

MARITIME FLYWHEEL

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1. INTRODUCTION

The project aims to investigate the feasibility of using flywheel energy storage systems on ships, with a specific focus on dredgers. The aim is to provide an initial assessment of the technical and commercial feasibility of flywheel technology.

The maritime sector aims to reduce net emissions from ships to zero in the long term. Energy storage systems can play a crucial role in optimizing energy efficiency and the deployment of alternative fuels. Dredging vessels typically have a highly variable power demand. It is expected that the results of this study will be more widely applicable to other ship types with variable power requirements.

1.1. Project overview

Project Title	Vliegwielen als energiebuffersysteem aan boord van schepen (Maritime Flywheel)
Project period	1 March 2024 – 28 February 2025
Proposal submitted by	Baggermaatschappij Boskalis B.V. Rosmolenweg 20 3356 LK Papendrecht
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Project Manager phone number	+31 6 51758440
Collaboration Partners	Quinteq, Bakker Slidrecht, Marin
Maritime Focus Area	Towards Zero Emissions

1.2. Process description and Project plan

The project partners have taken an efficient, pragmatic approach for the execution of the project. From the kick-off meeting on 3 March 2024, the partners have met 9 times, alternating online and in-person meetings. Meeting notes and file sharing has been facilitated in a Teams environment. In accordance with the project proposal, the following work packages have been identified, with tasks and planning assigned to the respective partners.

WP 1 Literature study to the application of flywheels in the maritime sector

March 2024: Boskalis 80h, Bakker 41h

What are the class requirements to maritime flywheel systems?

Input on existing knowledge to be collected by Boskalis (with partners and external sources)

WP 2 Defines use cases + selection for WP3-4

April-May 2024: Boskalis 80h

Project team agrees to select the Trailing Suction Hopper Dredger (Willem van Oranje) as a use case.

Other applications (cutter suction dredger and crane vessel) can be addressed if time/budget permits

WP 3 Exploration into application of flywheels as energy buffer

June-December 2024: Quinteq 206h, Bakker 48h

(size/weight/foundation/bearings/costs)

WP 4 Modelling load profiles dredging process, comparison with and without energy buffers

June-December 2024: Marin 120h, Bakker 40h

WP 5 Analysis, conclusions and recommendations

January-February 2025: Boskalis 80h, Quinteq 16h, Bakker 8h

1.3. Report Structure

The report follow the structure of the work packages in the project plan.
An overview of the literature study and reference are provided in Chapter 2. Etc.

2. LITERATURE STUDY

2.1. Literature Search

There is ample literature about general application of flywheels as energy storage system (FESS). Reference is made to reaction times (comparing to other options), optimization of energy density versus stability, minimizing friction losses in the FESS itself.

For ships a typical use is in combination with pulse power applied in naval applications (warships).

One study (simulation) considered a FESS for stabilizing the power fluctuations from a PV-system (solar power) under varying ship load, solar irradiation and effect of rolling of the ship on the PV power.

The effect of ship motions on a flywheel used as FESS (gyroscopic forces) is not researched very often. More general studies of flywheels used for stabilizing ship motions are found. Typical solutions for minimizing gyroscopic forces on the a ship have not been found.

2.2. Bibliography

The following references have been identified and studied to explore the potential of using a flywheel ESS onboard.

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2.3. Patent search

As part of WP1 literature study a small patent search has been performed, mainly to check to existence of conflicting patents with regards to the application of a flywheel as energy buffer on board of a dredger. To get a broader overview and not to miss out on anything, the search not only included maritime applications but also off-shore applications.

To limit the overview a bit, patents in which flywheels are solely used for mechanical stabilization of vessels were excluded.

20 patents have been found, of which 2 were rejected and 6 were withdrawn or abandoned.

Patents were found to convert wave or vessel motion into (electrical) energy, others to use flywheel stored energy for vessel or platform stabilization. None for or in combination with dredging systems.

Only one Chinese but withdrawn patent has been found related to dredging; a flywheel to power an air pump for river cleaning.

Interesting existing patents:

- Caterpillar Inc has been granted a patent for a "System and method for efficiently operating multiple flywheels". (US20140046538A1). This relates to control of the operating speeds of two flywheels to minimize the effects of parasitic loads losses between them.
- Nabors Drilling Tech USA has been granted a patent for "Flywheel based energy storage on a heave compensating drawworks". (US20100314168A1). In which a wire over a sheave is used to lower and hoist a drill. Could be a conflict with the wire crane application we consider as third option; would have to be investigated a bit further in case we want to continue with that.
- The University of Southampton has been granted a patent for "Marine vehicle using a gyroscopic system to generate power for a propulsion system". (GB2508399A). The flywheel is using in combination with a main power supply to either directly power the drive shaft or via an electric motor.

3. DEFINITION OF USE-CASES

For this study an exploration into feasibility and application of flywheels on ships with strong power fluctuations a selection is made from the following uses cases:

1. Trailing suction hopper dredger (Willem van Oranje)
2. Cutterdredger (Helios)
3. Dredge pontoon with hydraulic crane (Medusa-2)

The project team agrees to select the Trailing Suction Hopper Dredger (Willem van Oranje) as a use case. Other applications (cutter suction dredger and crane vessel) can be addressed only if time/budget permits. At the end of the project both time and budget were insufficient to address the remaining use cases.

The TSHD Willem van Oranje is a medium large dredger of 12000m³ with an installed power of 13.870kW. Due to the larger amount of available hopper dredgers and availability of information and load profile data this was mainly the reason to select this use case as the first one.

Propulsion is direct driven from the diesel fuelled engines. Dredgepumps, jetpumps and bowthruster as main consumers are electrical driven by frequency converters and motors. To investigate the behaviour of the load taken from the engines during different operation modes load profile data is needed to analyse. The project team was able to deliver in early stage the following information:

- Single line diagram of the electrical power plant
- Load profile data
 - Power of main consumers available (not for generator)
 - Added loads on diesel engine incl. fuel rack data

This study attempted to examine the influence of using different types of fuels in combustion engines. The main topic of the allowed change in power over time (dP/dt or ramp rate) from the engines using different fuels is important to know. At this moment information like ramp rates from combustion engines like dual fuel LNG and Methanol is hard to get out of available literature.

4. EXPLORATION INTO APPLICATION OF FLYWHEELS AS ENERGY BUFFER

This work package will investigate the technical and design requirements for integrating flywheel energy storage systems on ships. This includes considering factors such as available space, weight limitations, foundation requirements, and dealing with the gyroscopic effects of rapidly spinning flywheels. A preliminary exploration will also be made into the ability of the flywheel to peak shave the power profile of the selected ship.

Research questions

The following research questions were investigated in this work package:

- What kind of power and energy are roughly needed for peak shaving?
- What are the movement tolerances of the bearings, and what movements can we expect?
- How can the gyroscopic effects be mitigated?
- What specific (design) measures are needed to apply flywheels on board ships? (space, weight, position on the ship)

4.1. Research question 1

Application of flywheels for peakshaving of the WvO

To investigate how peakshaving can be applied aboard a dredging ship, data from the Willem van Oranje ship from Boskalis has been used. Three data sets have been supplied in which significant electrical power or ship motion have been recorded. In all data sets, the power consumption of consuming devices (eg pumps, thrusters), as well as the power delivered by generators is available. In order to not overcomplicate the analysis, the three datasets have been appended together in time to make them one, containing varying ship activities. A view of the data is available in Figure 1.

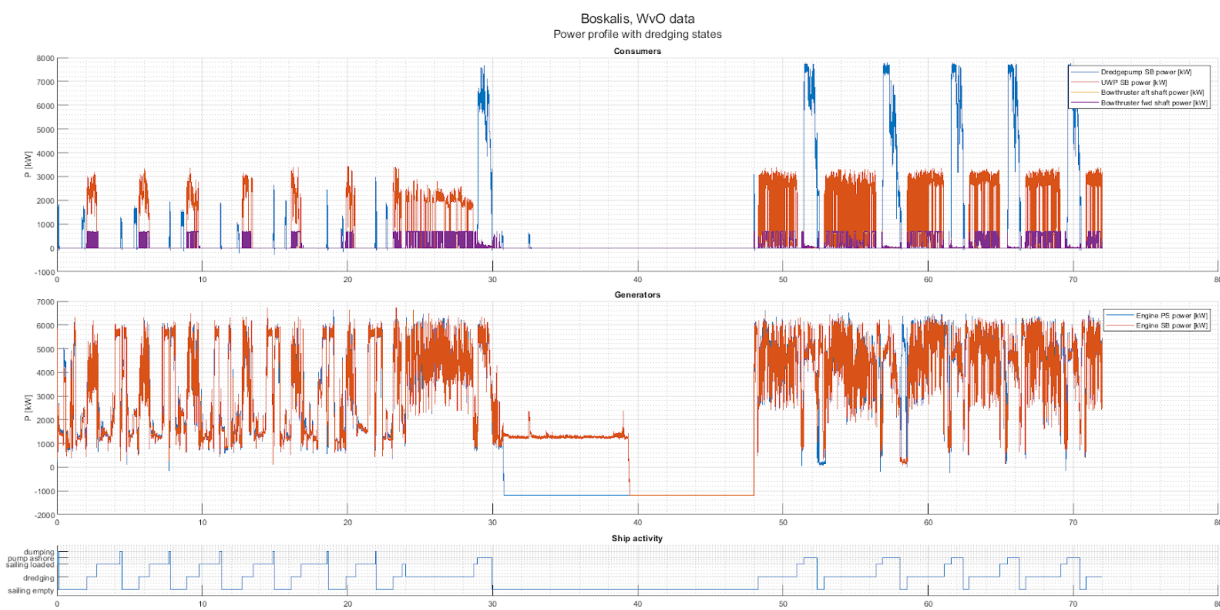


Figure 1: Power data of the Willem van Oranje of Boskalis, coupled to ship activity.

Flywheel analysis

To investigate if and how flywheels can be applied to peakshave a (micro)grid, an analysis is done based on data of the electrical power. The flywheel specifications (power and capacity) are given inputs to this analysis. Besides this, there is a desired level to keep the grid supplied power under. The goal of the flywheel is to deliver power to compensate for the consumption of power above this desired level, and to consume power to charge itself as soon as there is the option to do so, whilst staying under the defined power level. This analysis can be performed by taking the power data over time and computing for every step in time how much power the flywheel would have to deliver in this moment, and how that affects the state of charge.

Peakshaving the WvO for alternative power supplies

A flywheel is an energy storage device, it doesn't generate energy. The goal of placing flywheels on a dredging ship is to accommodate the use of alternative power sources that are more sustainable than the standard diesel generators that are used now. A known downside of hydrogen power sources, the alternative power source considered for this analysis, is their (generally) limited power ramp rate. This means that if the load behavior (ship consumers) stays the same, the hydrogen power source will fail to deliver. It is therefore the difference between the current power profile, and that of what a hydrogen power source could be delivered, that needs to be made up for. This is where flywheels come into play, with very high power ramp rates. The analysis described before is supplied with a varying power level for the flywheel that is the difference between the diesel engine and hydrogen engine power profiles.

Because the latter data (hydrogen engine power profile) is not available, it needs to be synthesized. To do so, an alternative power profile was created based on the diesel engine power profiles, but with a defined maximum ramp rate. This ramp rate was set at 10% of 6000 kW, so for the synthesized hydrogen engine profile there was a $dP_{max}dt = 600 \text{ kW/s}$.

The alternative profile was created by following the original diesel engine profile, but limiting the ramp rate per time-step in the data, which resulted in a profile that cannot 'keep up' with the original profile. The result is shown in Figure 1, from which it becomes clear that the synthesized and original profiles are similar. By subtracting the original and synthesized profiles and adding portside and starboard profiles together (Figure 3), the difference becomes clear and it shows exactly where and how the flywheel has to compensate.

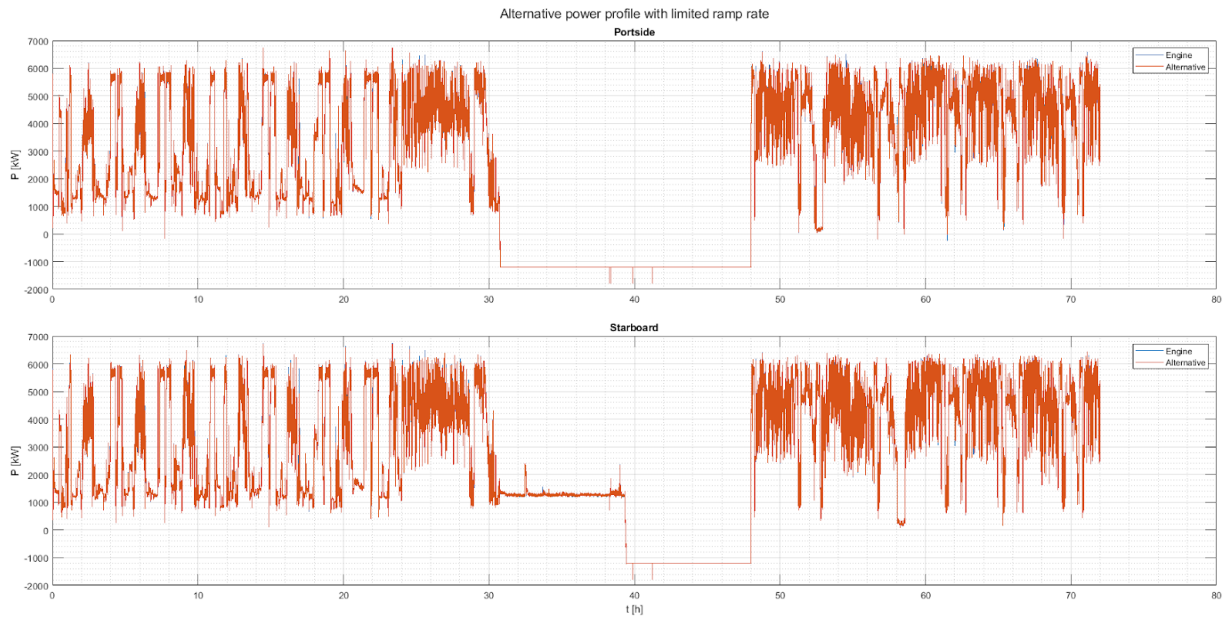


Figure 2: Alternative engine power profile with limited ramp rate, based on original diesel engine profile

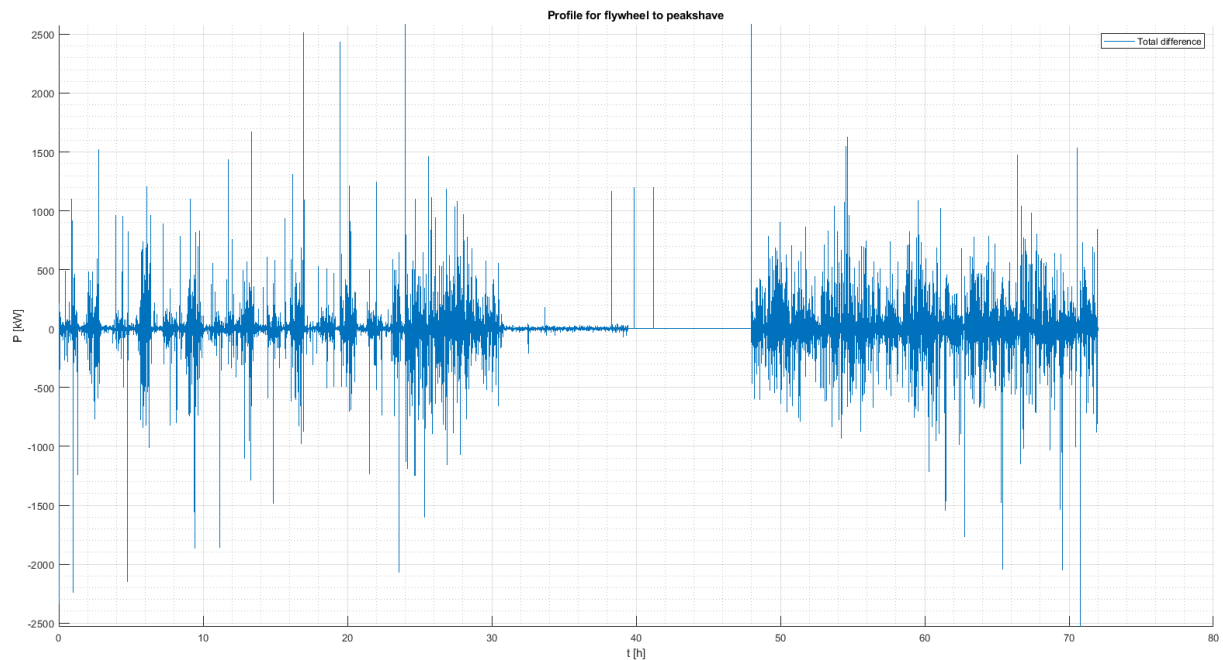


Figure 3: Resulting power profile for flywheel(s) to peakshave. Difference between original and new (alternative) power source. Note: two times the peaks are extremely high (out of axis). This is the result of appending different datasets together.

The profile in Figure 3 shows high but short peaks, and the average power is, as expected, near 0, since the ramp rate of the alternative power source is limited in both directions. This is a very fitting profile for flywheels, given their high power output and high power ramp rate. A time-based analysis shows the

application of a flywheel on the given profile. Assuming the flywheel size of a current QuinteQ system, which is a 300 kW, 4 kWh system, the difference between the original diesel engine and new alternative energy source profiles requires a minimum of 4 flywheels per ship side, assuming the ramp rate can be reduced somewhat by control of e.g. the pumps. This is simply due to the order of magnitude of power (MW's) that is at play on a ship like the TSHD Willem van Oranje. Figure 4 shows an example of this time-based analysis only for the Portside of the ship (Starboard is extremely similar).

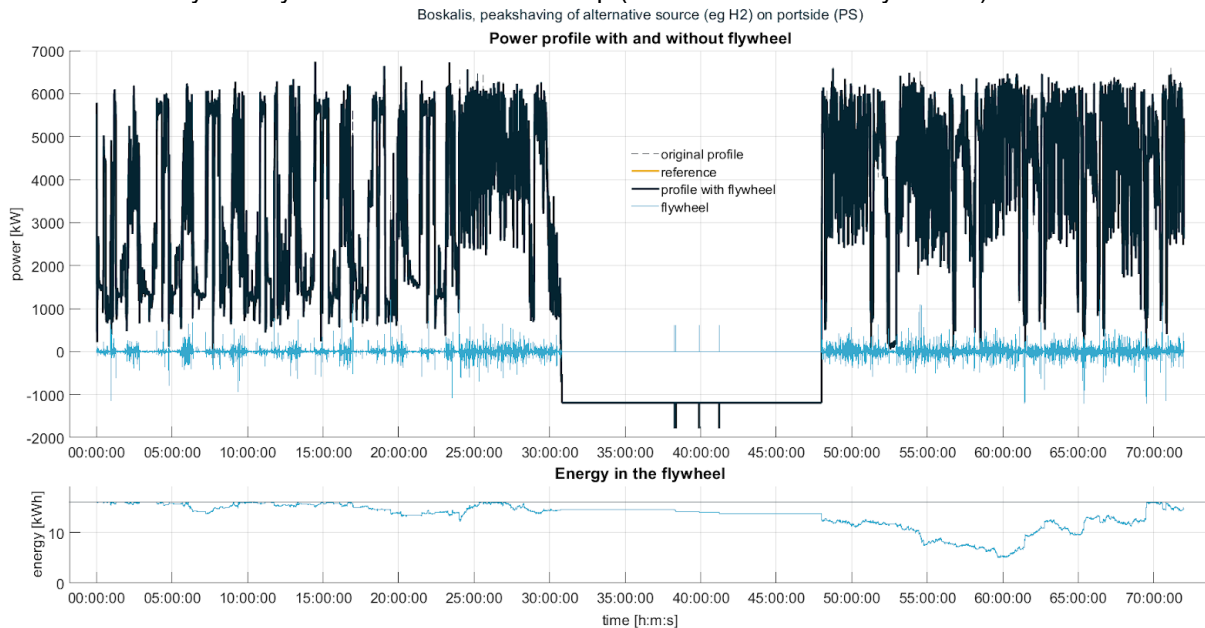


Figure 4: Peakshaving analysis of applying 4 flywheels to compensate for the gap between original engine profile and the alternative power source profile.

In the graph of Figure 4, the lines for 'original profile' and 'reference' (alternative power profile) have disappeared graphically under the 'profile with flywheel' line, because of the large amount of data displayed on the x-axis, and the difference of the y-values relative to their magnitude. More relevant and more interesting is the flywheel power and energy, showing indeed what is required to account for the limited ramp rate of an alternative power source like a hydrogen power source. In this analysis, the flywheel State of Charge (SOC) has not yet been optimized, which means opportunities for charging are not always used. This means that in reality, the SOC can be maintained better than this analysis shows.

Conclusion

For a dredging ship like the WvO to be powered by a more sustainable energy source like hydrogen power instead of the traditional diesel engines, flywheels are a fitting solution to account for the limited ramp rate of the alternative power source. With the specifications of QuinteQ's current flywheel, many flywheels are required on a single ship. This does, however, greatly depend on the maximum ramp rate of the chosen alternative power source. For this analysis, a maximum ramp rate of 600 kW/s was assumed. This number is not backed by any data, but some variation in this number can make a large difference in the required flywheel specifications. Therefore, before any further research is done into the applicability of flywheels on dredging ships, it would be very relevant to gain more knowledge on the power profile of the desired alternative power source. This is, however, outside the scope of this project.

4.2. Research question 2

The below spectrums were used to verify (bearing) forces on a single flywheel without any adaptations for ship use. The bearings were overloaded and hence we first focused on RQ3 and RQ4 to optimise against bearings overloading.

TSHD Willem van Oranje

- Waves coming in under 45 degrees, worst from front and back and SB or PS. No higher than the deico norm of $H_s \sim 3$ m for these conditions
- Wave frequency is set to 0.111Hz
- The vertical maximum acceleration occurs at a T_p of 9 s.
- The maximum horizontal acceleration increases with the wave period, truncated at T_p of 15 s.
- The vertical max angular velocity occurs at a T_p of 10.5 s.

This was used to come to the following input data used for the analysis:

- Accelerations: $f=0.111$ Hz
 - vertical = 4.3 m/s²
 - longitudinal = 1.9 m/s²
 - transverse = 1.9 m/s²
- Rotation Speeds:
 - Yaw = 2.25 deg/s
 - Roll = 4.9 deg/s
 - Pitch = 2.5 deg/s

4.3. Research question 3

The gyroscopic forces resulting from applying flywheels on ships can negatively impact:

- Bearing forces
- Structural forces on (ship-)construction/mounting

Using the principles below, these forces can be limited to acceptable levels:

1. Use a gimbaled setup to negate pitch & roll & yaw forces: the flywheel is allowed to remain in its initial orientation, there are no resulting (high) bearing forces and structural forces
2. Apply a flywheel with a horizontal shaft and orient the rotational shaft in the longitudinal direction of the ship (roll axis): this negates gyroscopic forces resulting from roll movements of the ship. This way the gimbaled setup is only necessary to negate pitch & yaw movement. As the roll movements (angular acceleration, angular speed, angle) are typically much higher than for pitch and yaw the roll axis is the evident axis to select.
3. To negate any forces on the flywheel-to-ship mounting and forces on the existing ship structure it makes sense to combine (a multitude of) two flywheels in the gimbal. With such a setup the bearing forces will act in opposite directions on the gimbal frames thereby essentially negating any gyroscopic forces to result in forces on the ship structure. The only forces on the ship structure are resulting now from gravity and ship accelerations acting on the CoG of the flywheel system.

4.4. Research question 4

Space required:

Obviously the space required heavily depends on the amount of kWh (and hence flywheels) required. This number of kWh required results from the difference between the kW/s for a traditional diesel generator vs the kW/s possible with alternative fuels. For this report the kW/s ramprate for alternative fuels was not known and the assumed number resulted in a high number of flywheels needed. It seemed unrealistic to try and fit these on a ship as it would result in a space claim of multiple 20ft containers. This topic should be revisited in a follow-on study when known/realistic ramprates are available.

Weight of system:

Following the same reasoning as the required space it is not realistic to put a number on system weight given the currently assumed alternative fuel ramprates. This topic should be revisited in a follow-on study when known/realistic ramprates are available.

Position on ship:

The more the system is installed in the Center of rotation of the ship, the less translational forces will act on the bearings. For the marked up locations on the ship the maximum accelerations (dredging state) were calculated (ref table below). To determine bearing forces we have assumed the aft location or worst case accelerations.

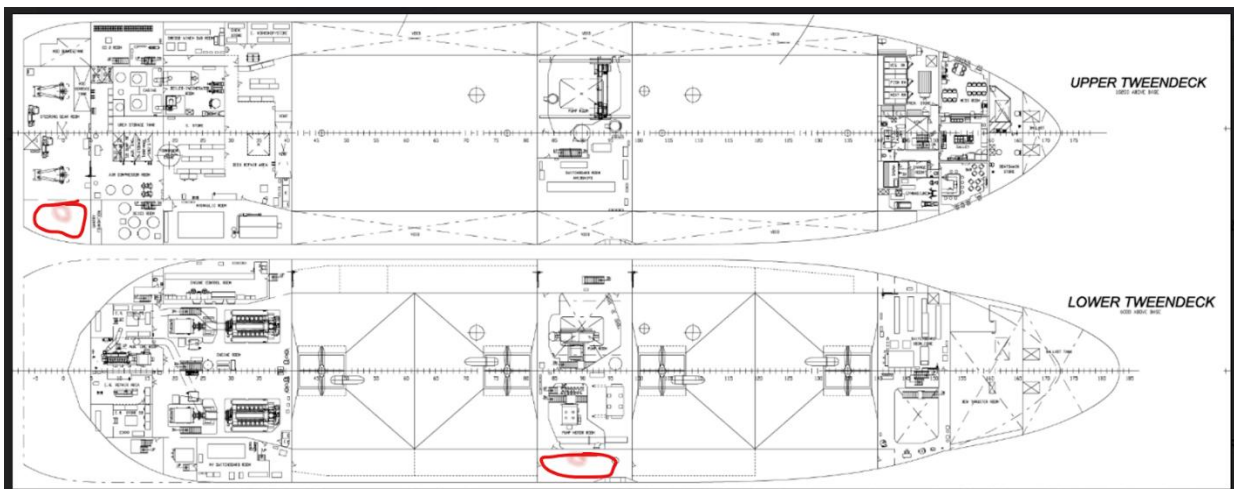


Figure 5:

	X-Y acc	Z-acc
	[m/s ²]	[m/s ²]
Aft	1.9	4.3
Mid	1.4	2.3

5. MODELLING LOAD PROFILES DREDGING PROCESS, COMPARISON WITH AND WITHOUT ENERGY BUFFERS

MARIN has provided a dynamical simulation environment suitable for the feasibility study of flywheel applications, as energy storage system for supporting the ships electrical grid. Example features of electrical storages system in ships are ramp rate compensation, peak shaving, and/or spinning reserve.

The simulation environment should help the users to:

- have a good insight in phenomena's that could occur in dynamic loading
- perform design and optimization of the control strategies
- size and select the needed equipment
- estimate the advantages and disadvantages in terms of system performance and fuel consumption for a given process power profile
- verify that the system is complaint with Class requirements

The simulation wants to provide an environment for further investigations, rather than demonstrating the advantages or disadvantages of installing a flywheel in the electric grid of a vessel.

The simulation model was set up in Simulink® graphical programming language.

5.1. Simulink model architecture

The simulation model has been created with the following features and assumptions:

- the simulation environment contains the model of an AC (alternative current) electrical grid
- there is only one GenSet connected to grid of which the ICE (Internal Combustion Engine) rotational speed is controlled by a PI (Proportional – Integral) controller
- for simplicity, the behavior of electrical components (electric motors/generators, inverters and etc.) and the electrical quantities (current, voltage frequency) are not modelled
- the simulation environment doesn't take any of electrical components efficiencies into account
- the simulation environment main quantities are:
 - ICE rotational speed (proportional to the grid frequency)
 - mechanical power at ICE shaft. The electrical power, requested by the consumer or by the energy storage system (flywheel) are converted , into a torque applied at the ICE shaft T_{GRID} , on the basis of current ICE rotational speed.
- The model solves the dynamic equation of motion at the ICE drive shaft in order to determine its rotational speed at each computation iteration (see formula below).

$$T_{ICE} + T_{GRID} + T_{FW} = 0$$

Where:

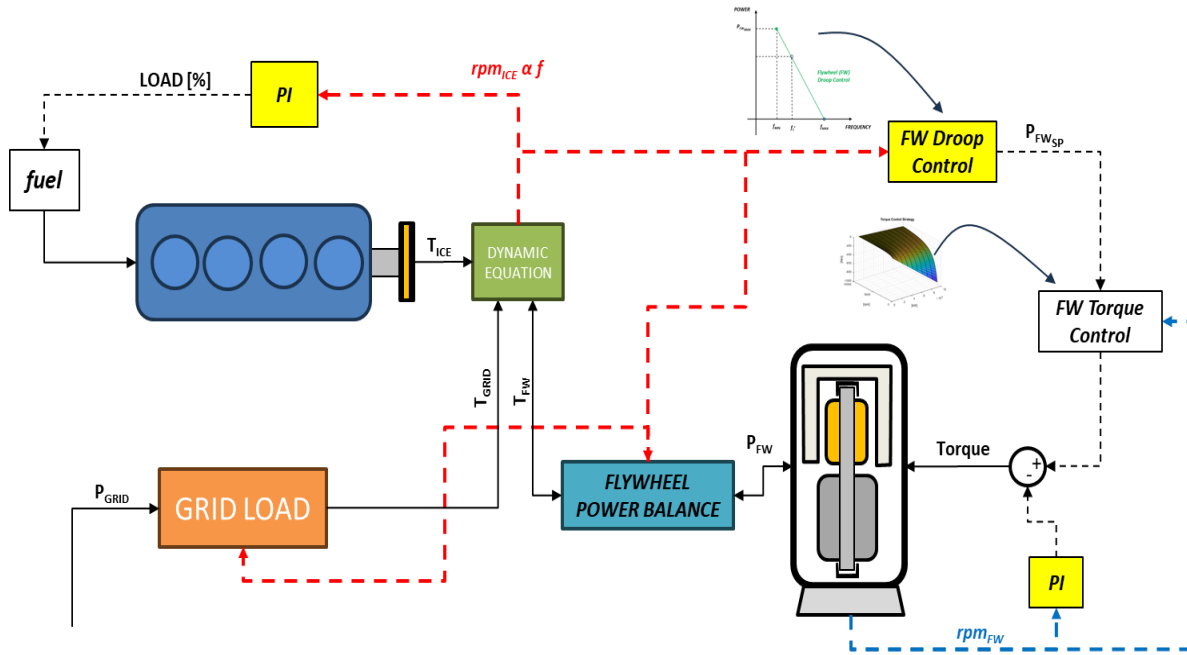
T_{ICE} is the torque provided by the ICE

T_{GRID} is the calculated torque applied by the grid to the ICE shaft

T_{FW} is the calculated torque applied by the flywheel to the ICE shaft

- The modelled components do not refer to a specific use case. They have been selected/made to test it functioning.
- Most of the component models have been implemented in order to easily set and change their parameters. That makes them “generic” and easily customizable to specific cases.

Figure 6 shows a sketch of the Simulink Model.



- PI** = Proportional – Integral Controller
- P_{GRID}** = power requested by the grid
- P_{FW}** = power delivered or harvest by the flywheel
- P_{FWSP}** = flywheel droop control power request
- rpm_{ICE}** = ICE rotational speed
- rpm_{FW}** = flywheel rotational speed
- f** = grid frequency

Figure 6 Simulink Model Logical and Functional Description

5.2. PPE Components

Considering that many of the PPE (Propulsion - Power & Energy System) component characteristics (Power and etc.) were not available in the existing library, MARIN decided to set up the simulation environment according the following process:

1. use the available and tested component of the Models Library (e.g. ICE,),
2. model the not available components (e.g. Flywheel),
3. model the local control algorithm of the components that were not available in the Models Library,
4. model the power management control algorithm,

5. setting the parameters of the components that were not available

The only available component selected at 1 has been a Dual Fuel (DF) Diesel-Methanol combustion engine with the power of 9.2 MW at 750 rpm.

The flywheel has been modelled as a rotating mass (Rotor Mass) with a moment of Inertia equal to the sum of the moment of inertia of the masses connected to the shaft. The stored energy is proportional to its rotational speed. In case of energy storage, the flywheel will harvest energy from the grid and convert it into kinetic energy. In case it is requested to provide energy to the grid, the flywheel will convert the kinetic energy of the rotating mass into mechanical energy.

5.3. Preliminary Results

The graphs in Figure 7 and Figure 8 show the result of a simulation executed according the following steps:

1. **FLYWHEEL NOT ACTIVE** : the flywheel is not connected to the grid and the ICE is providing all the power requested by the grid. In this phase (**Error! Reference source not found.**), the ICE is very “reactive” to load steps (stiff power delivery).

Test result: in this phase, the ICE is subject to strong load variation which are not ideal for a fuel consumption (over fueling) and engine wear point of view. The grid frequency (**Error! Reference source not found.**) is stable in load steps and load rejection and does comply with the grid frequency requirements by Class¹.

2. **FLYWHEEL CHARGING**: there is no load request by the grid and the flywheel is connected to the grid. In this phase the ICE is producing power to bring the flywheel rotational speed from 0 to the nominal speed.

Test result: the power requested by the flywheel to get charged doesn't create significant grid frequency drops or increases and does comply with the grid frequency requirements by Class¹.

3. **FLYWHEEL ACTIVE**: the flywheel is active and the ICE is controlled to have a smoother power delivery rate (**Error! Reference source not found.** - orange double arrow). The reason behind that strategy is to avoid the ICE over fueling due to a strong load step and, potentially, emulate the behavior of a low reactive ICE. The graph shows the fast reactivity of the flywheel in taking over a power step from the grid and progressively reducing its contribution, by that letting the ICE take over the total power requested by the grid.

Test result: the ICE has a more smooth power delivery which helps limiting the over fueling and wear. The grid frequency (**Error! Reference source not found.**) remains within the Class R requirements¹ but it takes more time compare to the step 1 before it reaches its nominal value. The flywheel should provide a more “step” kind of power profile increasing its help to ICE. It is important highlight that the flywheel needs progressively to reduce its provided power because it needs to keep, within a certain threshold, its state of charge (SOC). In specific part of the process, the flywheel will need to get charged, harvesting power from the ICE.

¹ According to BV NR467 – Rules for the Classification of Steel Ships, Part C, Ch 1, Sec 2 sub 2.7.6 Prime movers for driving generators of the main and emergency sources of electrical power are to be fitted with a speed governor which will prevent transient frequency variations in the electrical network in excess of $\pm 10\%$ of the rated frequency with a recovery time to steady state conditions not exceeding 5 seconds, when the maximum electrical step load is switched on or off.

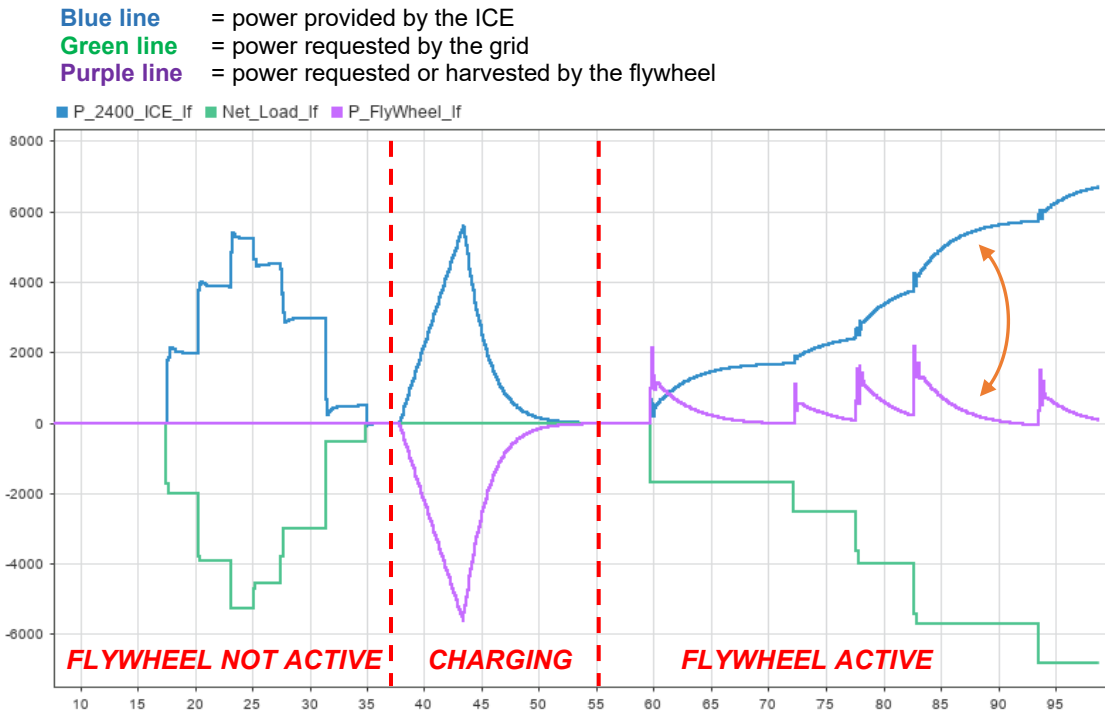


Figure 7 PPE System Power Balance

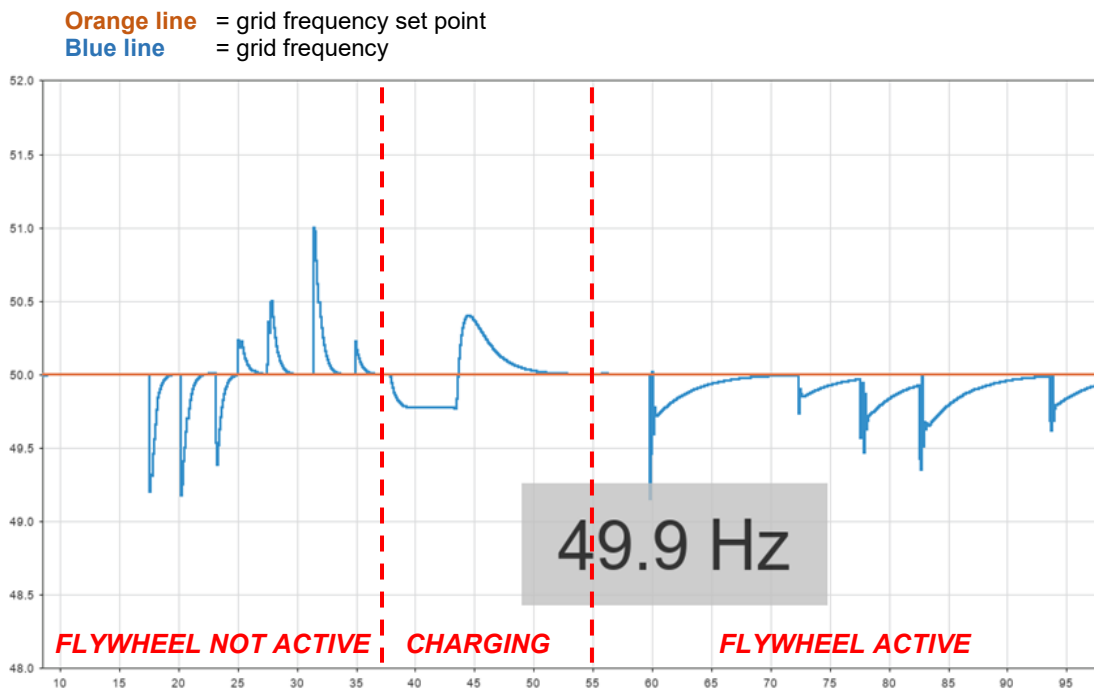


Figure 8 Grid Frequency Graph

5.4. Conclusions and Recommendations

A dynamic simulation model with a sufficient complexity (like the one detailed in *Simulink model architecture*) can highlight phenomena's and show system performances not evaluable with a quasi-static model or a calculation spreadsheet.

The use of a dynamic simulation model is strictly recommended to evaluate the installation of a flywheel in an early stage, like the feasibility study and equipment dimensioning.

The systems dynamic responses and the way of controlling them play a fundamental role in evaluate the advantage or not of the solution in subject. In particular, in cases, where fuel consumption, CapEx and OpEx evaluation (e.g. ICE maintenance) play a big role.

The increase in complexity of the ship PPE systems bring to the conclusion that integration is the key factor to let them operate in the best and efficient way. MARIN believe that these results are only achievable when assisted by an appropriate simulation environment. In a simulation environment it is possible to study, evaluate and design the integration between the different power sources and consumers.

6. ANALYSIS, CONCLUSIONS AND RECOMMENDATIONS

In this report, an exploration has been conducted to the application of a (high speed) flywheel as an energy storage system (ESS) on a trailing suction hopper dredger. The purpose of this is to shave peaks from power demand or accommodate fast transient power fluctuations, e.g. requested by the dredge pump. This can be important when using sustainable fuels such as methanol or hydrogen, since such power sources may not be capable of responding fast enough to provide instant power increases.

A literature review has been carried out, showing that maritime applications are known, in particular on naval vessels. Not much information has been found on the effect of ship motions (generating gyroscopic forces).

Flywheels are a technically fitting solution to account for the limited ramp rate of alternative power sources with ramp rates significantly lower than those of traditional diesel engines. Reliable data on ramp rates for alternative power sources is hardly available, so the analysis was based on assumptions. It is recommended to identify more reliable data on the ability of alternative power sources to increase power over time. Depending on the power profile of the vessel, multiple flywheels may be required (possible even up to more than 8 for the use case in this study).

Ship motions can induce gyroscopic forces, that act on the bearings and the foundation of the flywheel. Possible measures to avoid these forces are to mount the flywheel with its rotation axis in the sailing direction (roll axis) of the vessel. Moreover, flywheels can be installed in counter rotating pairs on a frame, so that gyroscopic forces cancel out (these forces will still act on the bearings, though). Hence, gyroscopic forces are not regarded as a limitation in the application of flywheels.

A dynamic simulation model has been developed in Matlab Simulink, which allows for evaluating design options and the dynamic responses and the way of controlling the energy system in an early stage.

The partners are keen to go in more detail in a follow up project to investigate the system efficiency benefits of applying flywheel(s) to reduce (sustainable) fuel consumption. Preferably, this project should be based on a specific vessel development.