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Optimising a Submarine Power Plant

Mean Value First Principle Model Balances Space, Mass and Operational Performance

A naval submarine sails in different operational modes: surfaced, at periscope depth or submerged. It needs an appropriate power plant to do so. The impact of the selected power plant on the overall submarine design is significant. Thus, selecting the right components of the power plant at an early stage is key to a successful design. In this research, a mean value first principle power plant model was extended with a PEM Fuel Cell model as Air Independent Power (AIP) system and a Permanent Magnet Synchronous Machine (PMSM) as propulsion motor.

The overall power plant model covers energy generation, storage and distribution to the main power demands “propulsion” and “auxiliary”. The model optimises a submarine power plant by balancing required space, mass and operational performances based on a pre-set operational profile. The result is insight into optimised design concepts considering volume, mass and efficiency given operational needs that extend beyond current submarine capabilities. Conventional diesel-electric submarines perform a wide range of missions, like anti-surface warfare, anti-submarine warfare, information gathering and special operations. The submarine should not be detected during these missions. Therefore, it is desirable that the submarine can stay submerged for long periods of time. Submerged time, however, is limited: when the air-independent batteries need to be charged, “snorting” is required for the air-dependent diesel-gensets. Therefore, a typical submarine mission consists of open and covert transit (diesel engines running), and surveillance and attack mode (submerged, power from batteries).

Master Thesis

This research was conducted as graduation assignment for the degree of Master of Science in Marine Technology at Delft University of Technology (DUT). It was performed at Nevesbu BV in Alblasserdam, a naval architecture and marine engineering company with high expertise in submarine design. Nevesbu and DUT have a history of good cooperation with regards to (graduation) research. The research and final report titled “Optimisation of a Submarine Propulsion System by Implementing a Proton Exchange Membrane (PEM) Fuel Cell and a Permanent Magnet Synchronous Machine (PMSM) in a First Principle Model” was in this case graded with a 9.0 and lead to the first author graduating cum laude. Her research also earned her a KNVTS Maritime Student Award 2018.

Mean Value First Principle Simulation Model

A mean value first principle simulation model of a diesel electric propulsion system has been created in earlier graduation research [1]. This time-domain model can be used for submarine design as it determines the dimensions of the system components. Note that time-domain models are required for the design of a submarine power plant as the size of energy storages (like batteries and fuel plus oxygen tanks) depend on accumulated power consumption. In the model, a DC propulsion motor, batteries and a diesel-generator set are included. For the batteries two options are present: lead acid batteries (LAB) or lithium ion batteries (LIB). Rietveld [1] reported two main recommendations to enable assessment of more challenging mission profiles with the created model:

- to extend the model with an Air Independent Power (AIP) system as a “range extender”; and
- to add a Permanent Magnet Synchronous Machine (PMSM) to increase system efficiency and decrease the required dimensions for the propulsion system.

These recommendations formed the starting point of this research.

AIP Concepts

Many different AIP concepts, such as a Stirling engine and different types of fuel cells, have been considered. It was decided to imple-

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ment the Proton Exchange Membrane Fuel Cell (PEMFC) in the model, because a fuel cell is noise and vibration free in contrast to mechanical AIP systems. Moreover, the PEMFC is a mature technology with many applications (including submarine power plants) and it has a good power density compared to other fuel cell types [2].
With the modelled components, eight different power plant configurations have been simulated, see the table below. All modelled configurations use a diesel generator set to charge the batteries during the transits.

#	Propulsion Motor	Batteries	AIP System
A	DC compound	LAB	None
B	DC compound	LIB	None
C	DC compound	LAB	PEMFC
D	DC compound	LIB	PEMFC
E	PMSM	LAB	None
F	PMSM	LIB	None
G	PMSM	LAB	PEMFC
H	PMSM	LIB	PEMFC

Modelled power plant configurations. LAB stands for cell mass and LIB for number of cells in parallel.

Model Overview and Design Procedure

The model input is a time-domain mission profile, as shown in figure 1, defining propulsion and auxiliary power demand respectively as a function of time. From the maximum propulsion power in the mission profile, the required propulsion motor dimensions are calculated using the method described in Stapersma et al. [3].
The propulsion motor requires a certain voltage to generate its maximum power. As this motor is powered by the batteries through a switchboard, this results in the minimum required number of batteries in series. The corresponding cell mass (LAB) or number of cells in parallel (LIB) is determined by a voyage simulation of the submerged part of the mission as described by Rietveld [1]. The simulation model uses the battery model developed by Stapersma [4]. This

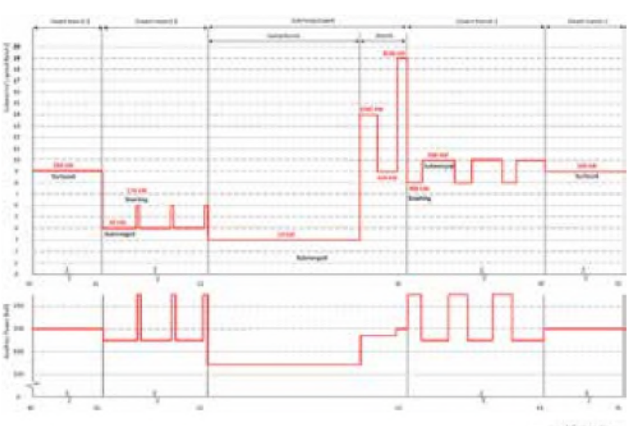

Figure 1. A time domain mission profile.

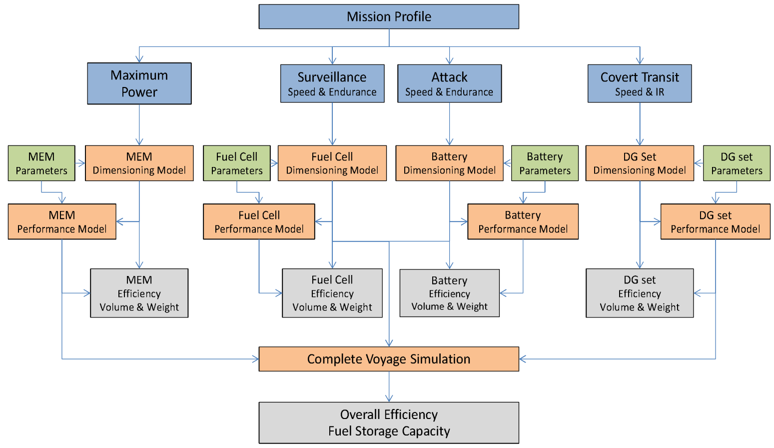

Figure 2. Overview of the design strategy.

results in the required battery dimensions and mass. The corresponding diesel generator power is calculated from the defined indiscretion ratio (IR) for the covert transit phase. The IR is defined as:

$$IR = \frac{T_{snort}}{T_{snort} + T_{submerged}}$$

Where T_{snort} is the snorting time and $T_{submerged}$ the submerged time during covert transit. The diesel generator set dimensions are determined with the method of Stapersma et al. [3]. For the concepts with an AIP system, the fuel cell is dimensioned for the required power in the surveillance phase, or as "range extender", while the batteries are dimensioned to supply power for the attack (as "power booster". An overview of the design strategy is given in figure 2.
Within this research, ten different mission profiles have been evaluated with this model: The surveillance time is varied between ten hours, three days, one, two or three weeks for a surveillance speed of three and five knots (the latter resulting in two different propulsion power demands). These mission profiles are chosen to be able to study the relation between surveillance time and speed and the optimal configuration. The model itself is generic and can be used to simulate other mission profiles as well.

Nomenclature

AIP	Air-Independent Propulsion
DC	Direct Current
DG set	Diesel Engine - Generator set
LAB	Lead-Acid Batteries
LIB	Lithium-Ion Batteries
MEM	Main Electric Motor (Propulsion Motor)
PMSM	Permanent Magnet Synchronuous Machine
PEMFC	Proton Exchange Membrane Fuel Cell

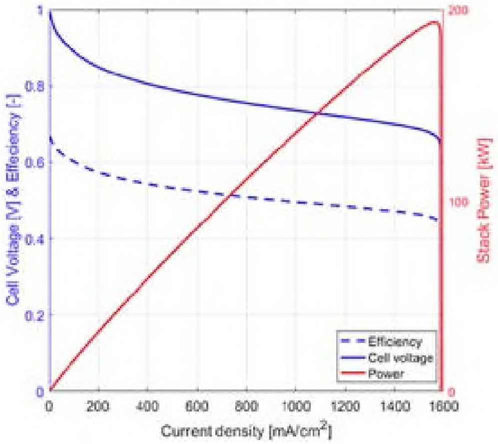

Figure 3. Polarisation curve of a single PEMFC.

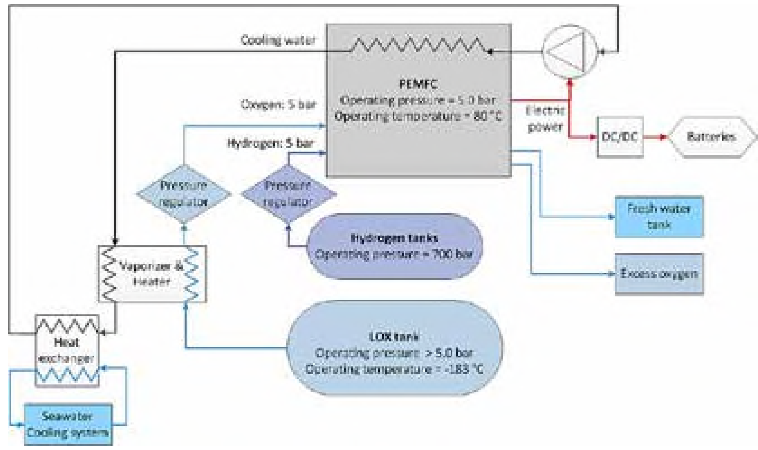

Figure 4. Overview of complete fuel cell system.

PEMFC as an AIP System

A PEMFC produces electrical power from hydrogen and oxygen based on the chemical reactions on the anode and cathode side:

- Anode: $2\ H_2 \rightarrow 4H^+ + 4e^-$
- Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

The potential between hydrogen and oxygen is dependent on temperature and pressure. In practice, each cell has a voltage potential of around 0.8 V. A fuel cell stack consists of several cells in series to produce a useful output voltage.

The fuel cell stack has to provide the required power for the submarine during the surveillance phase, when it sails submerged at a low speed for a long time. The stack is scaled for the required power by varying the number of cells in series and the cell active area.

The implemented PEMFC model is based on the polarisation curve shown in figure 3, which gives the relation between current density and voltage of a single fuel cell. From this figure, it can be seen that a fuel cell is more efficient in part load, which is the opposite trend of other, more conventional power suppliers. Therefore, in the selected concepts, a relatively large fuel cell stack is implemented: the design power is forty per cent of the maximum power. This results in a reduction in fuel consumption.

The PEMFC requires oxygen and hydrogen to operate. On board the submarine, the oxygen will be stored as liquid oxygen at -183°C and the hydrogen will be stored at room temperature at a pressure of 700 bars. Both are supplied to the fuel cell by a pressure regulator. The oxygen has to be preheated before it can enter the fuel cell, for which waste heat of the fuel cell is used. The remaining waste heat has to be transferred to the seawater. For this system, heat exchangers and a cooling water pump are required, as is shown in figure 4. To have a fair comparisor between the propulsion system concepts without an AIP system and those with an AIP system, the size and mass of the hydrogen and oxygen tanks and the auxiliary components are taken into account in the model as well.

PMSM as a Submarine Propulsion Motor

Based on a literature study, the PMSM seems a very promising concept for the submarine propulsion motor as it is said to be small, highly efficient and low in signatures. In order to see if a PMSM motor is actually more beneficial than the DC motor, this motor has been implemented in the model.

The PMSM model is based on a dynamic motor model, which can be found in electrical engineering literature [5], [6]. The model structure is illustrated in figure 5. The resulting efficiency curve of the PMSM motor is shown together with the efficiency curve of the modelled DC motor in figure 6. The steps in the graph are caused by the different electrical configurations for the different "speed modes" of the submarine.

Results

The simulations result in the minimum required volume and mass of all components for each power plant concept to fulfil a certain specified mission. Figure 7 shows the volume results for the studied mission profiles with a surveillance speed of three knots. The mission profiles with a surveillance time of two and three weeks are considered infeasible for the concepts with LABs without an AIP system due to sheer size of the LABs in these cases.

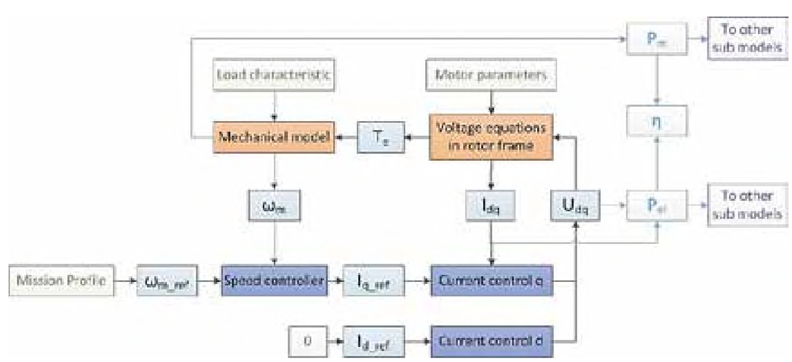

Figure 5. PMSM model structure.

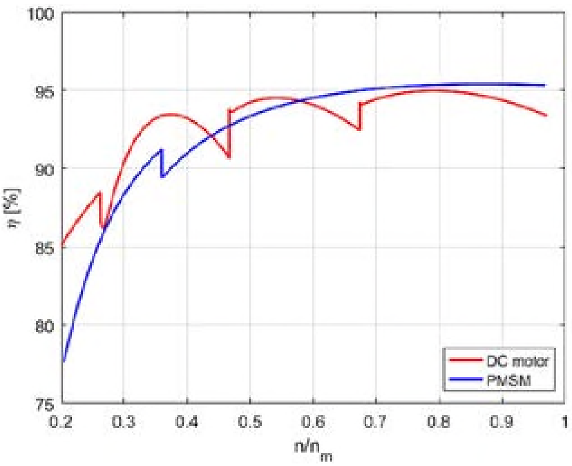

Figure 6. Modelled efficiency curve of the DC compound motor and the PMSM motor.

The results show that the fuel cell stack and its associated auxiliaries take only a very small amount of volume in the submarine. Additionally, the mass of this system is not significant. However, the storage of hydrogen and oxygen requires a lot of space. Therefore, it is beneficial for the overall system volume and weight to install a larger fuel cell stack for improved efficiency. Figure 7 shows that the hydrogen storage is the largest part of the overall volume. Despite the large space required for the hydrogen bottles, the AIP concepts still have the smallest volume to fulfil the missions, except for very short missions. From the investigated mission profiles, this is only the mission with a surveillance time of ten hours at three knots, where only lithium ion batteries (that is, no FC-based AIP system) are the smallest concept, although the volume is nearly equal. When comparing the DC compound motor with the PMSM, the DC motor is more beneficial in terms of volume, while the PMSM is preferred in terms of mass. From the perspective of efficiency, the DC motor seems to be more efficient at low speeds and the PMSM at high speeds, but the actual efficiency of the two different motors at low part load need to be researched further. Comparing the LIB to the LAB, the LIB is favourable on volume, mass and efficiency. The only (major) drawback of the LIBs is, that there is little experience with these batteries in submarine applications. Furthermore, the power and energy density of these batteries may in practice be smaller than assumed in this study, because of thermal runaway safety measures. Yet, it is expected that this effect will not negate the earlier statement and LIBs will remain the smaller, lighter and more efficient choice when compared to LABs.

For the overall system design, the main conclusion is: the longer the submerged time, the more is gained by using an AIP system. In almost all circumstances it is beneficial (from a volume and weight perspective) to combine AIP systems with "conventional" systems (diesel-electric with batteries). The design strategy to use the AIP system as a "submerged range extender" and the batteries as "power booster" is considered successful.

Mean Value First Principle Modelling Pays off

With respect to the evaluated mission profiles and system configurations, it is concluded that the optimal propulsion configuration in terms of mass is concept H (PMSM+LIB+PEMFC). If the submarine design is volume critical, concept D (DC+LIB+PEMFC) and H are the best options. From an efficiency perspective, concept B (DC+LIB) or D are the best choices if the DC compound motor indeed has a higher low part load efficiency than the PMSM.

With respect to the design methodology, the choice for mean value first principle modelling (for both dimension prediction and performance models) has paid off. This approach leads to versatile, flexible models that can cope with numerous system concepts and mission profiles. The fact that the mission profiles should be defined in the time-domain and the models subsequently simulate in the time-domain is considered necessary, positive and effective.

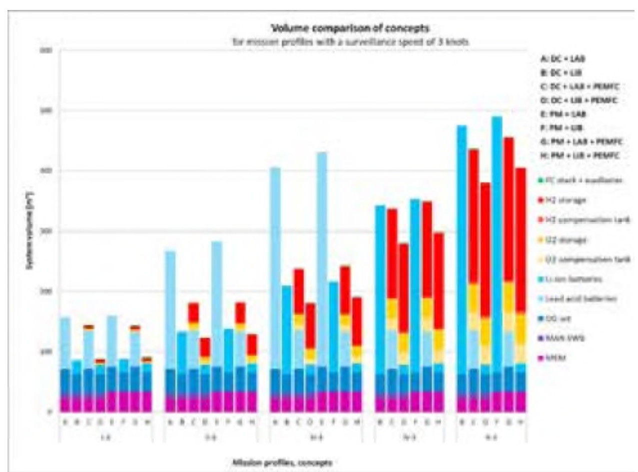

Figure 7. Example of results: Volume of components for all concepts for missions with three knots surveillance speed.

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