When peak power in intermittent mode is delivered, supply is limited by thermal boundaries. Electric troll quiet ship is for both average and peak power limited by the thermal boundaries of the battery.

6 Discussion

A thermal model for the Energy storage system, designed for sailing yacht Ethereal, was derived. Validation of the model occurred in the laboratory. Operational conditions in the experimental set-up were controlled in such a way that they approximated worst case conditions aboard the actual yacht. During the design process the model assisted in assessment of design choices, checking that battery temperatures would stay within acceptable levels. Furthermore a Safe operating area, which marks the thermal boundaries of the system, was defined. The safe operating area brought into sight thermal range prediction. This can be used to assist the captain of Ethereal during daily operation of the yacht. Thermal range prediction also shows that zero emission for several Ethereal missions can be achieved with this battery storage system.

7 References

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