Dynamic Consequence Analysis of Marine Electric Power Plant in Dynamic Positioning

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Abstract

Diesel-electric power and propulsion systems with electric thrusters are the industry standard for vessels with dynamic positioning (DP) systems. Diesel engines are paired with generators in generator sets and are used to produce electric power used by thrusters and main propellers during stationkeeping and transit, and other consumers such as hotel load, drilling drives, cranes, and heave compensators. Consequence analysis is used to verify the safety of a DP operation. It is used to check whether there is sufficient running power and thruster capacity available to retain sufficient thrust to maintain vessel position after a worst single failure. Recently, extensions of class rules enables standby generators to be considered in this analysis. This provides a more efficient configuration as relatively fewer generator sets may be running. However, DP performance is degraded during the transition from the fault occurrence until the plant is completely recovered. It is important to determine if this degradation leads to a loss of position during the transition. This study presents a simulation-based dynamic consequence analysis method that can be used to dynamically simulate fault scenarios such that the dynamics of the transient recovery can be analyzed. This analysis can be used for decision-support to configure marine electric power plants in DP. Results from the simulation study show that the currently used static consequence analysis method may provide non-conservative results under certain configurations.

Keywords: Marine power plant, unit commitment, dynamic positioning,

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1. Introduction

Dynamic positioning (DP) systems are used for the stationkeeping of marine vessels. The general safety requirement for classes 2 and 3 is that any single fault should not propagate into a loss of position [1]. This is enabled by redundancy, which means that if one redundancy group fails, remaining redundancy groups have sufficient capacity to maintain stationkeeping.

An online consequence analysis is required for DP vessels of classes 2 and 3 [1, Sec. 3.2.4.2]. The IMO rules state that: "This analysis should verify that the thrusters remaining in operation after the worst case failure can generate the same resultant thruster force and moment as required before the failure." An alarm should be raised if this verification is negative. Another tool is DP capability plots, which are used to determine the environmental limits of an operation. These plots show the maximum static or quasi-static wind, current, and wave loads in which the vessel can maintain its position, for all headings and different configurations (e.g., worst-case, nominal case). Specifications of this plot are given in [2]. Drift-off analysis is used during drilling operations to determine when to initiate the disconnection of the riser from the vessel to avoid damage to the riser [3]. Because, disconnection process of a riser during a drift-off is time consuming (e.g., in case of a blackout), a watch circle is set such that there is sufficient time to safely disconnect the riser if the process is started when the vessel passes the watch circle.

A power management system (PMS) is used for controlling the electrical power system. The main task of the PMS is to ensure the sufficient availability of power. In addition, the PMS coordinates fault recovery and typically optimizes the efficiency of a power plant. In the case of a major fault, loads must be quickly reduced to prevent the occurrence of under-frequency, because it takes time for diesel engines to increase their produced power. The PMS sends a *power available* signal to main consumers to ensure that only available power is used. This is the maximum allowed power for each consumer. It is calculated by acquiring the available power production level of each generator set and then allocating it to consumers based on their priority. *Fast load reduction* may be used when sudden load reduction is required (e.g., loss of producers), which sends a request to thruster drives to reduce their power. This proceeds as thruster drives can quickly reduce power consumption. Later, the available power of thrusters is increased back to normal.

In [4], a simulation-based consequence analysis is proposed. Notably, conventional DP capability analysis is non-conservative compared with time-domain analysis. Moreover, power constraints and transient recovery after faults are not considered in their analysis. A transient study was also performed, which showed that position excursion may be larger than acceptable during the transient recovery after a fault.

Recently, it has been proposed by the DNV GL DYNPOS-ER class notation that standby generators can be included in a consequence analysis [5, Part 6 Chapter 26 Section 2]. Other class societies have similar class notations, e.g., [6, Section 8]. Because the connection of generators can be blocked by hidden faults, it is conservatively assumed that one of the standby generators cannot connect because of a hidden fault. This provides the opportunity to run relatively few generator sets, which increases the efficiency of a plant. Typically, a marine diesel engine is at its highest efficiency when it delivers about 80% of its rated power. However, it is reported that during DP operations, diesel engines often deliver less than 50% and even down to 10% of the rated power. Moreover, during low-load conditions, other problems occur, such as sooting, increased maintenance because of extra running hours, and inefficiency of some NO_X reduction systems at low temperatures [7].

The analysis proposed in this paper can also be used as a decision-support tool for the optimal configuration of a vessel. Several configurations can be simulated to evaluate the safety and performance of each configuration. Today, an automatic start and stop table is typically used for commitment of generators on marine vessels [8]. Generator sets are started if the power demand is above a threshold for a certain duration of time, vice versa for disconnection. An optimized load-dependent start table was derived in [9], where the table was optimized with respect to fuel consumption and constrained by a safety requirement, so that disconnection of a generator will not lead to blackout. Algorithms to optimize the load-dependent start and stop tables are also presented in [10], based on the probability for each operational mode of the vessel. One of the problems with a start and stop table is its independence of operation. For diving and drilling vessels, the safety and redundancy requirements are much higher during operation than during transit. However, when using a start and stop table both operations will typically have the same configuration when the power demand is similar, even though this is not optimal. Therefore, some vessels have different start/stop tables for each mode and also a minimum number of generator sets for some modes to handle changing requirements. It is also common to override the automatic system by committing generators manually. For onshore and island power grids, multiple studies have looked into unit commitment, e.g., [11–16].

The main contribution of this paper is the development of a consequence analysis based on dynamic simulation of the transient recovery after a fault. The analysis is carried out by dynamic time-domain simulation of the vessel and its DP system for possible worst single failures. The simulations include power constraints and ramp constraints on the thrusters. This tool can also be used as a decision-support system for configuration of the power plant and selection of recovery-methods.

An earlier version of this paper was presented in [17]. In this present version, more emphasis is placed on the modeling of fault scenarios and fidelity of simulation. The article is divided into two parts. The method is presented in the first part and the second part presents a case study considering a drilling rig. The first part starts with an overview of the method followed by a presenta-

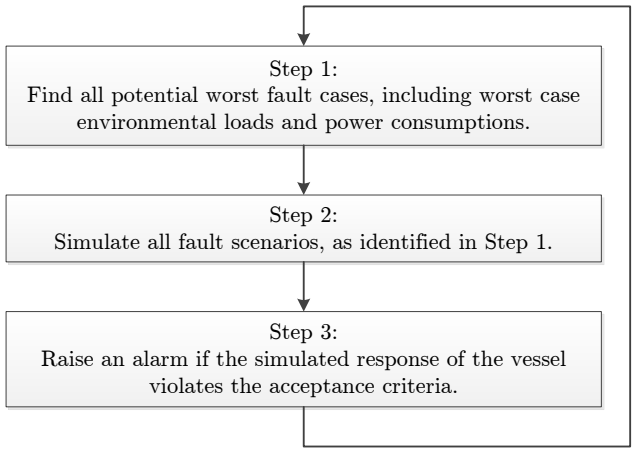

Figure 1: Steps in the dynamic consequence analysis.

tion of the simulator. In Section 4, the fault models are presented, followed by acceptance criterion and environmental models. The second part starts with a presentation of the case plant, and results of the simulations are presented. Two different recovery-methods are used for this case study, in addition to several configurations of the power plant. The results of the simulations are discussed further in Section 9, before conclusions are drawn.

Part I
Method

2. Method Overview

The problem to be solved is to verify that the vessel can maintain its position during the worst single fault. The analysis should capture the transient DP performance after the fault occurs and until the vessel is fully reconfigured, as the vessel may lose position during this period. We suggest the procedure shown in Figure 1 for this analysis. The analysis can be extended by repeating these steps for a number of alternative power plant configurations in order to compare and choose an efficient configuration.

3. Simulator

A dynamic simulator of the electric power plant and marine vessel is used. The simulator in this study should be regarded as an example implementation. Details of the simulator are given in [18]. We are mainly interested in the response of the DP-system due to faults in the power system. Hence, the implemented models are chosen to represent the DP-system as realistically as possible, with its algorithms, tuning, and constraints. The power system is included as it constrains the DP-system during fault recovery. The main components of the simulator are:

Vessel: A 6 DOF model is used to describe the motion of the vessel. The motion is divided into low-frequency motion and first-order wave frequency motion. The low-frequency motion includes non-linear drag, second-order mean and slowly varying wave, current, wind, and thruster loads. The first-order wave frequency motion is calculated from the wave spectrum and response amplitude operator (RAO) of the vessel.

Environmental Load: The wave spectrum used in this study is JONSWAP with a narrow banded directional spectrum, although any other wave spectrum could be used. This is used to generate discrete waves, which are used to calculate the second-order wave loads. The wind and current are modeled with constant speed and direction. The choice of environmental conditions is further discussed in Section 6.

Dynamic Positioning System: The DP controller is implemented as a PID-controller. The position and velocity are given directly from the low-frequency motion of the vessel, assuming an accurate heading and position reference system. This is discussed further in Section 6.

Thrust Allocation: The DP controller calculates a total thrust command for the vessel, the thrust allocation (TA) then allocates a thrust command for each thruster. This is an optimization problem, constrained by the available power.

Power Management System: A PMS is included to simulate the control of power generation and distribution. It includes power available allocation and fast load reduction.

Thrusters: The thruster model includes models of the motor drive, electric motor, propeller, and the local thruster controller. A four-quadrant model is used to calculate the thrust and torque on the propeller. The power consumption of the thrusters can be constrained by the PMS and the thrust allocation, this limits the power of the electric thruster motor.

Electric System: The electric system is assumed to be in steady state, as the mechanical systems in a diesel-electric propulsion system are much slower than the electric system. The modeled variables are frequency, voltage,

active power, and reactive power. This allows us to simulate the power flow and power constraints. However, fast dynamics, such as short-circuit and harmonic distortions, are not included in the model. Some protection relays are included in the model, such as under/over-frequency protection and reverse-power protection. However, as fast dynamics are not modeled, protection relays based on voltage measurements are not included.

Generator Set: The generator set consists of a diesel engine and a synchronous generator. The fuel injection of the diesel engine is constrained by a rate constraint. This engine protection is typically used to avoid large thermal stress. The fuel consumption is calculated by a Willans approximation [19]. All other fuel dynamics are ignored in this study, due to the conservative rate constraint. A governor is used to control the load sharing and speed of the engine. Typically, the governors use droop or isochronous control for the load sharing. An automatic voltage regulator is used to control the voltage and reactive power sharing.

Electric Loads: Loads other than thrusters and heave compensators are modeled as a time-series. These may be hotel loads, auxiliary loads, drilling drives, and cranes. These loads are prioritized, either above or below thruster loads in the PMS. Low-priority loads are reduced if the available power is not sufficient. However, high-priority loads will only be reduced if it is not sufficient to reduce both low-priority loads and thruster loads.

Heave compensators: Heave compensators are included in the model. The electric power consumption is proportional to the heave velocity when the velocity is positive, and zero when the velocity is negative. They may be assigned high-priority in the PMS.

A marine vessel simulator consists of hundreds of parameters and states that need to be initialized. These should be found automatically and may come directly from the status of the vessel. In addition, some values must be predicted, such as the electric power consumption and environmental conditions. As the power constraint on the thrusters is indirectly dependent on the power consumption of the other consumers, it is important that the predicted mean and variation of the power consumption are not underestimated. The power consumption of all electric loads, except thrusters and heave compensators, can be recorded and used as the load case in the simulation. However, a safety-factor may be used to include uncertainties of the future load.

The simulator must be able to run much faster than real-time to be able to return results that are not outdated before they are completed, because of this the consequence analysis should be performed online as the operation and environment may be constantly changing. Several simulations can run in parallel to increase the performance, since the scenarios are independent of each other.

The simulations are started with the vessel's systems in a steady state. This is to make sure that the controllers, such as the I-term in the DP's PID-controller, have settled.

4. Fault Modeling

The simulated cases should include all potential worst-case scenarios based on faults in the power plant and thruster system, and may be identified by a report of the DP system's failure mode and effects analysis (FMEA) [20] or hardware-in-the-loop testing [21, 22]. This could, for example, be faults such as loss of switchboard, loss of bus segment, loss of thruster, loss of generator set, fault in governor, frozen command signal, or equipment delivering maximum capacity when this is not desired (e.g., full thrust in drive-off). Incidents reports reveal that other causes, independent of the power plant, are as important, such as human error, faults in the reference system, and faults in the DP control systems [23, 24]. Subsystem faults, such as faults in the auxiliary systems, are not considered when selecting fault scenarios, but the worst-case consequence of such faults should be considered, for example, shut down of a diesel engines due to faults in the auxiliary systems.

Only single faults are considered, and it is assumed that all protection systems are handling the fault as designed. Therefore, common mode and software faults are ignored in this study, as common mode faults should be detected by FMEA during the design of the system. HIL-testing can also be used to detect common mode and software faults [21, 22].

5. Acceptance Evaluation

The method's third step is to evaluate the response of the simulated fault scenarios. An acceptance requirement can be that the vessel's position and heading error should be kept within the error tolerance. Other requirements may be more relevant in some cases, such as the riser angles for drilling vessels.

To evaluate the fuel consumption of the configurations, the simulation is carried out using the most recently recorded environmental conditions and power consumption.

6. Environment Modeling

The simulation of environmental disturbances is crucial for consequence analysis. It is hard to find the actual worst-case environment, as there are many random variables. For example, the wind gust can be strong and the waves can come in groups.

Therefore, each fault case can be simulated several times using different realizations of the environmental load. However, this is computationally expensive. It is assumed that the vessel's position in DP can be described as first-order wave frequency motion superimposed onto the low-frequency motion. Therefore, the consequence analysis considers only the low-frequency motion and the wave frequency motion is included in the positional error tolerance. This is done by determining the maximum expected wave frequency motion and subtracting

it from the acceptance range. The variance of the position is (from linear theory and variance of a signal given by its power spectrum):

$$\sigma_i^2(\theta) = \int_{\omega=0}^{\infty} S(\omega)\mathrm{RAO}_i^2(\omega,\theta)\mathrm{d}\omega \tag{1}$$

where $i = 1, 2, \ldots, 6$, θ is the angle between the heading of the vessel and the direction of the wave, $S(\cdot)$ is the wave spectrum, ω is the wave frequency, and $RAO(\cdot)$ is the position response amplitude operator for the vessel's wave frequency motion. It is assumed that the wave frequency vessel position is normal distributed, which is given by assuming normal distributed wave elevation [25] and the vessel motion response to be linear. This gives the expected maximum position error:

$$\eta_{i,max} = \sigma_i F^{-1}(1 - \varepsilon/2) \tag{2}$$

where $i = 1, 2, \ldots, 6$, ε is the probability quantile, $F^{-1}(\cdot)$ is the inverse normal cumulative probability function. Note that this procedure must be employed for surge, sway, and yaw, for all headings within the accepted range. This is an approximation as any correlation between surge, sway, and yaw is neglected.

The significant wave height, mean wind speed, and current velocity are increased by a safety-factor to include the uncertainty of the predicted environmental disturbance. The sea state can be estimated from the motion of the vessel (e.g., [26]) or from weather forecasts, and can be configured automatically. The wind velocity is measured directly, so that the time average of the velocity can be used. Some DP algorithms estimate an ocean current velocity, which can be used for future simulation. However, the estimated velocity includes other effects, such as thruster loss and modeling error, and should be used with care.

Part II
Simulation Study

An implementation of the proposed method (Part I) is used in this part. Several operational philosophies exist for control of marine electric power plant, and the response of the vessel is highly dependent on these philosophies. Results for two different fault recovery-methods are presented in this study. These should be seen as use cases of the dynamic consequence analysis, and are presented to illustrate the importance of some dynamic effects that are included in this analysis, but not in static analysis. Several configurations are also simulated to show that the method can be used to choose the optimal power plant configuration.

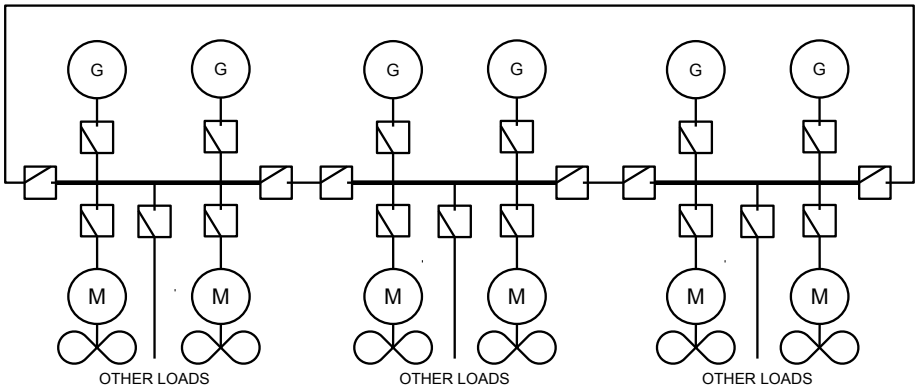

Figure 2: The propulsion system of the case study plant.

7. Case Plant

The simulated vessel is a drilling rig. The power and thruster system is shown in Figure 2 and consists of six diesel generator sets of 9.1 MW and six thrusters of 5 MW. Three 11 kV high-voltage AC switchboards are used to distribute the power, these are connected together in a ring topology. Details of the model are given in [18]. A drilling operation in DP is simulated, with a 2.1 m significant wave height, a mean wind speed of 7.94 m/s, and a mean current of 0.68 m/s. Further, the equipment is referred to by their placement in Figure 2, the numbering goes from left to right. An environment safety-factor of 1.1 is used during the fault scenario simulations. This gives a significant wave height of 2.3 m, an 8.7 m/s mean wind speed, and a mean current of 0.75 m/s. The wave, wind, and current forces have the same direction, and the angle between the vessel's heading and the environment forces is 10° (head sea). The resulting thrust on each thruster is approximately 43 % of the rated thrust.

Drilling drives are simulated as pulse loads of 1.6 MW on Switchboards 1 and 3 for 1 minute, repeating every 3 minutes. Low-priority loads of 1 MW on each switchboard represent non-essential drilling equipment, which can be reduced in the case of a fault. Also, 1 MW high-priority loads are attached to each switchboard. Heave-compensators connected to Switchboards 1 and 3 are included in the model and the gain from the heave velocity to the power consumption is 1 MW s/m. The acceptance criterion is that the vessel should not move more than 3 meters or 5° away from the set-point. The safety-factor for the loads is 1.1 and the high pulse of the drilling drives are simulated to start when the faults occurs.

For this case the wave frequency motion has a standard deviation of 0.51 m; the maximum wave frequency motion is then 1.18 m and 0.01° when using a probability threshold of 98%. The small heading change occurs since the rig is symmetric, the waves are coming close to head-on, and the directional spectrum

Table 1: Alternative configurations. A dash — and a vertical bar | are used to denote when switchboards are connected or disconnected via a closed or open bus tie-breaker, respectively.

Configuration	# connected gensets per swb. 1	2	3	Swb. groups				
1	1	1	1	1	—	2	—	3
2	2	1	1	1	|	2	—	3
3	2	1	1	1	—	2	—	3
4	2	2	1	1	|	2	—	3
5	2	2	1	1	—	2	—	3
6	2	2	2	1	|	2	|	3
7	2	2	2	1	—	2	—	3

of the waves is narrow banded. Consequently, the low-frequency motion must be within 1.82 m and 4.99°.

The configurations to be tested are shown in Table 1. Many more configurations are possible, e.g., open bus tie-breakers and one generator set per switchboard. However, these were chosen as they give sufficient power and represent a broad spectrum of configurations.

The following fault cases are simulated:

1. Loss of a generator set: a generator set is disconnected. Stand-by generator sets, if any, are connected after 45 seconds.
2. Loss of a thruster: Thruster 1 (left most) is disconnected.
3. Loss of a switchboard: both generators and all loads connected to Switchboard 1 (left most) are disconnected. Stand-by generator sets are connected to the healthy switchboards after 45 seconds.
4. Thruster full thrust: the thrust of Thruster 1 (left most) is fixed at full thrust. The thruster is disconnected after two minutes.

For Cases 1, 2, and 4 the PMS is configured to only reduce thruster loads. This is an example of an operational philosophy used to avoid frequent minor faults influencing the operation. During Case 3, it is simulated that the bus tie-breakers (directly or indirectly) connected to the faulty switchboard are opened. This strategy is typically used to avoid propagation of faults from one switchboard to the others. These faults are considered as possible worst-case scenarios for this simulated vessel. Note that Cases 1, 2, and 3 are possible drift-off cases, while Case 4 is a possible drive-off case.

The generators are running in droop mode with equal settings. This gives equal load sharing among the generators connected in each group. A fast phase back system (FPBS) is implemented on the thrusters based on [27]. The load reduction is initiated when the frequency falls below 95% of the rated frequency, the power is reduced linearly, and fully reduced at 92.5%.

Two fault recovery-methods are simulated. In Recovery A, fast load reduction and power available signal are used to make sure that the vessel is able to

Table 2: Results from scenario simulations.

	Configuration	1	2	3	4	5	6	7
Loss of position distance, Recovery A [m]	Loss of genset	**11.4**	0.4	2.8	0.4	1.2	0.4	0.6
	Loss of thruster	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Loss of switchboard	2.0	**0.7**	**4.6**	**0.7**	**5.3**	**0.7**	**0.7**
	Thruster, full thrust	0.5	0.6	0.5	0.6	0.5	0.6	0.6
Loss of position distance, Recovery B [m]	Loss of genset	**2.7**	0.0	0.0	0.0	0.0	0.0	0.0
	Loss of thruster	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	Loss of switchboard	0.8	**0.7**	**0.9**	**0.7**	**1.3**	**0.7**	**0.7**
	Thruster, full thrust	0.6	0.6	0.6	0.6	0.6	0.6	0.6
	Fuel consumption [t/h]	2.45	2.61	2.60	2.76	2.76	2.93	2.93
	Fuel consumption increase [%]	-6.0	0.0	-0.3	5.9	5.9	12.5	12.4
Frequency variations [%]	Maximum deviation	0.94	1.13	0.96	1.13	0.96	1.13	0.97
	Standard deviation	0.18	0.14	0.13	0.13	0.11	0.13	0.09

avoid under-frequency due to overload. In Recovery B, these methods are deactivated. Then, the power plant can use the rotating energy of the generator set during this recovery, and load reduction is only initiated through FPBS. This gives less of a safety-margin against under-frequency, which increases the risk of blackout. Many other fault recovery-methods exist, such as power limit ramps on consumers instead of available power, and the selection of bus tie-breakers to open when the switchboards fails.

8. Simulation Results

Results from nominal and fault simulations are shown in Table 2. The *loss of position distance* is the maximum distance from the reference point to the low-frequency position of the vessel during the simulation.

8.1. Recovery A: Power Available

For Recovery A, Configurations 2, 4, 6, and 7 are accepted, while the others fail due to loss of position during the transient recovery after a fault. Configuration 2 may be preferred as it gives the lowest fuel consumption.

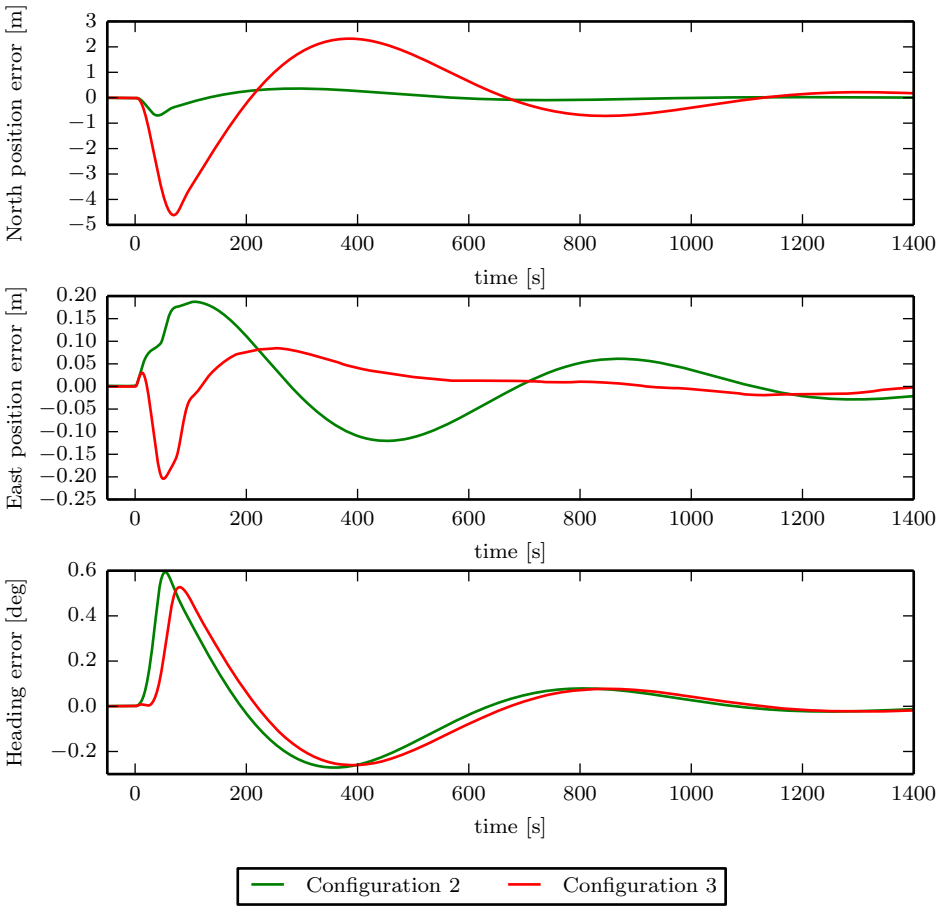

Figure 3: Position and heading error after loss of switchboard for Configuration 2 and 3, Recovery A. The fault occurs at $t = 0$.

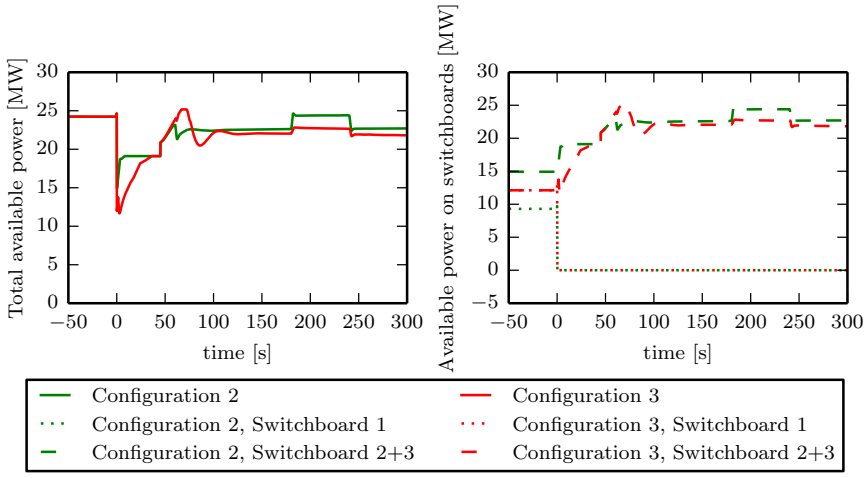

Figure 4: Available power after loss of switchboard for Configuration 2 and 3, Recovery A. The fault occurs at $t = 0$. Note that the available power is similar before the fault for the two configuration, while the load sharing between the switchboards differ for the configurations. After the fault, Configuration 3 has much less available power.

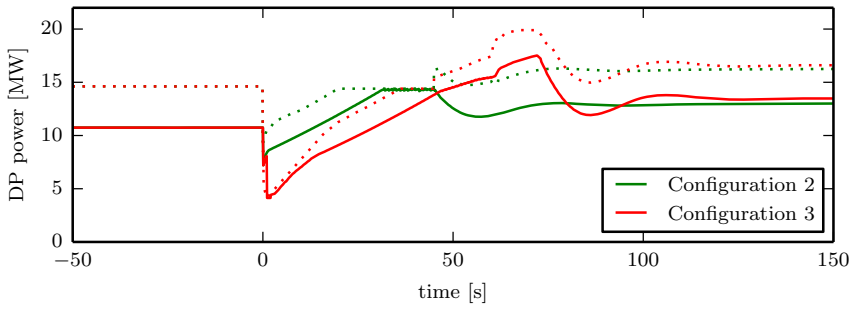

Figure 5: Thruster power consumption after loss of switchboard for Configuration 2 and 3, Recovery A. The fault occurs at $t = 0$. The dotted line is the available power for DP.

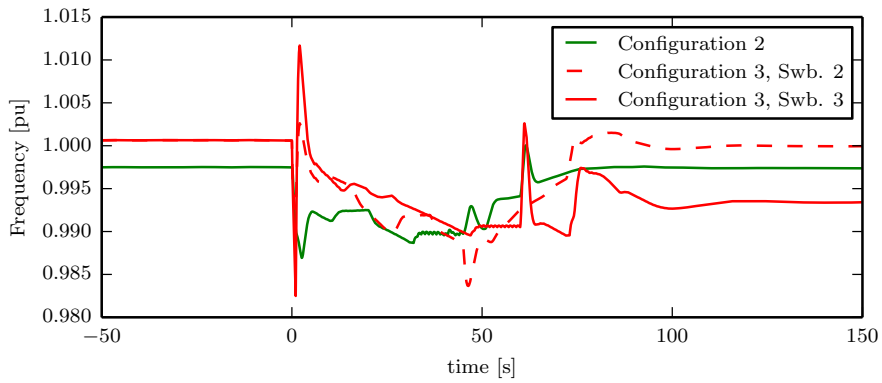

Figure 6: Electric frequency of switchboard after loss of switchboard for Configuration 2 and 3, Recovery A. The fault occurs at $t = 0$.

The position and heading error is shown in Figure 3, for Configurations 2 and 3 after loss of Switchboard 1. For Configuration 2, the bus tie-breaker between Switchboards 2 and 3 is closed after the fault, while it opens for Configuration 3 (since it is indirectly connected to the faulty switchboard). A large transient position error occurs for Configuration 3 after the fault, although both configurations are able to stabilize the vessel to the reference after the fault. This is a case where a transient simulation is necessary to determine the safety of the configuration. The reason for the difference between the configurations is that the available power of a generator set is dependent on the load of the generator. Therefore, the available power for the thrusters will differ, as seen in Figure 5. When using closed bus-tie and equal droop settings, all the generators produce equal amounts of power before the fault. For Configuration 3 (closed bus) this means that the two generators on Switchboard 1 produce the same amount as the two others, connected to Switchboards 2 and 3. Hence, the available power from Switchboard 1 is equal to the available power from Switchboards 2 and 3 combined. This is shown in Figure 4. The worst fault is loss of Switchboard 1, which results in the loss of half the available power. The load-sharing between the independent switchboards will typically be asymmetric during an open bus operation (Switchboard 1 is independent of 2 and 3 for Configuration 2). The worst-case is still loss of Switchboard 1; however, more power is available on Switchboards 2 and 3 after the fault with Configuration 2, which reduces the loss of position.

The electrical frequency of the switchboard is shown in Figure 6. The frequency drops immediately after the fault occurs. However, the fast load reduction quickly reduces the excessive load, and a large drop in frequency is avoided. The slow decrease in frequency is due to the increased power on each generator and the use of frequency droop.

8.1.1. Recovery B: Fast Phase Back System

The rotational energy of the generator set is utilized for emergency power when using FPBS. Results from the simulation of loss of a generator set with Configuration 1 are presented in Figures 7 and 8. This case shows another example of the need for a dynamic consequence analysis, as the vessel is not able to maintain position during the transient recovery, but arrives at a steady state afterwards. The position is plotted in Figure 7, where it is seen that the vessel drifts off by 2.7 m. The reason for this loss of position is shown in Figure 8. When the generator is lost, the other generators take its load immediately. This results in a higher load on the generators than the diesel engines are able to produce, and the frequency decreases. The thrusters reduce their load when the frequency gets low enough, which leads to the loss of position. A new generator set is connected after 45 seconds, the frequency increases again, and the thrusters can produce the necessary thrust to maintain the position of the vessel. Note that the frequency drop with Recovery B is much larger than with Recovery A, as seen by comparing Figures 6 and 8.

Results of the consequence analysis with Recovery A and B are given in Table 2, which show that these two methods give significantly different results. This highlights the fact that the performance is highly dependent on the recovery-methods. Hence, the implemented recovery-methods in the simulator and the real power plant must be as similar as possible.

8.2. Nominal Operation

The choice of configuration is economically important, especially in terms of fuel consumption and maintenance. The fuel consumption is 12.4% higher in Configuration 7 than in of 2. The reason is that the diesel engine can operate close to the optimal working point. In Configuration 2, the engines on Switchboards 2 and 3 are delivering about 35–50% of their rated power, while on Switchboard 1 and all engines in Configuration 7, the engines run at 20–25%. The last operational point is very low and results in high fuel consumption; however, it is reported that this does occur within the industry. It should be noted that Configuration 2 can be optimized further by letting the thrust allocation share the load optimally between the switchboards [7].

The frequency variations are presented in Table 2. These are the variations during nominal operation and are therefore independent of the recovery-method. The variation in the simulations are small and mostly due to the use of frequency-droop. However, it can be noted that running more generator sets gives a stiffer grid, as expected.

8.3. Maximum wind speed

An estimated maximum wind speed is calculated and presented in Table 3. The calculations are performed with environmental parameters from [5, Pt.6 Ch.7 App.B]. However, the wind velocity is calculated without any safety-margin and is only valid for the 10° heading. The accepted wind velocity is underestimated, since only values given from the environmental regularity-numbers in [5,

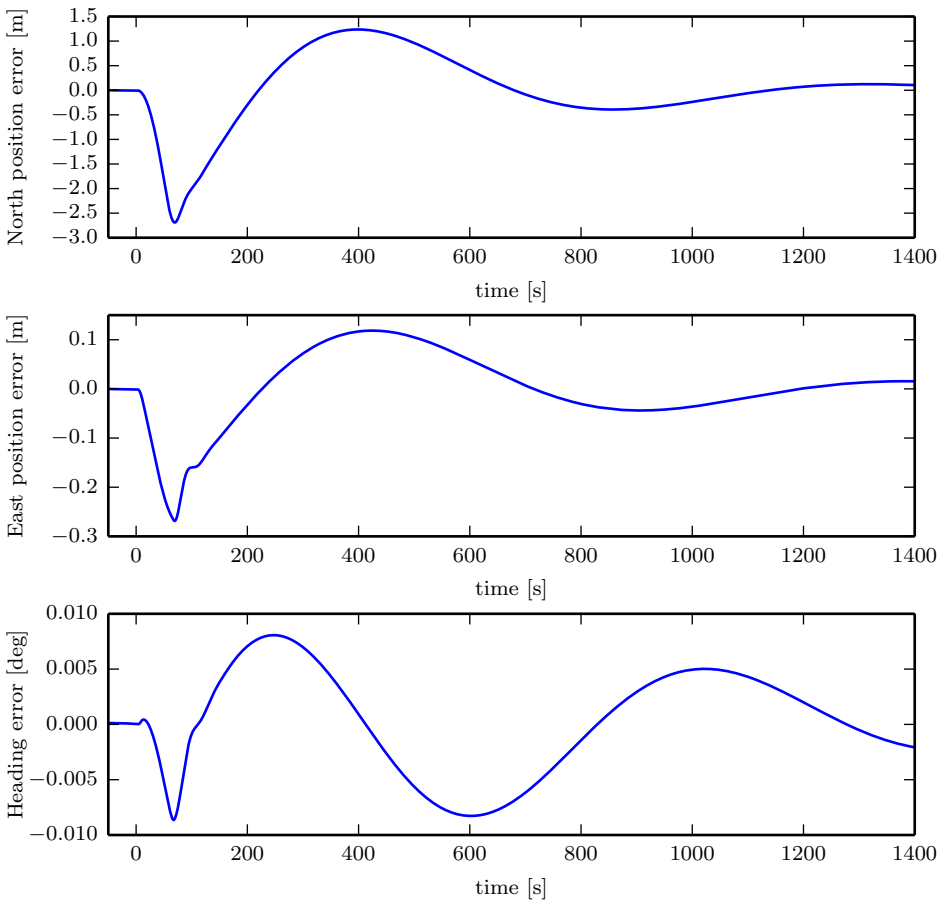

Figure 7: Position error after loss of generator set for Configuration 1 with Recovery B. The fault occurs at $t = 0$.

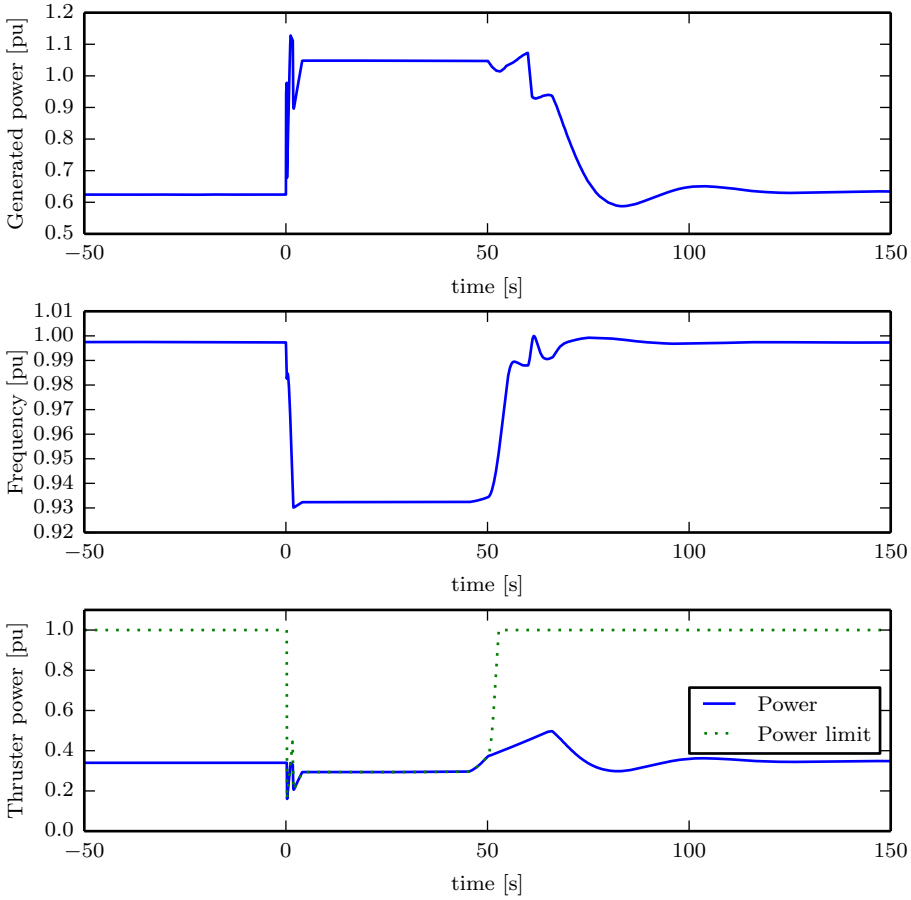

Figure 8: Generator power of Generator set 1, electric frequency, and consumed power and power constraints by FPBS, all in per unit, for Configuration 1 and Recovery B after a loss a generator set. Note that the FPBS in the thruster reduces the power when the frequency drops. This stabilizes the power of the generator set and the electric frequency. The fault occurs at $t = 0$.

Table 3: Maximum wind speed for different configurations and Recovery A.

Configuration	1	2	3	4	5	6	7
Maximum wind speed [m/s]	2.19	10.01	7.48	10.01	6.21	10.01	10.01

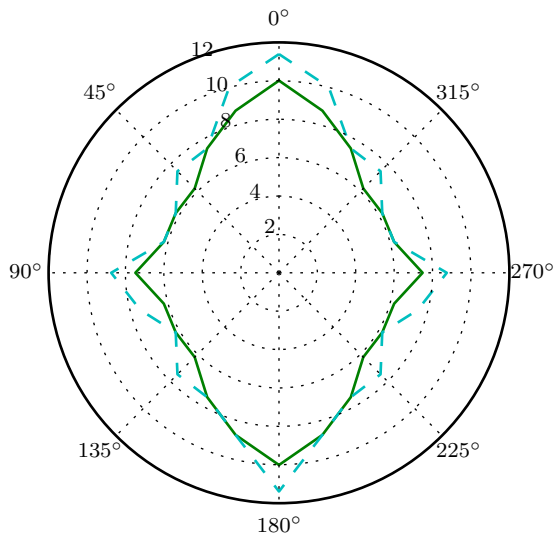

Figure 9: DP-capability plot, for Configuration 2, worst-case scenario and Recovery A. This shows the maximum wind speed the vessel can withstand after the single worst-case scenario. The solid green line shows the results using the method presented in this article. The dashed cyan line shows results using standard static analysis.

Pt. 6 Ch. 7 App. B] were tested. For example, the velocities 10.01 and 11.39 m/s were tested for Configuration 2, and the fault scenarios passed for 10.01 m/s, but not for 11.39 m/s. Therefore, the configuration's maximum allowed wind velocity is between 10.01 m/s and 11.39 m/s.

8.4. DP-capability plot

A DP-capability plot is shown in Figure 9. It is calculated, for varying headings both with the standard static method, see for example [5, Pt.6 Ch.7 App.B], and with the method presented in this paper. In this case no safety-margins are used for either method. The presented method gives a conservative estimate compared with the static method, since it includes both the transient recovery and the power constraint.

9. Discussion

The results from this case study show that a vessel may be able to withstand the mean environmental forces after a fault, but during the transient fault recovery the vessel may temporarily lose position. It is also shown that different fault recovery-methods result in significantly different responses of the power plant and the vessel. Therefore, the consequence analysis can be used to choose the configuration of the power system and recovery functions.

The safety-factor in this simulation study is chosen as 1.1, as an example. Since the wave-drift forces are proportional to the square of the wave height, the force increased by 21% from the nominal to the fault scenario. Similar consideration can be made for both current and wind forces, as they are proportional to the square of the velocity. This approach is conservative, because it assumes that the power plant's worst fault event coincides with the worst-case waves, current, wind, and power consumption. Another approach may be to give a probability-threshold then calculate a safety-factor. However, this is outside the scope of this article. It should be noted that the safety-factor can be changed with the operation. A high factor can be used during critical operations, such as diving and drilling, while a lower factor can be used during non-critical operations, such as standby.

The simulation cases consider a vessel with AC switchboards; however, more and more vessels are now equipped with DC switchboards and batteries for emergency power [28]. This consequence analysis is well suited to these types of vessel, as a dynamic model is able to verify the transient performance of such vessels. The method can also be used to check that the batteries have sufficient power and energy capacity to recover the power plant and terminate the operation, as required by [29, Pt. 6 Ch. 3 Sec. 1 4.3.1]. A simulation-based approach may be needed as batteries may get warm during high power demands, and in such cases the batteries may disconnect due to safety protection systems.

The switchboard voltage will be low during a short circuit of the equipment connected to the switchboard. Hence, equipment with low voltage protection may disconnect. The simulator is not able to simulate such fast transients of the electric system. Therefore, fault ride through capability of the essential equipment should be verified by other methods to avoid that equipment being disconnected or damaged during the recovery of the power plant.

Not only is the configuration of the switchboard important, the parameter settings of some functions, such as load sharing, load shedding, and thrust allocation, are also important. Optimization of these parameters is necessary to obtain optimal power plant operation. However, care should be taken when optimizing with respect to only a few scenarios. In such cases the optimum will sometimes result in changing the worst-case scenario from one scenario to another. For example, if the optimized worst-case is a blackout of Switchboard 1, the optimum may be to increase the load on the other switchboards and let Switchboard 1 produce no load. This changes the worst-case from blackout of Switchboard 1, to blackout of one of the other switchboards. Therefore, individual blackout scenarios for each switchboard must be included and not

only those for the most critical switchboard. Optimizing the parameters is also a much more computationally expensive task, since many values of the continuous parameters must be checked to find the optimum.

The simulation study in [4] considers stationkeeping performance after the transient fault recovery was complete. They did show that the vessel may not be able to maintain its position even though the vessel had sufficiently available thrust for the mean force. The method in this paper cannot detect such performance issues as only the low-frequency motion is simulated. Therefore, a combination of the transient simulation in this paper and the "steady-state" wave-frequency simulation in [4] is necessary.

As noted in [30], more analysis is necessary to verify the integrity of a power system. Such dynamic analysis may include selectivity, short-circuits, and earth fault analysis. It is also assumed that each switchboard is independent of the others, and this must be verified (e.g., with an FMEA).

Reactive power is not considered in this simulation study; however, a generator set can trip due to reactive power overload. Consequently, load reduction and fault analysis with regard to reactive power should be considered.

During simulations, not shown in this paper due to space limitations, the transient loss of position after a fault was seldom a problem for cases when the standby generator sets were not accounted for in the consequence analysis.

10. Conclusion

A dynamic consequence analysis tool based on time-domain simulation is shown in this study. Different configurations were simulated during multiple fault scenarios to evaluate the DP-performance during transient recovery. It is observed for the chosen cases that the transient recoveries after faults are the limiting factor when choosing a configuration, as the vessel may be able to maintain its position before and after the fault, but not during the transition. This is especially important for configurations where one or more standby generators are connected after a fault, as recently allowed by some class notations. It is seen that the result of a reconfiguration can be unpredictable as the thruster system and power plant are complex systems. This method allows the power plant to be configured depending on the required safety level, since more safety-margins can be used during critical and non-critical operations.

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