Reducing power transients in diesel-electric dynamically positioned ships using re-positioning

Aleksander Veksler*, Tor Arne Johansen*, Roger Skjetne†, and Eirik Mathiesen‡
*Center for Autonomous Marine Operations and Systems
Department of Engineering Cybernetics
Norwegian University of Science and Technology (NTNU), Trondheim, Norway
E-mail: aleksander.veksler@itk.ntnu.no, tor.arne.johansen@itk.ntnu.no
†Department of Marine Technology
Norwegian University of Science and Technology (NTNU), Trondheim, Norway; e-mail: skjetne@ieee.org
‡Kongsberg Maritime, Kongsberg, Norway; e-mail: eirik.mathiesen@kongsberg.com

Abstract—**A thrust allocation method with a functionality to assist power management systems by using the hull of the ship as a store of potential energy in the field of environmental forces has been recently proposed and demonstrated to work in simulation. This functionality allows the thrust allocation algorithm to decrease the power consumption in the thrusters when a sharp increase in power consumption is demanded elsewhere on the ship. This way, the high-frequency part of the load variations on the power plant can be reduced, at the expense of minor (typically less than 1 meter) variations in the position of the vessel. The advantages from reduced variations in load include reduced wear-and-tear of the power plant, more stable frequency on the electric grid, reduced risk of blackout due to underfrequency, and more reliable synchronization when connecting additional generators or connecting bus segments. In the present work, this functionality is improved further by continuously monitoring the environmental forces and modifying the setpoint of the dynamic positioning algorithm to place the vessel a short distance (e.g. 20 cm) in the direction of steepest increase of the environmental force potential, thus maximizing the available potential energy. The increased potential energy creates additional capacity for assisting the power plant, which is shown in simulation to be significant.**

I. INTRODUCTION

A marine vessel is said to have dynamic positioning (DP) capability if it is able to maintain a predetermined position and heading automatically exclusively by means of thruster force [1]. DP is therefore an alternative, and sometimes a supplement to the more traditional solution of anchoring a ship to the seabed. The advantages of positioning a ship with the thrusters instead of anchoring it include:

- Immediate position acquiring and re-acquiring. A position setpoint change can usually be done with a setpoint change from the operator station, whereas a significant position change for an anchored vessel would require repositioning the anchors.
- Anchors can operate on depths of only up to about 500 meters. No such limitations are present with dynamic positioning.
- No risk of damage to seabed infrastructure and risers, which allows safe and flexible operation in crowded offshore production fields.
- Accurate control of position and heading.

The main disadvantages are that a ship has to be specifically equipped to operate in DP, and that dynamically positioned ships consume a lot more energy to stay in position, even though anchored vessels also have to expend energy to continuously adjust the tension in the mooring lines.

DP is usually installed on offshore service vessels, on drill rigs, and now increasingly on production platforms that are intended to operate on very deep locations.

To maximize the capability of the DP system, the thrusters should be placed on distant locations on the ship, which makes mechanical transfer of power from the engines less practical compared to electrical distribution. This and other operational advantages [2, p. 6] result in electric power distribution being almost ubiquitous in offshore vessels equipped with DP today.

The type of prime mover predominantly in use is the diesel engine, although other types such as gas engines and gas turbines are also available. A power grid on a DP vessel typically consists of several diesel engines mechanically coupled to electrical generators, delivering power to the thrusters and other consumers through a reconfigurable distribution network with several separable segments and several voltage levels. Often, the thruster system requires more power from the generators than all the other consumers on the grid combined.

The control architecture for the resulting system is highly distributed, with independent controllers for diesel engine fuel injection, generator rotor magnetization, circuit breakers, centralized and local thruster controllers, etc. First, a high-level motion control algorithm considers the current position and orientation of the ship, and determines the total force and moment of force (together called "generalized force") that needs to be applied on the ship. After the generalized force is calculated by the motion control algorithm it is passed as an input to a lower-level thrust allocation algorithm, which determines the forces and angles the individual thrusters should produce. The main goal of the thrust allocation algorithm is to ensure that the combined generalized force that the thrusters generate matches the output from the high-level motion control algorithm. The output from the thrust allocation algorithm is

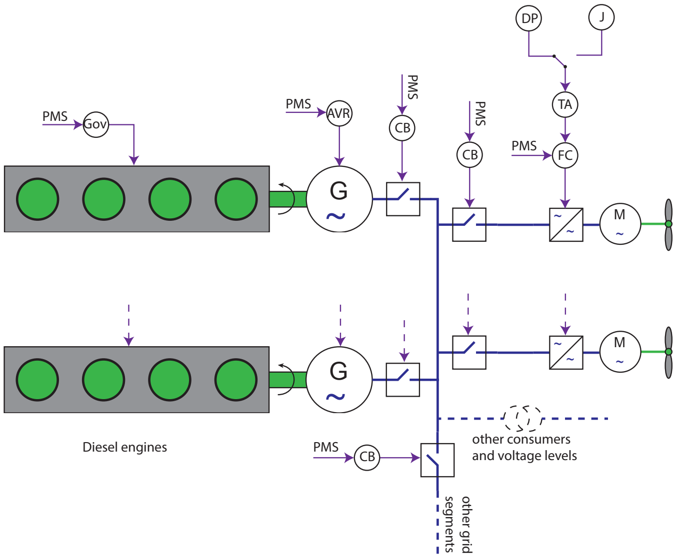

Fig. 1. An illustration showing some of the controllers on the electric grid. A diesel engine speed controller, conventionally called governor (Gov), adjusts the amount of fuel injected into the engines; An Automatic Voltage Regulator (AVR) adjusts the magnetization of the rotor coils of the generators (G); various circuit breakers (CB) connect and disconnect equipment and also isolate faults such as short circuits; the Frequency Converters (FC) are used for local control of the thruster motors (M), and receive commands from both the Thrust Allocation (TA) and the Power Management System (PMS). Finally, the TA can receive the generalized force command from either the DP control system or from a Joystick (J).

then sent to the local thruster controllers. An example of such network with controllers is shown on Figure 1.

While diesel engines are efficient in terms of fuel consumption [3], use of primarily diesel electric power grid introduces a range of challenges for the control system in terms of both stability and minimizing fuel consumption. Stability relates to maintaining stable frequency and voltage on the grid in presence of large and sometimes unpredictable disturbances in load, as well as stable load sharing when a grid segment is powered by more than one generator set. Modern marine diesel engines are almost always turbocharged. Turbocharging limits how fast the engine can increase its output because increasing the output requires building up pressure in the scavenging receiver, which puts a physical limit on how fast a diesel-electric power plant can increase its output. A rapid load increase can therefore lead to a mismatch between the generated mechanical and consumed electrical power. This mismatch can become unrecoverable even if the load rate constraints on the governors are disabled. The result of this mismatch is deficit consumption that extracts energy from the rotating masses in the engines and the generators. If unchecked, it will lead to a rapid drop in frequency, and then a blackout due to engine stall or protection relay disconnect.

Economic and environmental concerns are somewhat coupled, because factors that lead to pollution often also lead to increased economic costs. Increased fuel consumption leads to both increased fuel expenses and (under most circumstances) more pollution. Pollutants such as carbon monoxide, unburned hydrocarbons, soot and $\mathrm{NO_X}$ emissions constitute a minor part of the combustion process in terms of energy, and have therefore a negligible impact on the engine process [4, p. 194]. However, those emissions tend to increase during load transients, especially upwards transients [5, ch. 5 and p. 37]. Those transients also increase wear-and-tear on the engines because of the resulting thermic expansion and contraction. In addition, load variations on the power plant as a whole may lead to excessive start and stop of generator sets, with additional pollution and wear-and-tear due to cold start transients.

Because of this, variations in the power consumption have recently received increased attention in the literature. A cost term for variations in force produced by the individual thrusters is included the thrust allocation optimization problem in [6], which has a dampening effect on the combined load variations. The thrust allocation that is described in [7] includes functionality to handle power limitations and other power-related features in the optimization process.

Additional improvements are possible if one considers that the very large inertia of a typical marine vessel means that short-term deviations of the force output in the thrusters result in relatively insignificant deviations in the position of the vessel[8]. Deviating from the command from the high-level motion control algorithm allows a certain measure of control over short-term power consumption in the thrusters, which can be used to dampen the high-frequency components in the load on the power plant. Several recently-proposed implementations explore this possibility. [9] introduced a modification directly in the local thruster controllers, allowing them to deviate from the orders they receive from the thrust allocation algorithm. In [10] the task of counteracting the frequency variations was moved up to the thrust allocation algorithm. In [11], the modified thrust allocation algorithm was tested on a simulated vessel with a power plant consisting of three generator sets. In [12], a similar effect was achieved by using the available power signal from the power management system to the local thruster control. [13] introduced a modification of the thrust allocation algorithm that allows control of power distribution between the electric buses by adjusting the cost of using different thrusters in the thrust allocation optimization task.

The method in [10] works by adjusting the load from the thrusters by modifying the thrust allocation algorithm. The thrust allocation algorithms in the literature usually attempt to minimize the amount of power that the thrusters use, and in practice they do not use significantly more power than is necessary to fulfill the orders that the thrust allocation algorithm receives from the dynamic positioning or the joystick. This means that to be able to temporarily reduce the load from the thrusters that method must allow the thrust allocation to deviate from the orders; provisions are made to ensure that the ship does not drift further than permissible by the operational requirements from what the position would have been if the orders to the thrust allocation were executed exactly. The resulting deviation should typically be on the scale of $1\mathrm{m}$. The goal of adjusting the load is to reduce the variations in the total load on the power generation system. This method

Symbol	*Description*
T	Current time, i.e. time when the thrust allocation problem is solved.
T_s, T_e	Lower and upper limits for the integrals in (6), (7) which calculate deviations in velocity and position at time T_e.
$\nu_e(t)$, $\eta_e(t)$, $\nu_{e,\,T}$, $\eta_{e,\,T}$	Deviation in respectively velocity and position of the vessel from what they would have been if thrust command was allocated exactly, as functions of time. $\nu_e(t)$, $\eta_e(t) \in \mathbb{R}^3$ contain longitudinal, lateral and heading components; $\nu_{e,\,T} \triangleq \nu_e(t = T)$, $\nu_{e,\,T} \triangleq \nu_e(t = T)$
$\nu_{e,\,max}$, $\eta_{e,\,max}$	Maximal allowed values for $\nu_e(t)$ and $\eta_e(t)$
τ, τ_d	Actual and desired generalized force produced by all thrusters. τ, $\tau_d \in \mathbb{R}^3$ contain surge and sway forces, and yaw moment.
ω_g, ω_{0g}	Respectively actual and desired angular frequency of the voltage on the electrical network. For a 60 Hz electric network, $\omega_{0g} = 2\pi \cdot 60$.
$B(\alpha)$	Thruster configuration matrix. It is a function of the vector α consisting of orientations of the individual thrusters. In this paper, α is assumed to be constant.
N	Number of thrusters installed on the ship.
f	$f \in \mathbb{R}^N$, the force produced by individual thrusters. The elements of f are typically normalized into the range $\left[\begin{array}{cc} \underline{f}, & \overline{f} \end{array}\right] = \left[\begin{array}{cc} -1, & 1 \end{array}\right]$.
K	$K \in \mathbb{R}^{N \times N}$ such that Kf is the vector of forces in Newtons.
P_c	$P_c \in \mathbb{R}^{1 \times N}$ such that equation (4) holds.
Ψ	$\Psi \succ 0$, quadratic cost matrix of variation in force produced by individual thrusters.
Θ	$\Theta \in \mathbb{R}^+$ is the cost of variation in total power consumption.
P_{th}	The total power consumed by the thrusters per equation (4)
$\dot{P}_{ff}$	The desired rate of change of power consumption by the thrusters. This signal can be used to reduce either frequency or load variations on the electrical network.
P_{min}	Minimal power consumption by the thrusters needed to produce commanded thrust.

TABLE I
LIST OF ABBREVIATIONS

effectively uses the hull of the vessel as an energy storage.

In the present work, the effectiveness of this algorithm is further improved by continuously observing the direction of the environmental force, and modifying the setpoint to the DP control algorithm to increase the operational margins for the modified thrust allocation algorithm. This is illustrated in Figures 2–3. Within the analogy of using the hull as an energy storage, this modification allows more energy to be recovered from the hull before the deviation in position and velocity becomes unacceptably large.

The thrust allocation algorithm from [10] is described in Section II, while the modifications introduced in this paper are described in Section III. The results are presented in Section IV.

II. POWER MANAGEMENT-AWARE THRUST ALLOCATION

The trust allocation algorithm in [10] expands on the idea of allowing the thruster system to deviate from the commanded thrust over a short time in order to improve the dynamics of the power distribution system. This idea was first explored in [14], where deviations were introduced on the level of the local thruster controllers. Coordinating the deviation from the dynamic positioning controller orders in the thrust allocation algorithm makes it possible to estimate and limit the resulting deviations in the velocity and the position of the ship.

This algorithm is based on solving a nonlinear optimization problem, similar to [15].

$$P_{min} = \min_{f,s} P_c K \left|f\right|^{3/2} + \left\|s\right\|_{Q_1}^2 \tag{1}$$

subject to

$$B(\alpha)Kf = \tau_d + s \tag{2}$$
$$\underline{f} \leq f \leq \overline{f} \tag{3}$$

This method is well-documented in the literature – although usually with quadratic cost function; see [16].[1] The cost matrix Q_1 must be large enough to ensure that the slack vector s is significantly larger than zero only when constraints (2)–(3) would otherwise be infeasible. The solution to this optimization problem provides a minimum P_{min} to which the power consumption can be reduced while delivering the requested thrust τ_d, at least as long as the condition $s \approx 0$ holds. Power consumption in the thrusters is estimated by the nonlinear relationship

$$P_{th} = P_c K \left|f\right|^{3/2} \tag{4}$$

which is similar to what was used in [15]. The variables P_c, K, f, $B(\alpha)$, K, $\underline{f}$, and $\overline{f}$ are defined in Table I.

In [10], the following thrust allocation optimization problem is used for thrust allocation when there is no thruster power bias requirement:

$$\begin{aligned} \min_{f,\tau_e,s_1,s_2} & P_c K \left|f\right|^{3/2} + \left\|K\dot{f}\right\|_{\Psi}^2 + \Theta\left(\dot{P}_{th} - \dot{P}_{ff}\right)^2 + \\ & \left\|\tau_e\right\|_{Q_2}^2 + \left\|s_1\right\|_{Q_3}^2 + \left\|s_2\right\|_{Q_4}^2 \end{aligned} \tag{5}$$

subject to

$$-\nu_{e,\,max} \leq \nu_e + s_1 \leq v_{e,\,max} \tag{6}$$
$$-\eta_{e,\,max} \leq \eta_e + s_2 \leq \eta_{e,\,max} \tag{7}$$

$$B(\alpha)Kf = \tau_d + \tau_e \tag{8}$$
$$P_{max} \geq P_c K \left|f\right|^{3/2} \tag{9}$$
$$\underline{f} \leq f \leq \overline{f} \tag{10}$$

This optimization problem includes cost for variations in power consumption and in force produced by individual thrusters. It uses a smaller cost Q_2 on deviation from thrust

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[1] The notation used here and in the following is that $\|x\|_A^2 \triangleq x^T A x$ and $|x|^p \triangleq \left[\begin{array}{cccc} x_1^p & x_2^p & \cdots & x_N^p \end{array}\right]^T$ for any x, A and p of suitable dimension.

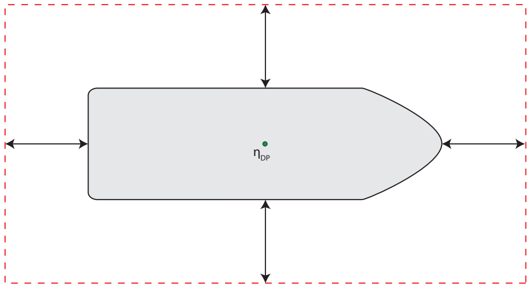

Fig. 2. The DP setpoint and safety margins. Typically, the safety margins are significantly smaller than illustrated.

allocation command τ_d, that is $Q_2 \ll Q_1$. This is to allow the produced generalized force τ to deviate from τ_d when beneficial.

The deviations in the produced generalized force result in deviations in velocity and position of the ship from what they would have been if the thrust allocation algorithm followed the command from the motion control algorithm exactly. Assuming approximately constant orientation of the dynamically-positioned ship, those deviations can be approximated per

$$\nu_e(T_e) = M^{-1} \int_{T_s}^{T_e} \left[B(\alpha)Kf(t) - \tau_d\right] dt \tag{11}$$

$$\eta_e(T_e) = \int_{T_s}^{T_e} \nu_e(t)dt \tag{12}$$

In an exact physical interpretation T_s must be the time when the thrust allocation started running. In practice it can be noted that the motion control algorithm will also detect and attempt to correct the deviations. It will do so on a time scale that is relatively slow compared to that of the thrust allocation algorithm. This can be represented as "forgetting" deviations that happened before a certain point in time. In the implementation, the choice was made to let integration start five seconds in the past relative to when the thrust allocation is solved, therefore assuming that a deviation in velocity and position that was present before that would have been corrected by the motion control algorithm. The constraints (6)–(7) are only evaluated at the time T_e when the solution from the next iteration of the thrust allocation algorithm is available. This is further discussed in Section IV of [10].

The velocity deviation is constrained within a predefined range by imposing (6), and the position deviation is constrained in (7). The constraint (7) is illustrated in Figure 2

A limit on maximal power consumption has to be imposed; it is introduced as P_{max} in (9). This limit necessitates the slack variables s_1 and s_2 in the constraints (6) and (7), with cost matrices Q_3 and Q_4 large enough to ensure that s_1 and s_2 will significantly deviate from zero only if the constraints (6) and (7) would otherwise be infeasible.Thruster bias is not used in this work, but if it was then the power consumption $P_c K \left|f\right|^{3/2}$ in (9) would have to be constrained from below as well.

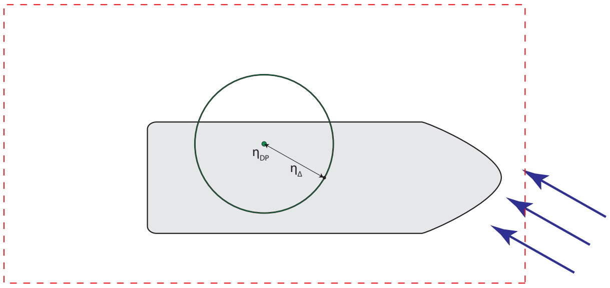

Fig. 3. The original DP setpoint η_{DP} is dynamically modified by η_{Δ} as the environmental forces, here illustrated with blue arrows, change. Typically, the magnitude of η_{Δ} is much smaller than illustrated.

Without the $\dot{P}_{ff}$ signal, the third term in (5) would be zero if the thrust allocation consumed exactly the same amount of power as in the previous iteration of the algorithm (assuming forward Euler discretization). The power feedforward term P_{ff} signals a "soft" requirement for thrust allocation to increase or decrease its power consumption compared to power consumption in the previous iteration. Two applications for this signal are discussed in [10]; however, the only way this signal is used in this work is to compensate for other power consumers that rapidly vary their consumption in predictable patterns. The signal $\dot{P}_{ff}$ is used to reduce variations in the total power consumption by setting

$$\dot{P}_{ff} = -\dot{P}_{others} \tag{13}$$

where P_{others} is the power consumption by other consumers on the vessel. Since the diesel-electric power plant is able to handle rapid load reductions much better than rapid load increases, in this paper the cost of a load reduction is set to a fraction of the cost of a load increase, by changing the value of Θ in (5) depending on whether $\dot{P}_{th} - \dot{P}_{ff}$ is positive or negative.

III. REPOSITIONING

The direction of the environmental forces tends to change slowly. This can be exploited by repositioning the vessel away from the initial DP setpoint towards the environmental forces. This way, when it becomes necessary to reduce the power consumption of the thrusters, the environmental forces will initially push the vessel towards the original setpoint. This allows more time before the thrusters have to increase their consumption again, which is important since the turbocharged diesel engine has an asymmetric step response during large load steps. In [17] the operator is instead provided with a drift-off analysis tool to help him or her determine manually if the setpoint position should be modified to improve the time margins to a drift-off error. Doing this would however require a constant attention from the operator, leaving the operation vulnerable to human error. In this paper, the repositioning can optionally be performed automatically, requiring only minimal attention from the operator.

It is not possible to introduce a constant offset in position by modifying the thrust allocation algorithm alone, because the dynamic positioning control algorithm would detect a constant deviation and attempt to compensate it. The offset is therefore introduced in the dynamic positioning control algorithm. After calculating the offset, the dynamic positioning algorithm informs the thrust allocation algorithm that it now has better margin of safety in some directions and smaller margin of safety in others. This is equivalent to replacing (7) with

$$-\eta_{e,\,max} + \eta_\Delta \leq \eta_e + s_2 \leq \eta_{e,\,max} + \eta_\Delta \tag{14}$$

where $\eta_\Delta \in \mathbb{R}^3$ is the repositioning vector in surge, sway and yaw. This is illustrated in Figure 3. In practice, the repositioning in yaw is usually kept at zero to avoid increasing the wind and wave drag. For improved performance, the constraint (6) was also modified to allow larger velocity deviation in the direction where the safety margin is larger. The repositioning distance should be chosen according to a trade-off between maximum allowed position deviation and the variability of environmental forces. Its choice will depend on the vessel location e.g. relative to other installations, weather conditions and the requirements of the operation, a choice which is best left to the operator.

This modification can be summarized as following:

1) Start the dynamic positioning operation with the thrust allocation algorithm as described previously.
2) Detect the resultant direction of the combined environmental forces. If the dynamic positioning algorithm is PID-based, this can be done simply by measuring the integrator states.
3) Modify the setpoint for the dynamic positioning by moving it a predetermined distance against the environmental forces. Define η_Δ as the vector from the original setpoint to the new one.
4) Replace the constraint (7) with (14).
5) Possibly allow a similar asymmetric modification of constraint (6) to allow a larger velocity deviation in the direction in which the safety margin is larger.

IV. RESULTS

The new algorithm was tested on a simulated vessel with a diesel-electric power plant, same one as in [11]. It is based on SV Northern Clipper, featured in [16]. It is 76.2 meters long, has four thrusters, with two tunnel thrusters near the bow and two azimuth thrusters at the stern. Since this thrust allocation algorithm does not handle thrusters with variable thrust angle, the azimuth thrusters were locked in position 45° towards the center line. This layout is illustrated in Figure 4. All the thrusters are assumed to be symmetric, each capable of producing a thrust equivalent to 1/40 of the ship's weight. The simulated ship is in dynamic positioning mode, dynamic positioning being implemented with three independent PID controllers, one in each degree of freedom. The following limits on velocity and position errors were selected: $\nu_{e,\,max} = \begin{bmatrix} 0.1 & 0.1 & 0.1 \cdot {}^{\pi}\!/_{180} \end{bmatrix}^T$, $\eta_{e,\,max} = \begin{bmatrix} 0.5 & 0.5 & 0.5 \cdot {}^{\pi}\!/_{180} \end{bmatrix}^T$.

Fig. 4. Thruster layout of the simulated vessel

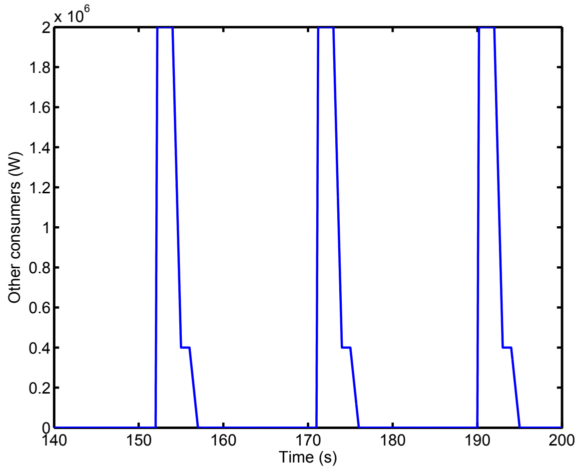

Fig. 5. Load from the other consumers

The setpoint for the dynamic positioning algorithm was set to the origin, and the repositioning distance was set to 0.5 meters. The propulsion system had to compensate for an environmental force on the vessel, which was equivalent to 1% of the weight of the vessel. In addition to the thrusters, the load consisted of a constant load of 300 kVA and periodic load spikes of 1.4 MVA, which after two seconds dropped to 0.2 MVA and after two additional seconds to zero. The power factor was set to 0.95 for the thrusters and 0.75 for the other consumers. The other consumers loaded the vessel as shown on Figure 5. The position of the vessel relative to the set point is shown on Figures 6–7, and the electric bus frequency is shown in Figures 8–9.

V. CONCLUDING REMARKS

Introduction of a repositioning scheme allowed larger absolute variations in the position of the vessel, which allowed some reduction in the fluctuation of the electric bus frequency. The improvement is not overwhelming, but significant in certain operating conditions.

VI. ACKNOWLEDGMENTS

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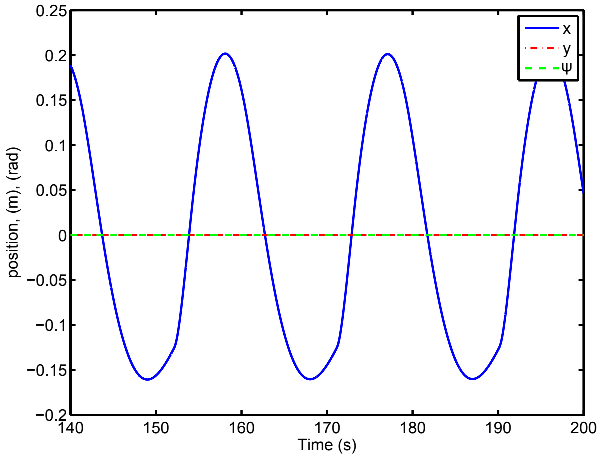

Fig. 6. Position of the vessel with repositioning disabled

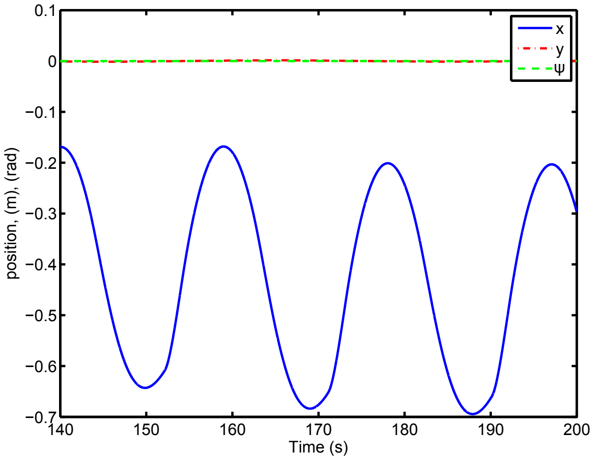

Fig. 7. Position of the vessel with repositioning enabled

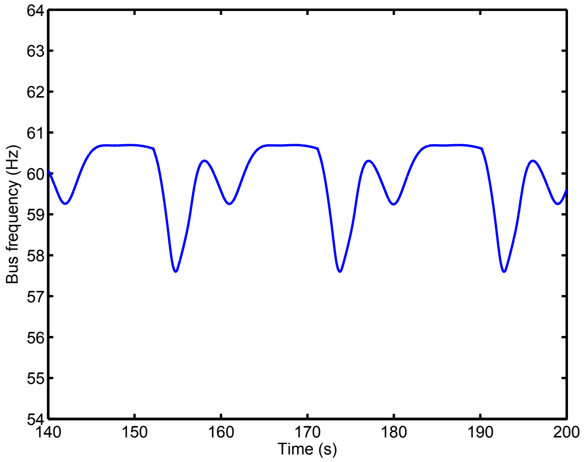

Fig. 8. Bus frequency with repositioning disabled

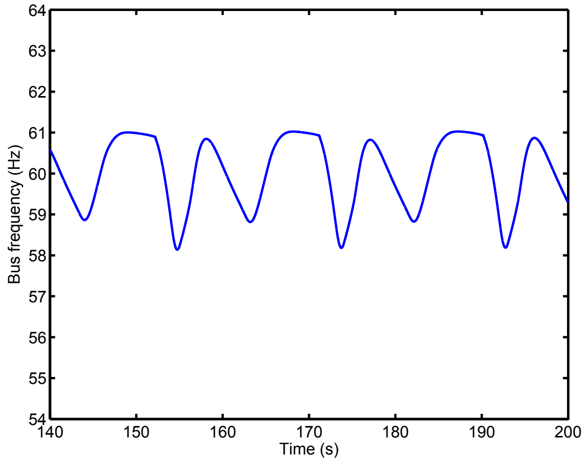

Fig. 9. Bus frequency with repositioning enabled

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