Hybrid marine electric propulsion system

With super-capacitors energy storage

JESSIE WENJIE CHEN, JOHN OLAV LINDTJØRN, FRANK WENDT – In order to reduce the effects of system load fluctuations on the power plant, a hybrid converter based on super-capacitors is considered for fast-acting energy storage for marine vessels. The super-capacitors work as energy buffers, reducing the load variations as seen by the system generators, thereby improving system stability and under certain conditions allowing for a more fuel-efficient operation of available diesel gensets.

The use of electric propulsion in certain vessel types is well-known. In marine applications, nearly all the energy is produced by diesel engines. Using an electric propulsion system, where the energy transmission is electrical and the propulsion and thruster are variable speed electrically driven, fuel consumption can be reduced significantly for many vessel types with environmental benefits. But in some special working conditions, such as dynamic positioning (DP) operation, the load varies substantially, for instance with wave disturbance and weather influence. The sudden load variation is a continuous disturbance of the electric system and the prime movers. Furthermore, to keep to the safety margins of the power generation plants, the average loading of running engines has to be reduced, which increases fuel consumption and environmental emissions.

Nomenclature

DP: Dynamic positioning

SC: Super-capacitor

OSV: Offshore support vessels (general term for a range of vessel types for offshore operation)

DCU: Drive control unit

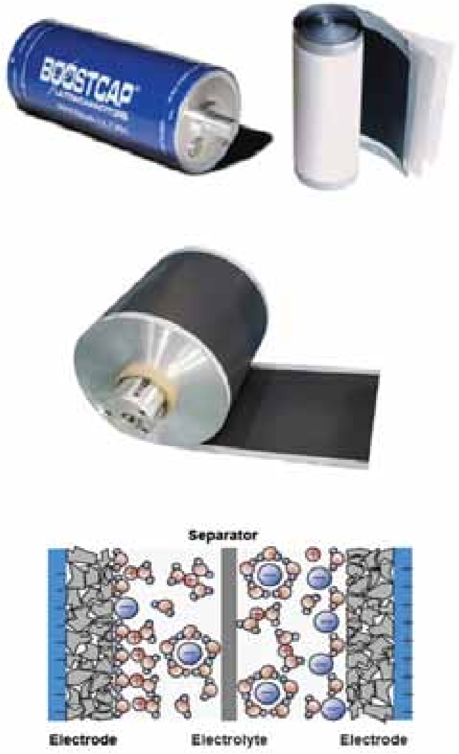
PMS: Power management system

MCR: Max continuous rating

ECR: Engine control room

1 **Propulsion and control system layout for a DC grid vessel**

2 **Structure and outlook of the super-capacitors by Maxell**



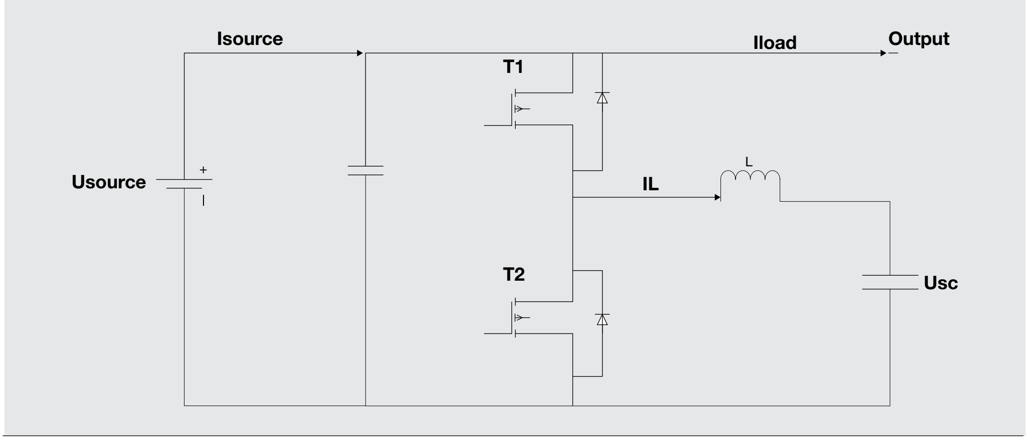
Fast-acting energy storage systems can solve these problems by effectively reducing load power fluctuations in a power system, due to their energy storage capacity. This will smooth sudden changes in power demand, improve the system's stability and possibly increase the average loading with fewer running engines and thus reduce fuel consumption and maintenance. Super-capacitor technology is one among other solutions, such as batteries, flywheels or possibly in the future superconductors. In this paper, an offshore support vessel (OSV) is chosen as the target vessel. A hybrid converter incorporating super-capacitors will be modeled and simulated in Matlab/Simulink simulation environment.

An OSV with electric propulsion is equipped with an electric power plant with variable speed drives to control the main propulsion and thrusters. ABB recently released the Onboard DC Grid solution. It adds to the full freedom for integrating and combining different engery sources, including renewables, gas and diesel, and a greater flexibility in placing system components in the vessel design. The main electric propulsion system topology for DC Grid system is shown in Figure 1. The super-capacitor can be used both in AC and DC Grid system to realise the energy storage function and increase the efficiency up to 20 percent.

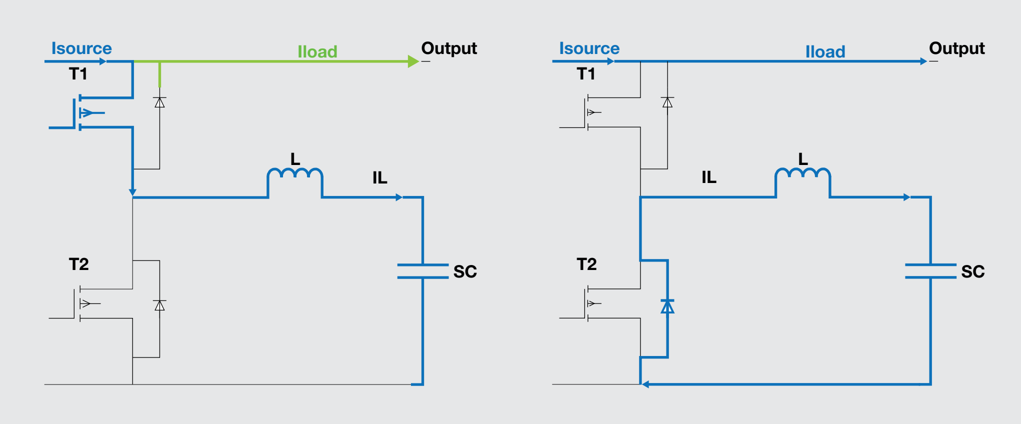
Super-capacitors technology is a new type of energy storage device used increasingly in industry and automotive applications, such as cars, buses and high-speed trains. Unlike conventional capacitors, super-capacitors have a larger area for storing the charge and closer distance between the electrodes, which is why they achieve much greater capacitance within the same volume.

Compared with the batteries, super-capacitors have several advantages: super-capacitors can be charged extremely quickly, while many battery technologies are damaged by fast charging; super-capacitors can be cycled several hundred thousands of times whereas batteries are capable of only a few hundred cycles. They can deliver frequent pulses of energy without any detrimental effects while batteries experience reduced life-time if exposed to frequent huge power pulses. Super-capacitors can also be charged to any voltage within their voltage rating while batteries operate within a narrow voltage range. On the other hand, batteries can store much more energy than the same size of super-capacitors.

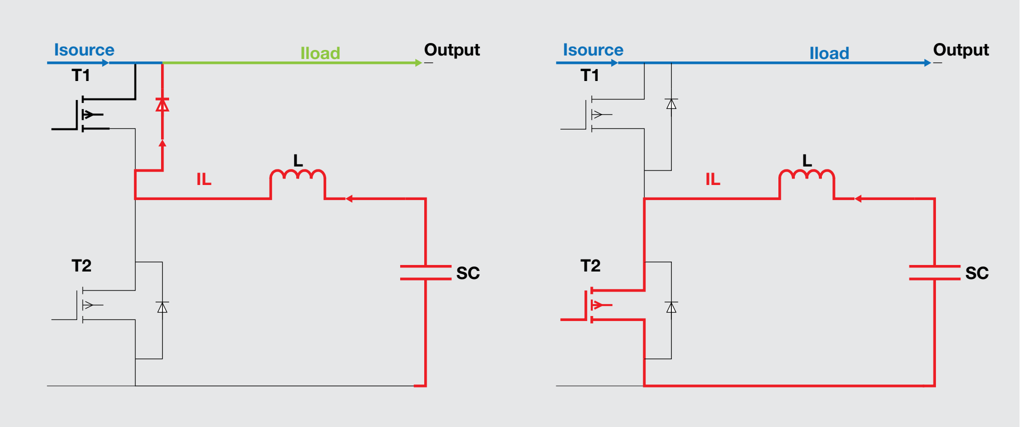
3 Basic structure of super-capacitor system



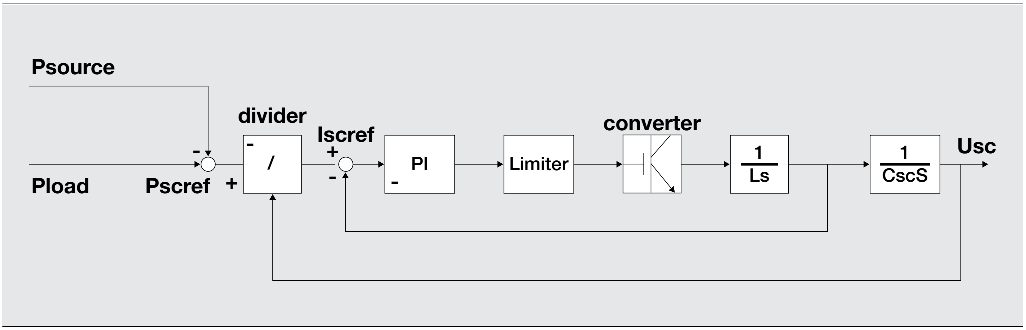
4 Buck converter mode



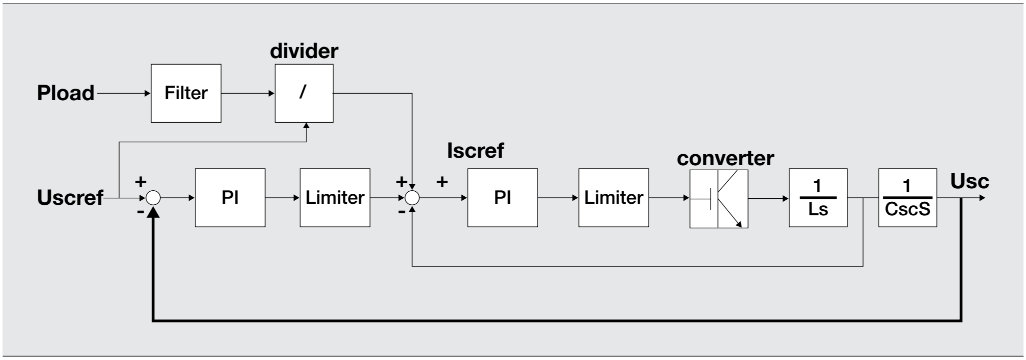
5 Boost converter mode



6 Power control method



7 Improved power control method



Super-capacitors have a high power density, long lifetime, high efficiency, and low cost device, but their energy density is still limited.

Figure 2 shows the basic structure of super-capacitors, whose electrode film consists of the highly porous carbon particles that are compacted and bounded together into a matrix and in electrical contact with aluminum foil.

Design for DC-DC converter

The most typical structure for controlling the power flow for a super-capacitor is shown in Figure 3.

The DC-DC converter that controls the energy flow to the super-capacitor is connected directly to the DC bus of the frequency converters. This configuration permits its power transfer in both directions. The DC-DC converter is a combination of a buck and a boost converter. This converter operates in buck mode while charging the super-capacitor and in boost mode while discharging it. The direction and value of the super-capacitor current is controlled by the duty cycle D of the semiconductor bridge.

Buck mode

In buck mode, which works as in Figure 4, energy flows from the network to the super-capacitor. The super-capacitor is charged.

$$\frac{U_{sc}}{U_{source}} = D_1$$

D1 is the duty cycle of the buck mode.

Boost mode

In boost mode, as shown in Figure 5, the energy flows from the super-capacitor to the network. Super-capacitor discharges to release energy.

$$\frac{U_{source}}{U_{sc}} = \frac{1}{1 - D_2}$$

D2 is the duty cycle of the buck mode.

It is clear that here D1=1-D2. The controlled trigger signal for T1 and T2 will always be opposite each other.

$$\frac{U_{sc}}{U_{source}} = D_1 = D$$

Design for control method

There are several classical control methods, such as traction control strategy, current flow control, fuzzy logic control and power flow control. Here the power flow control is chosen as it is more practical to implement in both control and simulation systems, compared with traction control and fuzzy logic control and it is more accurate than current flow control.

The power flow control method

The power flow of the system follows the energy conservation law. The power value of the source, the load and the super-capacitor can be represented as in the following equation.

$$P_{source} = P_{load} + P_{sc}$$

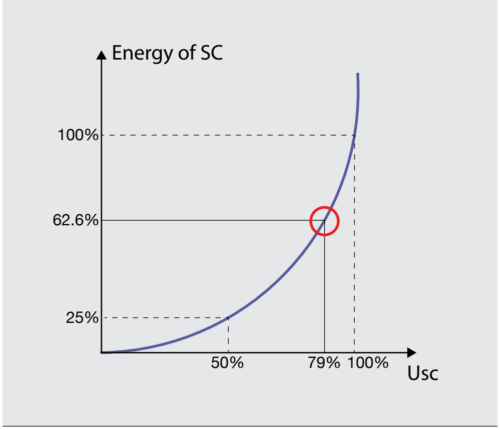
The sum of the super-capacitor power and the load power should be equal to the power drawn from the source. The reference super-capacitor current can be calculated as super-capacitor power divided by the super-capacitor voltage. Figure 6 shows the control flow chart.

There are several problems coming from this control diagram. First, it is a single closed loop control with one PI controller. super-capacitor current is the control variable, while super-capacitor voltage will not be regulated and may drift. Second, Usc that is used as a variable to calculate the current reference is a measurement with high noise level that will prompt disturbances in the regulator.

The improved average power control method

The voltage of the super-capacitor is a crucial variable and relates directly to how much energy the super capacitor cell stores. To ensure that the power supply system is under control and prevent the super-capacitor voltage from drifting excessively causing it to be over or undercharged, Usc must be regulated. An improved average power control method is therefore designed.

8 Reference voltage value setting



The control flow chart is shown as Figure 7. Compared with the traditional power flow control, the improved average power control method will regulate the average super-capacitor voltage.

In order to regulate the working voltage to be in the range of the rated value, a voltage balancing circuit is used as the outer loop in this case. Super-capacitor releases 75 percent of its energy when the voltage reduces to 50 percent. The energy ranks from 25 percent to 100 percent, as shown in this equation.

$$Q = \frac{1}{2} \cdot C_{sc} U_{sc}^2$$

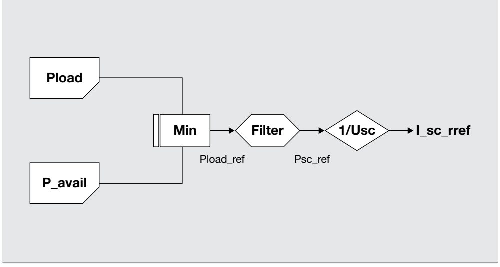
If the level of 62,5 percent is assumed as the normal value of the energy storage, the average voltage of the super-capacitor should be kept close to 79 percent. So here 79 percent is chosen as the setting point value of the super-capacitor voltage, as shown in Figure 8.

A double-closed loop control method is designed. The outer loop controls the average voltage while the inner loop is the current control loop that controls the instantaneous power flow. The two PI controllers must be tuned in a way that the inner loop will be capable to fulfill the instantaneous power control requirements while the outer loop avoids drifting of the voltage to over or under voltage.

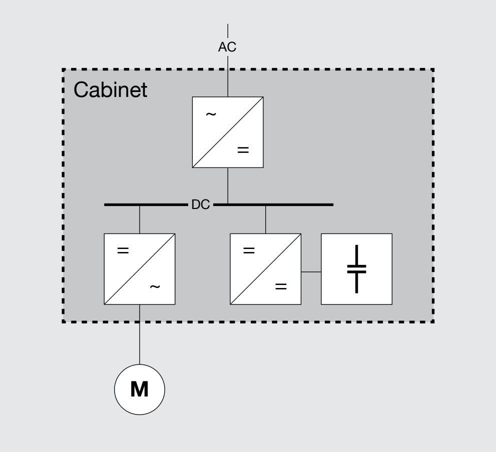
Modifications design for DCU system

Drive control unit (DCU) is the ABB application control system/product for a thruster drive. The main purpose

9 Rules of new DCU system



10 Topology of VFD with SC



is RPM control based on references received from the DP control system or the speed levers from the bridge/engine control room (ECR). The original DCU could not give attention to both the variation of the load and the super-capacitor. Modifications have been designed specifically for the super-capacitors electric converter to ensure that the average load power consumption is not higher than the available power from the online generators. The power available signal would normally be received from a power management system.

Figure 9 shows the basic principle of the supplementary function of the DCU. The power of the load demand should not be higher than the source capacity. Pavail is the capacity of the plant.

This DCU modification helps the system to:

- Regulate the controlled signal to the load according to the capability of the source
- Regulate the power delivery of the super-capacitor, and prevent it from overloading

Modeling and simulation

The structure of the electric propulsion system with a DC distribution and super-capacitor is shown in Figure 10.

Introduction of super-capacitors as energy storage will not imply major changes of the original frequency converter hardware layout. The super-capacitor converter is connected between the rectifier and the inverter, directly on the existing DC bus.

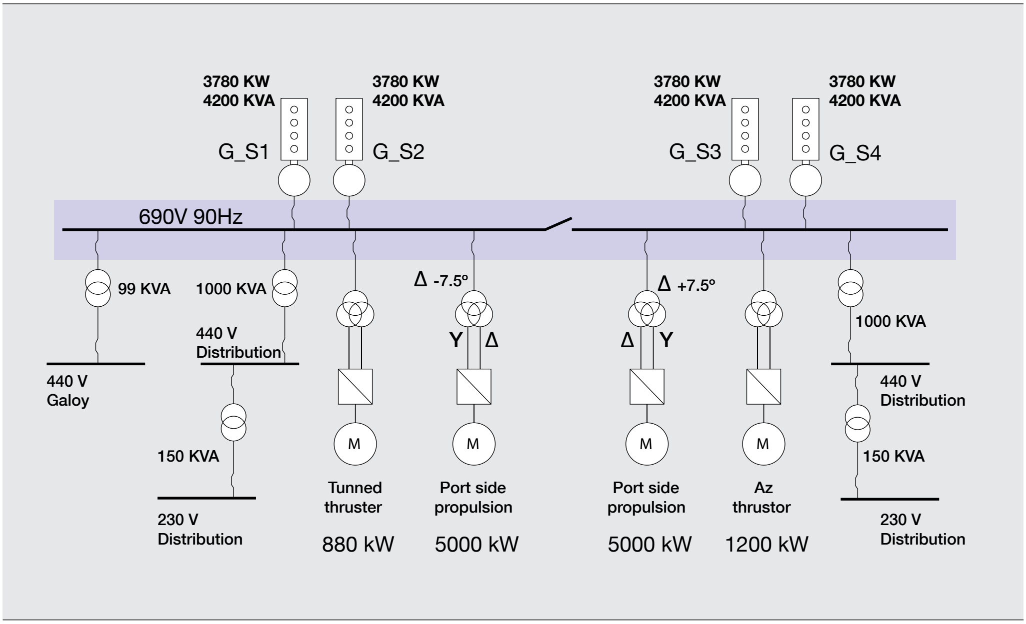
In Figure 11, the OSV chosen as the target vessel is shown to be equipped with electric propulsion, where the main propulsors and station keeping thruster are driven by variable speed electric motor drives, supplied from the common ship electric power plant with constant frequency and voltage.

Model establishment

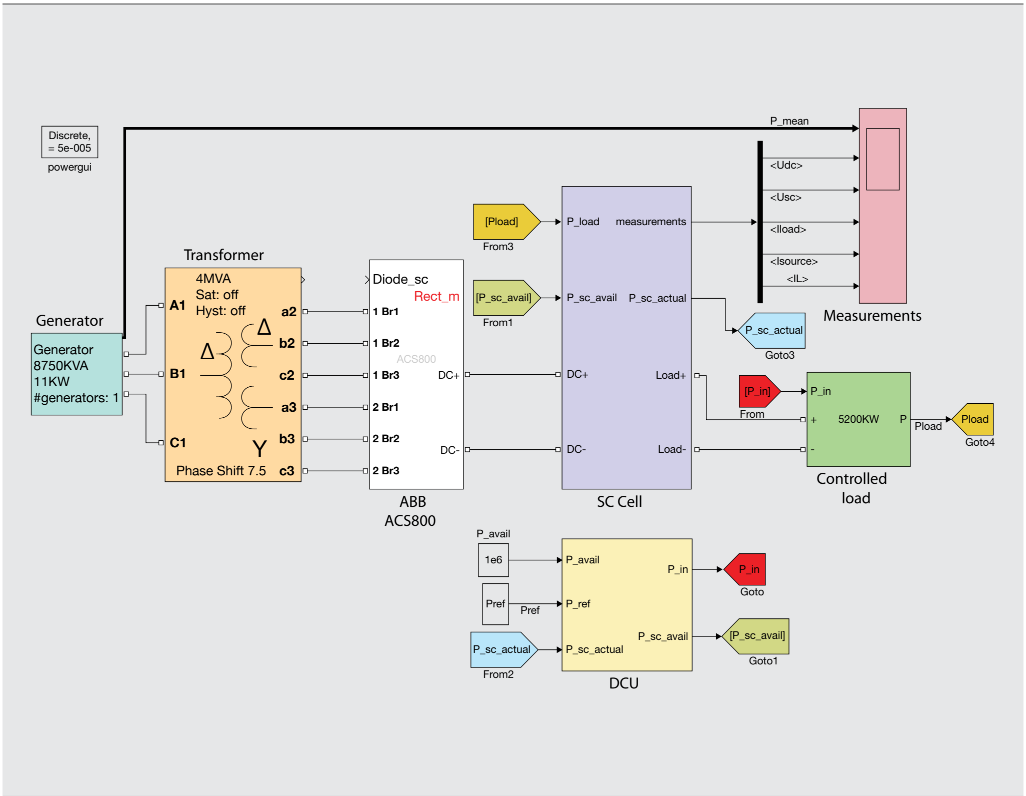
The system was modeled in MATLAB/Simulink environment using the ABB library. A typical thruster system was constructed as shown in Figure 12.

The electric propulsion system consists of a generator, transformer, rectifier (ACS800) and a controlled load. To simplify the simulation models, different types of loads such as inverter, motor, and pumps are be modeled as a controlled current sources. The super-capacitor block consists of two parts: DC-DC converter and control loop part.

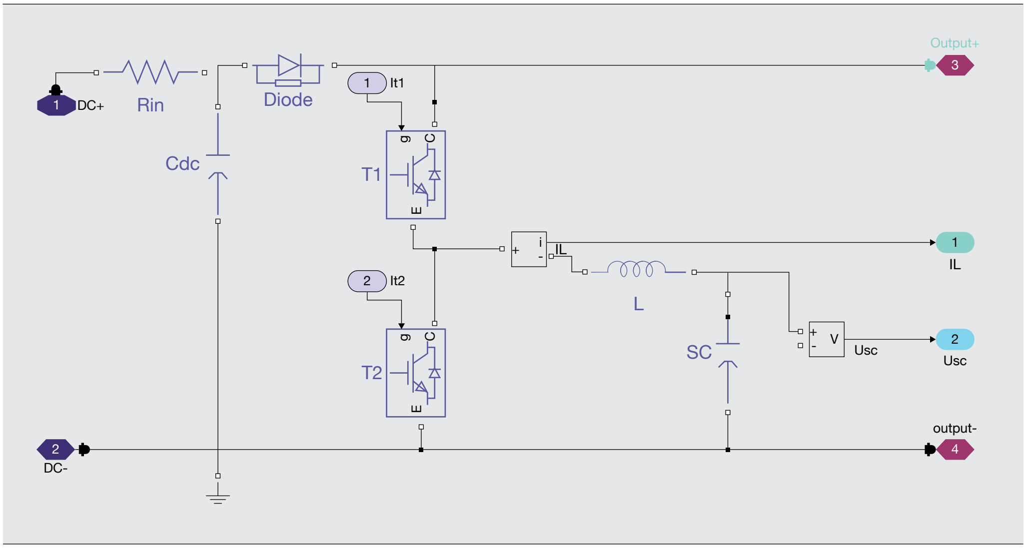
11 Configuration for diesel electrical OSV



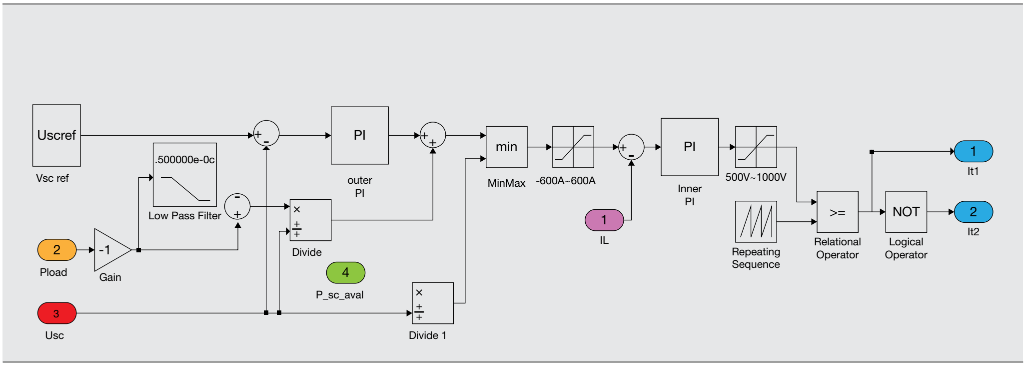
12 Electric propulsion system modeling



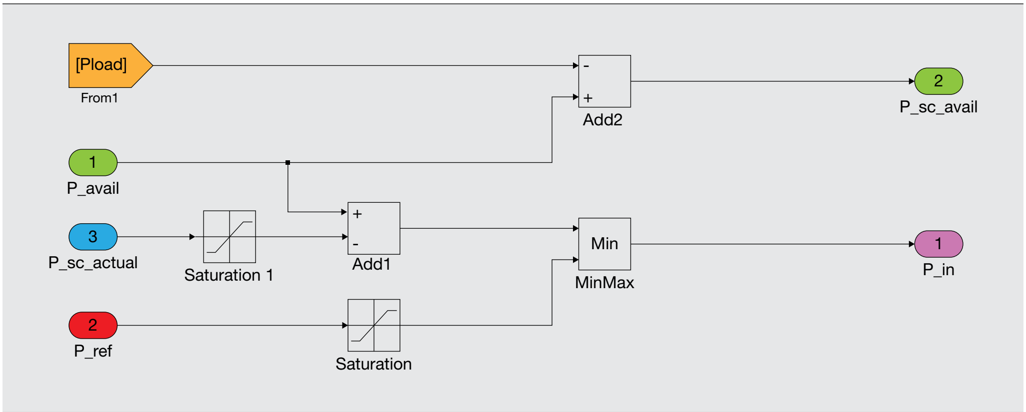
13 Super-capacitor DC-DC converter model



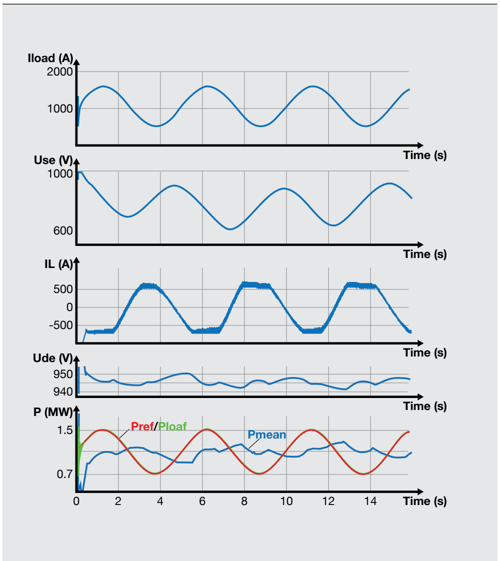
14 Improved control method block



15 Power available control block in Simulink



16 Simulation results (1)



A current and voltage limiter is added to the controlled block, as shown in Figure 14, to protect the system from overloading. Two PI controllers have to be tuned during the simulation. Figure 15 shows the power available control model in Matlab.

Results analysis

For this analysis the dynamic load variation for the thruster was assumed to be from 0.5 MW to 1.5 MW with a period of 5s.

Case one

The thruster system is not limited by the power available signal from the PMS.

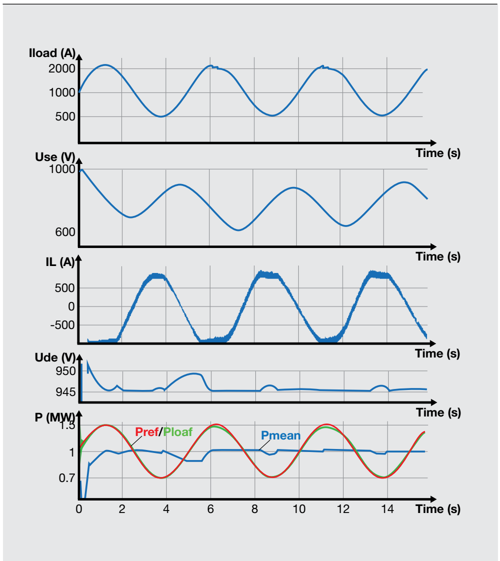
The simulation results in Figure 16 show that during low load conditions the super-capacitor is charged, super-capacitor voltage rises and the current to the super-capacitors is positive. When the load increases, the super-capacitor is subsequently discharged; the super-capacitor current becomes negative and the voltage decreases.

The voltage stabiliser and power limitation functionality works as expected. This control method also reduces the load disturbances of the power plant.

Case two

The thruster system is limited by power avialable signal from PMS at Pavail = 1 MW.

17 Simulation results (2)



As shown in Figure 17, the power drawn from the network remains almost constant at 1 MW, even with the varying thruster load. The thruster, on the other hand, operates virtually unimpeded by the applied power available signal, which also works as a power protect function, to always limit the power of the source under the safety margin.

Therefore, the available power in the electrical plant at any given time must be greater than the sum of anticipated loads in the system, otherwise the target vessel could not keep the position during the DP operations.

The super-capacitor system could achieve the improved performance with less number of running engines and lower fuel consumption with less environmental emissions.

Fuel consumption savings calculation

The optimum operation point of a diesel engine will typically be around a load of 85 percent of the Max continuous rating (MCR). Moreover, the efficiency level drops quickly as the load becomes lower than 50 percent of MCR, as shown in Figure 18.

With the help of the electric system, the mechanical propulsion primer mover is replaced by diesel-electric prime movers that will automatically start and stop as load demand varies. In comparison to a conventional vessel with mechanical propulsion, this enhances the efficiency of the energy usage and reduces the fuel consumption by keeping the average loading of each running diesel engine close to its optimum load point. However, in DP vessel applications, the load variations can be large and rapid. It is impossible to make the generators switch on and off every five seconds as would be the case in the examples above. By using super-capacitors to supply the load variations, and hence let the diesel engines provide the average load, the peak power of the power plant will be reduced, allowing the average loading of the engines to increase to a more optimal point with lower specific fuel oil consumption.

The savings in fuel consumption will depend on many parameters such as actual variations in the load, the average load and the number of prime movers. For example, if one could increase the average loading of the running engines from, for instance, 40 percent to 60 percent, fuel oil consumption would be reduced by more than 10 percent.

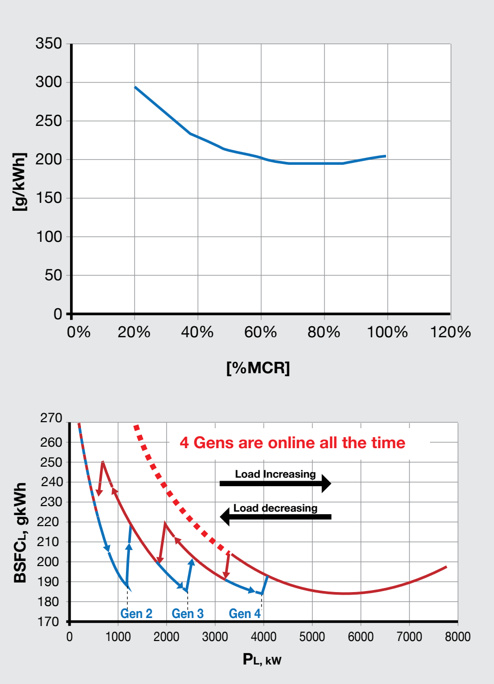
Conclusion and further works

In the case studies above it has been shown that the use of super-capacitor for short-term energy storage in a thruster system can effectively limit the power fluctuations seen by the supplying network.

The advantages of this are twofold. First, this reduction in power peaks can offset the need for bringing additional diesel engines online, thereby increasing the average loading of each diesel and improving diesel fuel efficiencies. Second, when a diesel engine is loaded and unloaded quickly, the combustion process in the diesel engines is adversely affected. A reduction in rate at which they are loaded and unloaded will also reduce their fuel consumption significantly.

For further work, it is important to quantify possible fuel savings and lifetime costs for larger systems. Investigation into other frequency converter applications found on board ships should also be performed.

17 Simulation results (2)



Jessie Wenjie Chen
ABB
jessie.chen@sg.abb.com

John Olav Lindtjørn
ABB
john.o.lindtjorn@no.abb.com

Frank Wendt
ABB
frank.wendt@no.abb.com

Acknowledgment

This article is based on Jessie Wenjie Chen's Master's degree thesis "Dynamic Modeling of a Super-capacitor Hybrid Converter." The authors gratefully acknowledge the contributions of Alf Kåre Ådnanes and Jan Fredrik Hansen for their work on the original version of this document and the guidance and use of ABB simulation library for electric thruster systems.

References

[1] Alf Kåre Ådnanes, "Reduction of fuel consumption and environmental footprint for AHTS and OSVs using electric or hybrid propulsion"
[2] Jan Fredrik Hansen, John Olav Lindtjørn, Klaus Vänskä, "Onboard DC Grid for enhanced DP operation in ships," Dynamic Positioning Donference, Houston, Oct. 11-12, 2011
[3] Maxwell Co. Ltd., "Super–capacitor characteristics and comparisons"