Modelling and control of a hybrid propulsion, ice-capable cargo ship

Yi Zhou*, **Kayvan Pazouki, Rose Norman**

Marine, Offshore and Subsea Technology Group, School of Engineering, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

*Email address: y.zhou28@newcastle.ac.uk

Abstract

One of the consequences of climate change is that the Northern Sea Route (NSR) has become a viable, economic option for cargo transportation between South East Asia and Europe, necessitating the development of new, ice-capable cargo vessels. Conventional diesel propulsion would be inefficient at the low speed, high torque operating points required for icebreaking, increasing emissions and exacerbating the impact on the sensitive arctic environment. Nuclear power has been utilised on icebreakers but would not generally be appropriate for commercial shipping and diesel-electric systems can suffer from poor partial load efficiency when icebreaking. Hybrid propulsion can address the latter issue by utilising battery storage technology to optimise the engine loading in a diesel-electric configuration. This paper presents detailed modelling of the hybrid energy and propulsion plant for an ice-capable vessel with low-level functional control of the system components and high-level load sharing control. The hybrid propulsion plant is compared with a standard diesel-electric system for both open water and icebreaking conditions, the hybrid system offering fuel savings of up to 40% over a typical operating cycle.

Keywords: Hybrid power system, Modelling, Simulation, Power management, NSR shipping.

1 Background

According to the National Aeronautics and Space Administration (NASA), since 1978, carbon pollution has caused a reduction of the Arctic Ocean's ice at a rate of 13% every decade [1].The decreasing of Arctic ice provides possibilities for shipping and offshore energy development. In the warmest months of the year, some routes that have been avoided because of the ice in past, have become increasingly accessible. Researchers have estimated that Arctic shipping could account for a quarter of cargo trade between Europe and Asia by 2030 with the distance of the Northern Sea Route (NSR) measured at 2100 compared to 2900 nautical miles for the shortest conventional route between Northeast Asia and Northern Europe [2]. In order to seize the opportunities, more ships with ice-breaking ability are in demand for Arctic shipping.

Direct diesel engine propulsion systems installed in ice-breaking capable ships suffer from significant drawbacks because of poor fuel efficiency and high emissions when sailing at low speed [3], therefore advanced technologies have been applied to the design of the propulsion systems suitable for icebreakers since the 1930s. The developed configurations are generally diesel electric or nuclear powered propulsion, however, drawbacks still exist in these systems. For diesel electric propulsion systems, poor fuel efficiency at low speeds is the major problem during icebreaking operations. For nuclear power, there are limitations such as high initial cost, management of nuclear waste and the fact that the required knowledge of nuclear technology has been acquired by only a few countries.

An alternative, more environmentally-friendly, economical and safe solution, is the use of hybrid systems consisting of diesel-electric propulsion with energy storage elements. The proposed hybrid propulsion system *Figure 1.2* differs from a conventional diesel-electric propulsion system *Figure 1.1*, because of the inclusion of the energy storage system. Due to the limitations of technology (battery size and capacity), energy storage systems are often used in hybrid propulsion to optimize the performance at high power demands. This addition provides tremendous benefits when compared with traditional diesel-electric propulsion for part load conditions, because the energy storage system can provide the required power, which allows one or two engines, that would otherwise be running inefficiently, to be switched off. Then energy storage system is recharged when the engine operates at a point with minimal specific fuel consumption (SFC), and hence low CO_2 and NO_x emissions [4], thus addressing the problem of poor fuel efficiency in diesel electrical system.

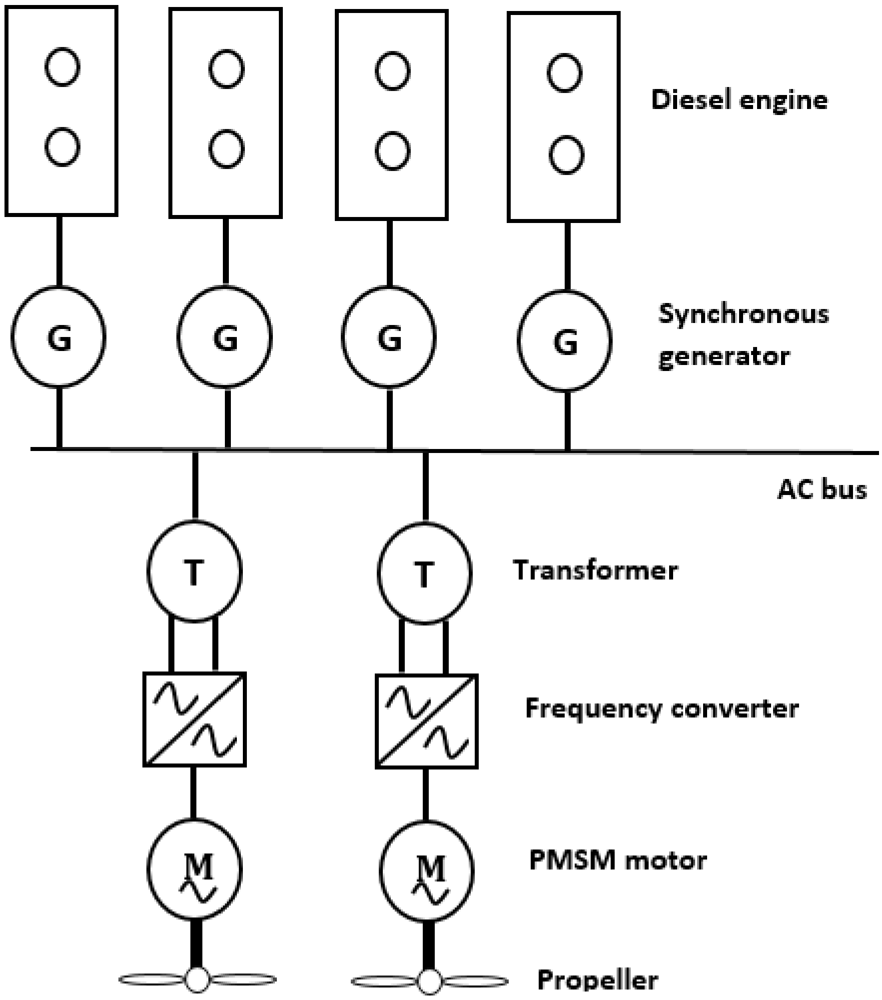

Figure 1.1. Typical diesel electric propulsion system layout

Challenges exist when hybrid propulsion systems are applied to vessels. Emissions such as CO_2 and NO_x are produced by the diesel engine prime mover, thus these air-emissions and the fuel consumption need to be minimised by rationally charging and recharging the energy storage system [3]. Moreover, an optimal control strategy is required to share the dynamic load caused between the prime mover and energy storage system to reduce the fuel and maintenance costs. In addition, a logical control strategy for the power converters is required to minimise the harmonics in variable speed drives, which means that in future research in dynamic load, battery will play a role to balance load ripples for its fast response speed. Thus, an appropriate algorithm and control strategy are necessary to achieve the above requirements.

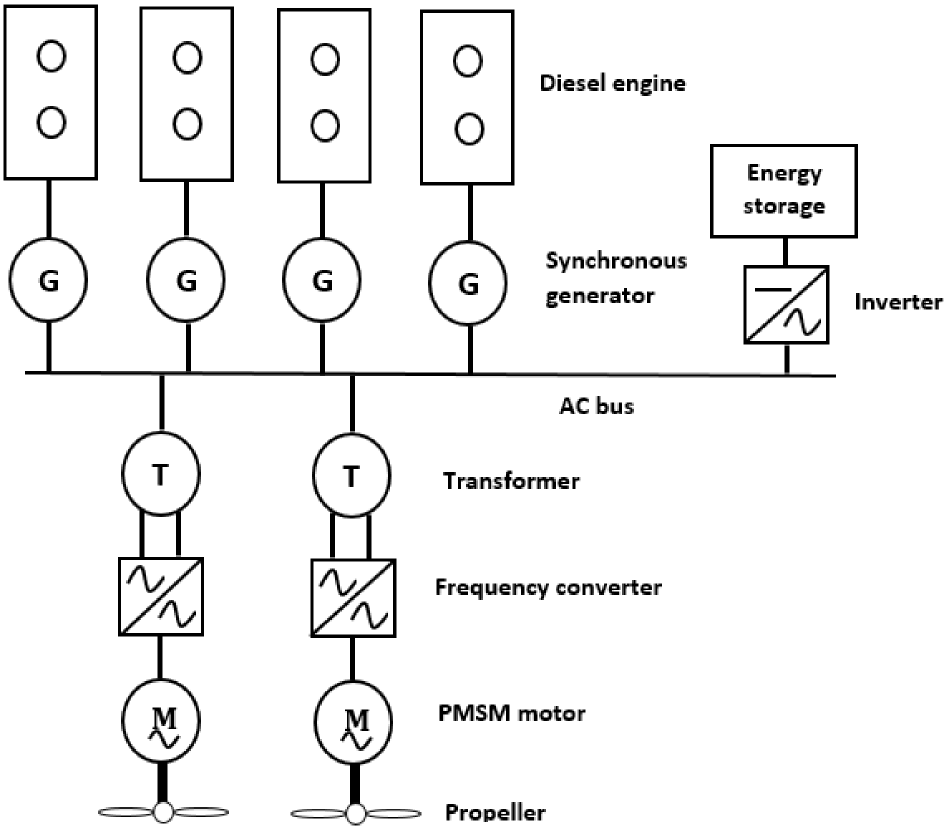

Figure 1.2. Electric propulsion with hybrid power supply

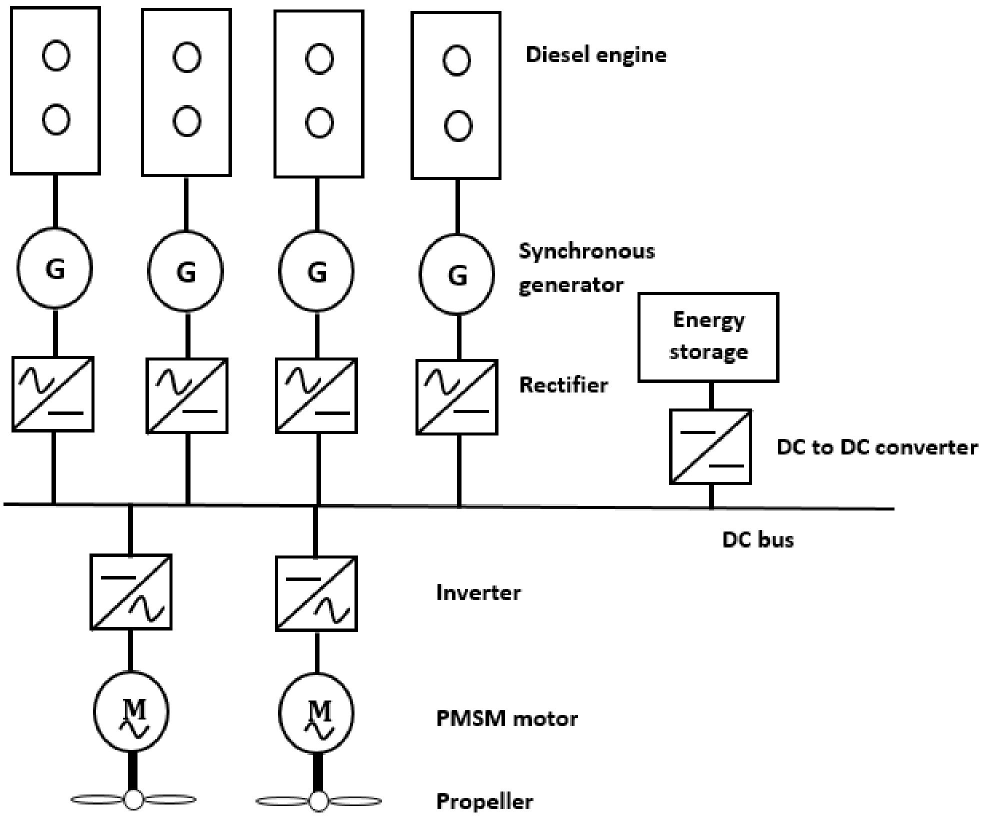

Figure 2.1. Typical DC hybrid power system

2 Model development

In this paper a DC hybrid system arrangement is considered as the propulsion system as shown in *Figure 2.1*, to benefit from reduction in fuel consumption, emissions and engine mechanical and thermal loading [3]. Generally, a typical hybrid power system consists of 4 major parts: motor drive system, diesel generator rectifier system, energy storage system and DC bus. The detailed modelling process and control strategies will be discussed in the following sections.

2.1 Permanent magnet synchronous motor model and control strategies

The permanent magnet synchronous motor (PMSM) is mathematically modelled in the d-q rotating reference frame [5]. A control strategy based on the d,q frame is required in order to achieve the necessary level of performance.

Field oriented control (FOC) of a PMSM is one of the efficient vector control methods [6]. *Figure 2.2* illustrates the scheme of speed regulation based on FOC. The speed of the motor can be regulated by controlling the d,q components of the stator current. Advantages such as fast response and minimal torque ripple can be obtained when this method is applied.

Generally, this technique is implemented using two current regulators (d-axis component and q-axis component) and one speed regulator. The i_d =0 method is applied for the purpose of acquiring the maximum ratio of torque to current for the PMSM, and the speed control can be achieved by regulating q axis current alone [5].

In an FOC control system, the inverter needs to draw power from a DC supply and Space Vector Pulse Width Modulation (SVPWM) is a commonly used technique to accomplish this operation. This method aims to utilize the concept of the space vector and its geometrical features to derive the on-off time durations for each switch, thus controlling the inverter to output the required reference voltage to drive the target motor.

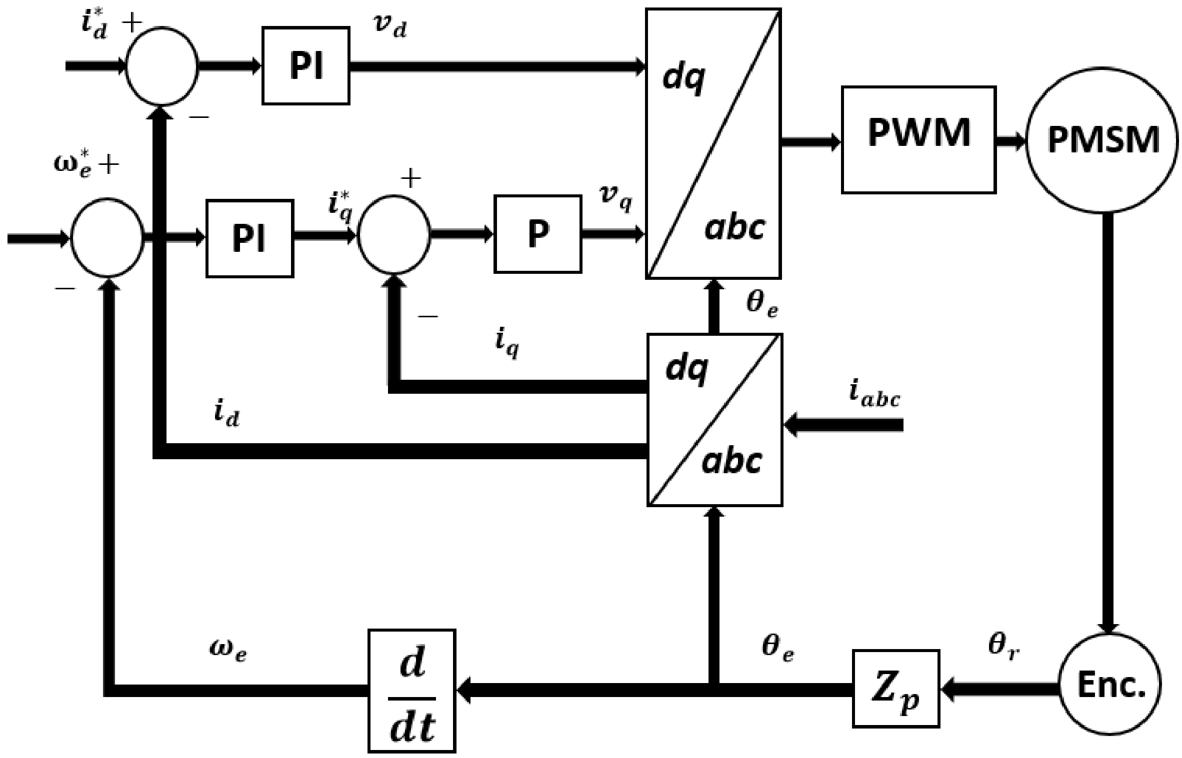

Figure 2.2. Speed Regulation Algorithm Based on FOC

2.2 Diesel-generator rectifier system modelling and control strategies

In this section, a diesel-generator rectifier system, which is shown in *Figure 2.3*, is modelled for a DC power system.

The mathematical model of a synchronous generator can also be obtained by transferring the abc-phase model to a dq-axis model using the Average-value technique [7]. An excitation system is required for the synchronous-generator-rectifier system in order to regulate the dc-link voltage. Here, a PID controller was implemented in the DC exciter system to adjust the DC bus voltage by controlling the error between demanded DC bus voltage and actual voltage.

The diesel engine model was made up of three parts: an actuator to convert the controller output to mechanical action, a delay block to demonstrate the time delay caused by actuator, combustion process, and thermodynamic process and a diesel engine governor was implemented to adjust the speed of the diesel engine; proportional integral derivative (PID) control is widely adopted in governor systems and hence was also utilised in this case. The parameters of controllers are tuned with the critical ratio method to obtain control performance according to system demand [8].

For the rectifier, the Average-Value Model (AVM) technique was applied to model the operation by establishing a relationship between the dc-link variables on one side and the ac variables transferred to a suitable reference frame on the other side [7]. Through this strategy, the inputs and outputs of the synchronous generator and rectifier can be related based on load current, which means that the AVM rectifier system is used to provide dq-axis voltage as inputs for the synchronous generator, and the synchronous generator provides dq-axis current for the AVM rectifier system.

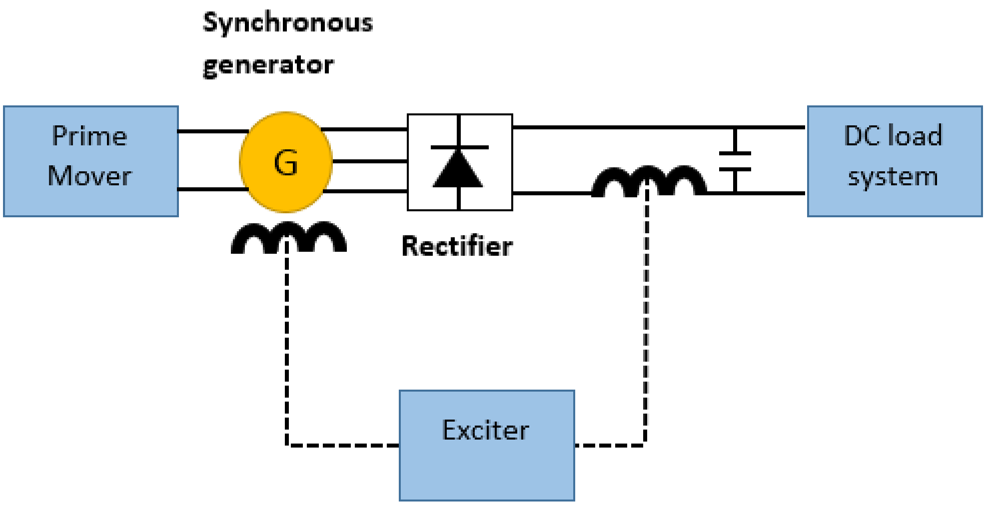

Figure 2.3. Typical DC power system

2.3 Energy storage system modelling

A Li-ion battery was selected for the system because of its high power density and good dynamic response. The mathematical model of a 150Ah Li-ion battery, which is commonly used in ship industry, can be built based on its generic model equations [9].

Discharge:

$$V_{batt} = E_0 - Ri - K\frac{Q}{Q-it}(it + i^*) + Aexp(-B \cdot it) \quad (1)$$

Charge:

$$V_{batt} = E_0 - Ri - K\frac{Q}{it-0.1Q}i^* - K\frac{Q}{Q-it}it + Aexp(-B \cdot it) \quad (2)$$

$V_{batt} = battery\ voltage\ (V)$
$E_0 = battery\ constant\ voltage\ (V)$
$K = polarisation\ constant\ (V/(Ah))$
$Q = battery\ capacity\ (Ah)$
$it = actual\ battery\ charge\ (Ah)$
$A = exponential\ zone\ amplitude\ (V)$
$B = exponential\ zone\ time\ constant\ inverse\ (\mathrm{Ah})^{-1}$
$R = internal\ resistance\ (\Omega)$
$i = battery\ current\ (A)$
$i^* = filtered\ current\ (A)$

The hybrid ship propulsion system then requires a bidirectional DC/DC converter to connect the DC main switchboard and the battery. A dual half-bridge converter topology with soft zero-voltage-switching (ZVS) was used for this purpose [10]. This technology is able to achieve efficiency up to 96% when operated with high switching frequency [11]. Soft-switching is accomplished by applying a capacitor connected in parallel and a diode connected in anti-parallel to the switching devices. The equivalent circuit is shown in *Figure 2.4*. In this system, three control variables are involved, which are switching frequency and the duty cycle, the phase angle shift between the AC voltages of the Low Voltage Side and High Voltage Side. By controlling any of these three parameters or all of them together, power flow can be controlled in either direction. In this paper, the duty cycle and switching frequency are set to constant values of 50% and 20000Hz, respectively. In order to regulate DC bus voltage, a PID controller was applied to generate the reference phase angle shift for transformer based on the error between the reference DC-link voltage and the actual voltage.

2.4 Hybrid power system control strategy

In this research, the control strategy for the hybrid power supply consists of three levels: primary control, secondary control and tertiary control [3], which is shown in *Figure 2.5*.

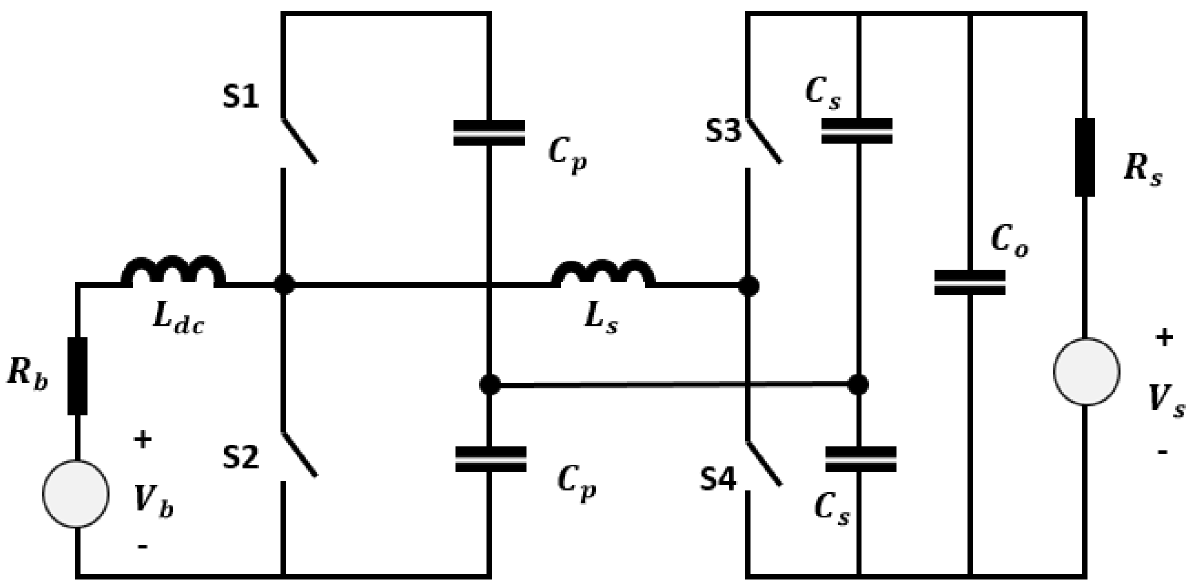

Figure 2.4. The equivalent circuit of soft-switched bi-directional half-bridge dc-dc converter

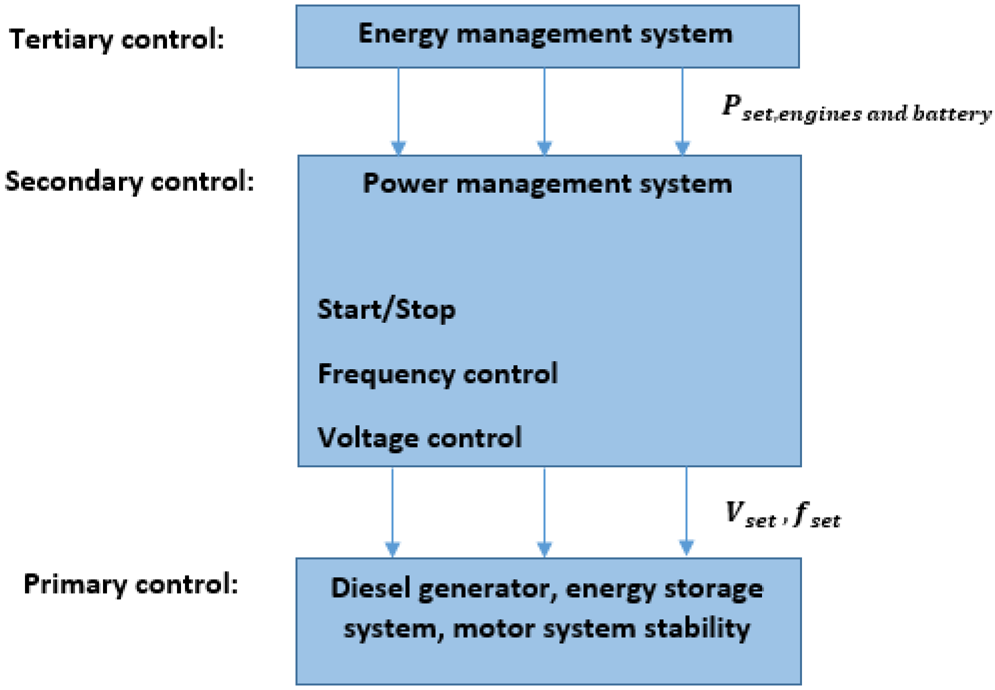

Figure 2.5. Hybrid power system control strategy

Firstly, the primary control aims to achieve voltage and frequency stability, as in the PID control strategy discussed in the previous sections. With this control strategy, components such as the diesel engine, generator, battery and motor will follow the reference set points to maintain the system stability.

Secondary control plays a role to balance demand and supply. The different power sources are controlled (engine start/stop, battery charging/discharging) to compensate the target load optimally. The set points for the reference voltage and frequency are calculated for primary control at this stage.

Tertiary control is an energy management system, where an equivalent consumption minimisation strategy is applied. The optimum power management set points are calculated with an optimal control problem formulation to minimise the fuel consumption of the engine and the equivalent fuel consumption of the battery (recharged), as well as different types of losses (generator, converter and rectifier).

In this paper, primary and secondary control strategies are applied in hybrid system. Tertiary control will be included in further research.

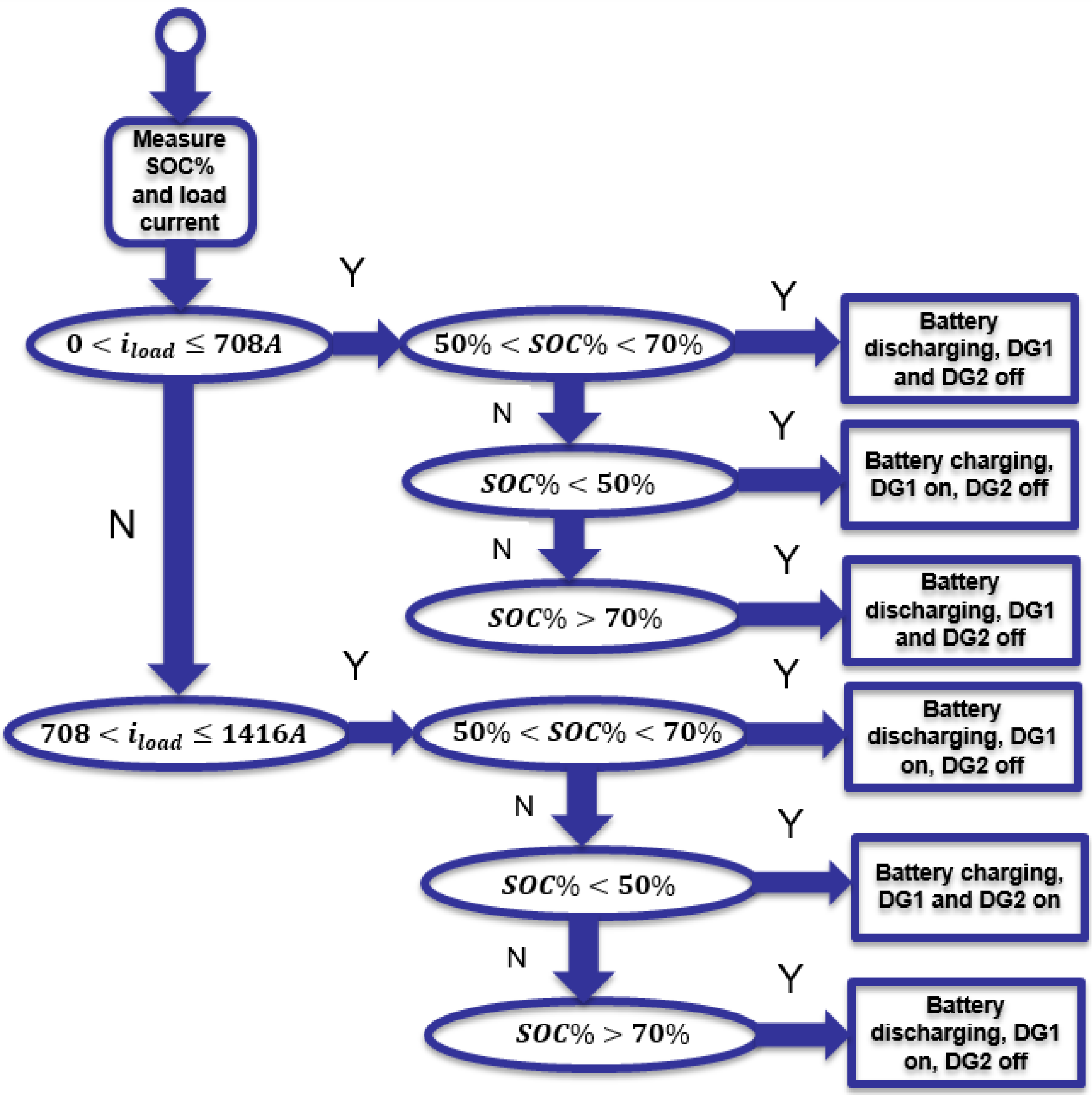

Figure 2.6. Flow chart of the load current control strategy for hybrid propulsion

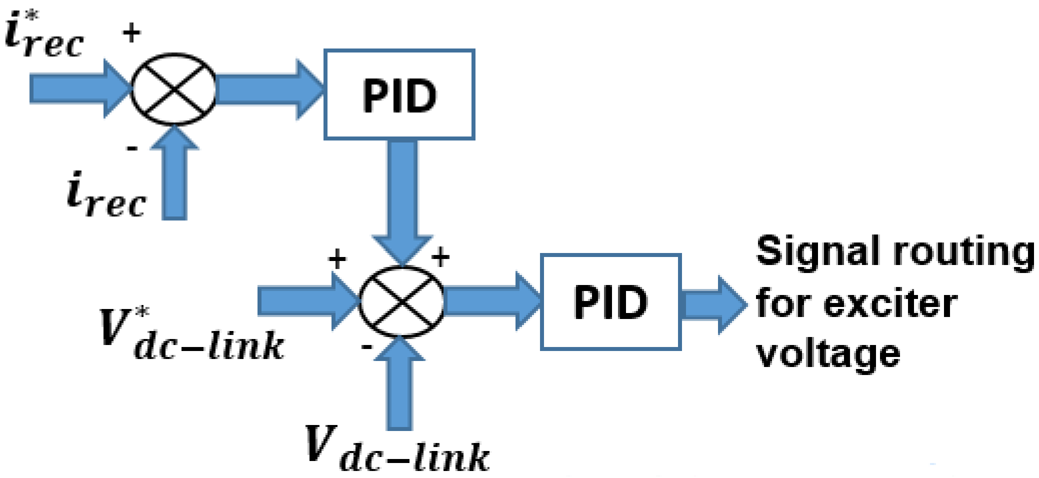

Figure 2.7. Secondary controller

Figure 2.6 shows the flow chart of the load current control strategy. This control strategy is based on the load current i_{load} and battery State of Charge (SOC)% with logical control applied to command start/stop of the diesel engine (DG), charging/discharging of the battery. To prevent the battery from aging rapidly, the SOC% is limited to be within the range of 50% to 70%. In addition, the target diesel engine (Bergen B32:40V diesel engine) is controlled to always run at the optimal SFC point (the DC-source power is set to a constant value of 5242kW) with rectifier system efficiency analysis applied. A secondary control compensator in the exciter control systems is used, which is shown in *Figure 2.7*, to regulate the rectifier output current. As the output of the diesel generator-rectifier system is constant, the energy storage system (ESS) is applied to control the DC-link voltage through charging/discharging of the battery.

3 Model conditions

This model was evaluated under the conditions below:

Difference between water and ice density: $\rho_{\Delta} = 125kg/m^3$ (Sea water density $1025kg/m^3$, sea ice density $900kg/m^3$)

Ice bending strength: $\sigma_f = 500kPa$

Hull/ice friction: $\mu = 0.15$

3.1 Ship parameters and load estimation

An existing ship model ENVIK was used to calculate ship resistance in ice with its basic parameters [12], which is shown in *Table 3.1*:

Table 3.1: *Ship parameters*

Ship	ENVIK
Waterline entrance angle α	29°
Stern angle ϕ	39°
Length of the bow part of ship at waterline L_{bow}	25.6m
Length of parallel mid body of the ship at the waterline L_{par}	38m
Length between perpendiculars L_{pp}	96m
Beam of ship B	16.2m
Ship draught T	5.2m
Ship power P_s	2.74MW
Ship displacement Δ	5583t

When a ship is driven in ice conditions, ice resistance R_i can be determined according to ice thickness and condition, and open water resistance is eliminated as its effect is very small when compared with ice resistance [12]. For ship with relatively slow speed and high block coefficient, viscous resistance contributes approximately 85% of the total resistance [13]. Thus the open water resistance can be estimated from the proportion.

3.2 Propeller parameters and model

A propeller fitted in Canada R-Class icebreaker ship was selected. The full-scale characteristics of this propeller are shown in *Table 3.2* [14]:

*Table 3.2**:** the full-scale characteristics of modelled propeller*

Basic parameters of propeller	Data
Diameter, m	4.12
Number of blades	4
Design pitch/diameter ratio	0.779
Expanded area ratio	0.670
Depth of cut/diameter ratio	0.125

Once the ship resistance and propeller parameters has been determined, ship propeller load can be calculated through ship-propeller mathematical model [14].

3.3 Diesel generator rectifier system efficiency analysis

Losses in the diesel generator rectifier system are made up of four major parts: copper loss, core loss, mechanical loss and rectifier loss. Target diesel engine (Bergen B32:40V diesel engine) is controlled to always run at the optimal Specific fuel consumption point (6800kW, 750rpm at 85% load) during current simulation process. Where $P_{DC-source}$ is the rectifier output power without considering loss in generator rectifier system, and $P_{DC-source,actual}$ is the rectifier output power when the losses are considered. In this paper these losses are related together to calculate the efficiency of whole diesel generator rectifier system, which is shown in *Table 3.3* [4].

Table 3.3: Diesel generator-rectifier system efficiency analysis chart

Engine power (kW)	2000	4000	6000	6800	8000
$P_{loss,copper}$ (kW)	58.9	171	338	417	552
$P_{loss,core}$ (kW)	202	224	244	252	261
$P_{loss,mechanical}$ (kW)	4.9	4.9	4.9	4.9	4.9
$P_{loss,rec}$ (kW)	0.826	1.966	3.398	4.026	5.06
$P_{DC-source}$ (kW)	1887	3626	5291	5920	6867
$P_{DC-source,actual}$ (kW)	1620	3224	4701	5242	6044
η(%)	85.85	88.91	88.85	88.55	88.02
SFC (g/kWh)	215	188.6	182.5	182	184

4 Simulation results

The components of the hybrid propulsion system have been modelled in Simulink and the control strategies implemented. In addition, a model was also developed of the equivalent, conventional diesel electric propulsion system. A load change with the vessel moving from open water to 0.5m thick ice 300s after the start of the simulation, was applied to test the whole system performance. At current stage, only stable ice load is considered to test average system performance. In real ice milling process, high impact load is involved, how the dynamic load shared by power sources will be researched in future. The results of the hybrid system are shown in *Figure 4.1* and those of the conventional diesel electrical propulsion system are shown in *Figure 4.2* for comparison.

As shown in *Figure 4.1*, for the hybrid propulsion system, the load current increased to maintain the ship speed due to the rising load in ice conditions. Output current of the diesel generator rectifier system was kept at a constant value to ensure that the diesel engines always ran at the optimum SFC point. The DC bus voltage is kept stable as 7400V by supplying enough power to balance load to achieve system stability. Battery SOC% is controlled in the range of 50% to 70% by charging and discharging the battery to meet the load demand whilst the output of diesel engines is controlled to be constant. With the same loading conditions, the fuel consumption results of the hybrid system and the diesel electric system may be compared. In order for the starting and final SOC% to be same, the fuel consumption is compared at 506.25s.where at this point, the results of fuel consumption for the hybrid system and the diesel electrical system are 128.0kg and 212.5kg, respectively, which shows that the hybrid system achieve a 39.8% fuel consumption reduction during this period of time.

5 Conclusion and future work

The subsystems and control strategy for a hybrid propulsion system have been modelled in software. Simulation results for a short target journey have shown an initial 39.8% fuel consumption reduction when compared with a conventional diesel electric propulsion system.

The current work has limitations in that only the engine SFC chart is considered to decide the optimal engine operation points. Due to power losses in the energy storage system, the optimal operation will not necessarily be achieved by keeping the engine operating point at the minimum SFC point. A compromise needs to be considered between the minimum engine SFC, the efficiency of the DC to DC converter, and the duty cycle of the energy storage system. Moreover, only average load is used to test the system stability, in real ice milling process, high impact load is included. In the future, robustness and sensitivity analysis will be conducted to test the system performance in dynamic load. And a tertiary control strategy will be implemented that will consider the overall efficiency in an optimal control problem formulation. Moreover, at this stage only open water load and stable ice load have been considered but other ship operation modes (such as dynamic positioning, zero-emission mode in harbor and an open water voyage on the NSR) need to be analyzed and modelled so that the control strategy can be improved to ensure that the system can always achieve the optimal operation conditions.

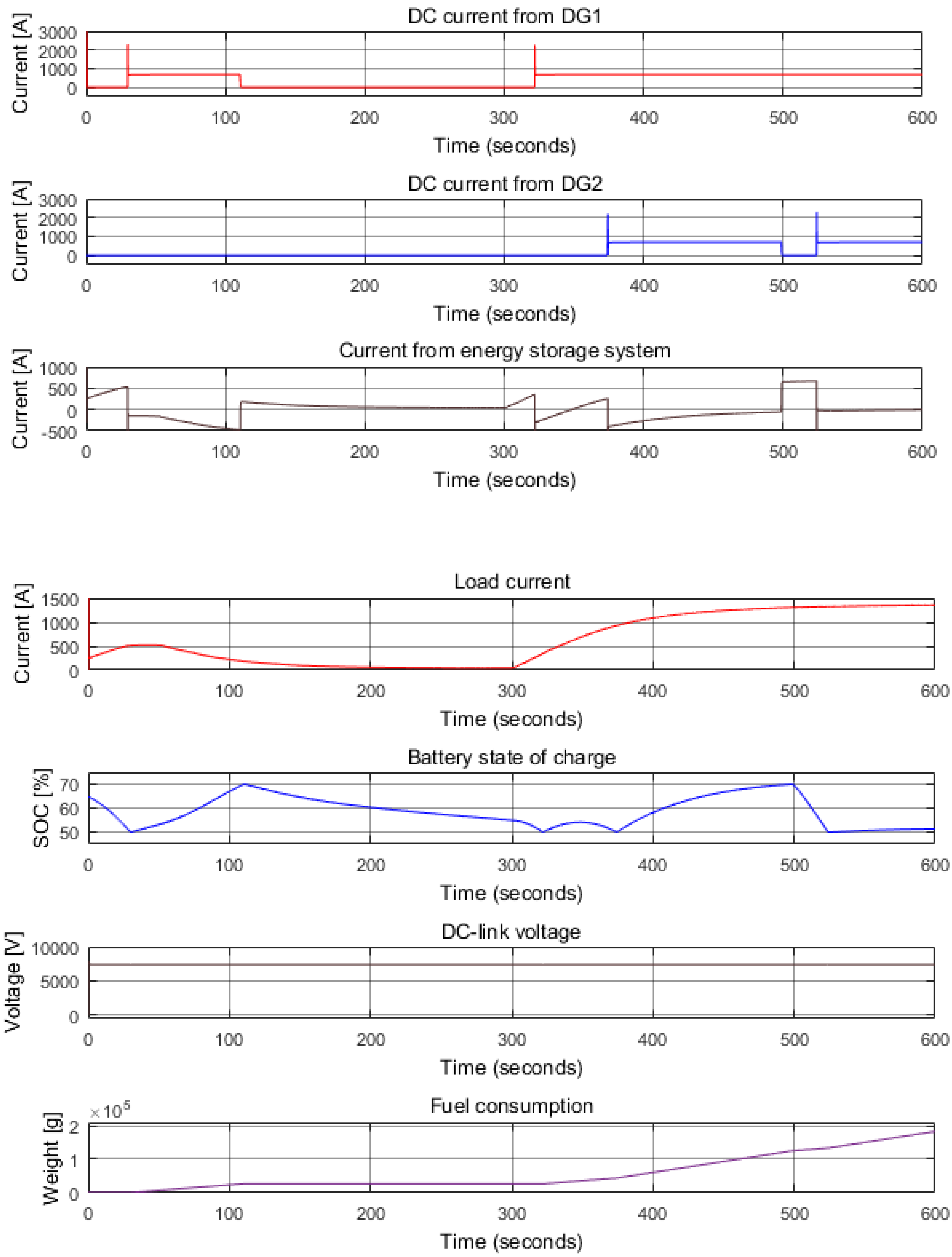

Figure 4.1: Simulation results of hybrid propulsion system

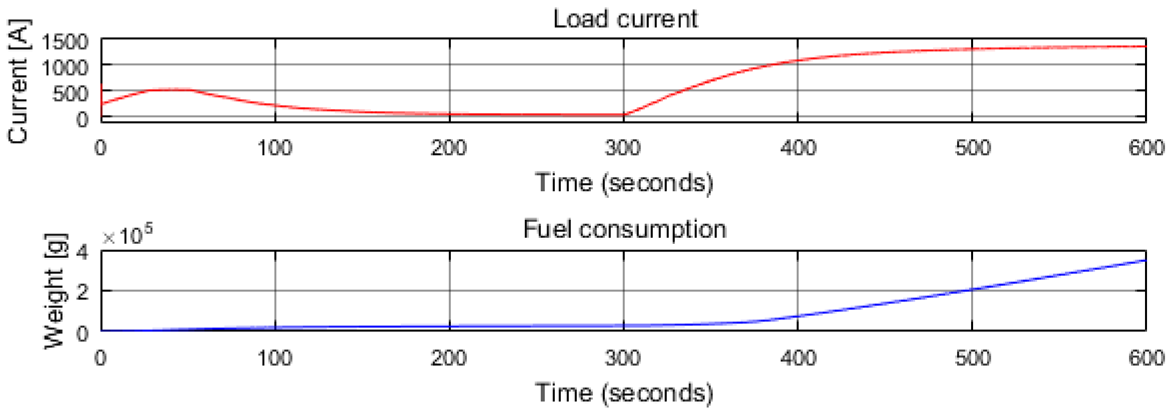

Figure 4.2: Simulation results of diesel electrical propulsion system

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