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Model Predictive Control of Marine Vessel Power System by Use of Structure Preserving Model ⋆

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Abstract: The paper presents model predictive control (MPC) based on an optimization model drawn from the structure preserving model (SPM) for marine vessel power systems. Three objective functions are proposed to control frequency, transient load and power flow. The objective functions, in addition to a benchmark controller, are applied to a simulated power system.

Keywords: Marine systems, Power control, Power management, Power system control, Power systems.

1. INTRODUCTION

The electric power system in marine vessels consists of producers and consumers which are often tightly interconnected. The control of these components therefore calls for consideration of the system as a whole.

Model predictive control (MPC) is an algorithm which optimizes the control input to a model. The optimization typically has objectives determined from the model output and constraints according to the control limitations. Optimization is performed repeatedly as time progresses, calculating the optimal control over a limited and receding horizon. Since the model can represent several subsystems and their interaction, MPC provides for holistic system control. Also, the optimization can alleviate for expected future disturbances.

MPC has already been used for design of power control for marine vessels. Stone et al. (2015) demonstrated constrained nonlinear MPC on a medium voltage DC test bed for shipboard power system. Optimal power dispatch was studied by Paran et al. (2015). A real time MPC for shipboard power system, consisting of multiple power sources and loads, was presented by Park et al. (2015). Handling of faults scenarios was implemented by Bø and Johansen (2013).

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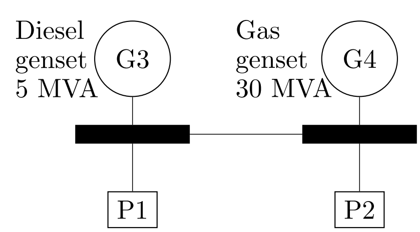

Fig. 1. Example plant single line diagram

The optimization model is crucial for the implementation of MPC. On one hand, it must reflect the main physical properties of the system. On the other, it must not be exceedingly computationally demanding so that optimization can complete in time to apply the control. This is reason to research models and their properties.

The structure preserving model (SPM) for marine vessel power systems by Dahl et al. (2017) models power producers and consumers, and the network interconnecting them by differential equations. It is derived from the stability analysis model by Bergen and Hill (1981) and Hill and Bergen (1982). The SPM calculates the frequency dynamics and the real power based on a graph representation of the system. Each consumer and producer is considered as a node with a voltage magnitude, a relative angle, and—for generators—an acceleration.

Initial investigation of the applicability of the SPM for MPC is the main contribution of this paper. The study is performed as a proof of concept on a simulated example plant.

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2. CONTROL DESIGN

The plant under consideration consists of two generators supplying two loads, as shown in Fig. 1. The generating sets, colloquially referred to as gensets, are rated at 30 MVA and 5 MVA and driven by a gas turbine and a diesel engine, respectively. The loads can represent many types of power consumers, including propulsion, hotel loads or even energy storage devices.

A model describing the system is the starting point for the design. Subsequently, model variables can be used to formulate control objectives which in turn make up the basis for the optimization.

2.1 Optimization Model

The expanded model is

$$D_1\dot{\alpha}_1 = P_1 - \frac{V_1V_2}{X_1}\sin(\alpha_1-\alpha_2) - \frac{V_1V_3}{X_2}\sin(\alpha_1-\alpha_3)\ \text{pu} \tag{1a}$$

$$D_2\dot{\alpha}_2 = P_2 - \frac{V_2V_1}{X_1}\sin(\alpha_2-\alpha_1) - \frac{V_2V_4}{X_3}\sin(\alpha_2-\alpha_4)\ \text{pu} \tag{1b}$$

$$\dot{\alpha}_3 = \left(\omega_1 - \frac{M_1\omega_1+M_2\omega_2}{M_1+M_2}\right)\omega^{\mathrm{B}}\ \ \text{rad/s} \tag{1c}$$

$$\dot{\alpha}_4 = \left(\omega_2 - \frac{M_1\omega_1+M_2\omega_2}{M_1+M_2}\right)\omega^{\mathrm{B}}\ \ \text{rad/s} \tag{1d}$$

$$M_1\dot{\omega}_1 = \tau_1 - \frac{S^{\mathrm{R}}}{S_1}\frac{1}{\omega_1}\frac{V_3V_1}{X_2}\sin(\alpha_3-\alpha_1)\ \ \text{pu} \tag{1e}$$

$$M_2\dot{\omega}_2 = \tau_2 - \frac{S^{\mathrm{R}}}{S_2}\frac{1}{\omega_2}\frac{V_4V_2}{X_3}\sin(\alpha_4-\alpha_2)\ \ \text{pu} \tag{1f}$$

where, for node i, α_i is the node angle referred to the center of inertia, V_i is the node voltage, P_i is the power injected, D_i is the load damping parameter. Further, for generator i, ω_i is the generator frequency, M_i is the generator inertia constant, τ_i is the torque exercised by the prime mover, S_i is the machine-specific rated power, and S^{R} is the plant voltampere base. Even further, X_k is the reactance of line k. The velocity base,

$$\omega^{\mathrm{B}} = 2\pi f^{\mathrm{R}}\ \ \text{rad/s}, \tag{2}$$

follows directly from the system rated frequency f^{R}. Finally, the generators are droop controlled, i.e.

$$\tau_i = u_i - (\omega_i - \omega_{\mathrm{ref}})\frac{1}{R}\ \ \text{pu},\ \ i=1,2, \tag{3}$$

where u_i is the load setpoint, ω_{ref} is the speed reference, and R is the percentage droop of generator i.

Equation (1) is a slightly modified version of the model by Dahl et al. (2017, Eqs. 43-44): rather than referring to the last generator (Ibid., Eq. 19), the angles are expressed relative to the centre of inertia (Stanton, 1972, Eq. 2),

$$\delta_{\mathrm{COI}} = \frac{\sum_i M_i\delta_i}{\sum_i M_i}. \tag{4}$$

Also, genset frequency dynamics are expressed with machine specific bases, rather than with respect to the total plant base. Finally, genset internal nodes are merged with the terminal nodes.

2.2 Optimization Problem

The optimization to be solved at every control step is

$$\min_{\boldsymbol{u}_1,\ldots,\boldsymbol{u}_N} J(\boldsymbol{x}_0,\boldsymbol{u}_0,\boldsymbol{P}_0,\ldots,\boldsymbol{P}_N,\boldsymbol{u}_1,\ldots,\boldsymbol{u}_N) \tag{5a}$$

$$\text{subject to} \qquad \boldsymbol{0} \le \boldsymbol{u}_j \le \boldsymbol{1}\ \text{pu}\ \forall j, \tag{5b}$$

where $J(\cdot)$ is the objective function minimized by the control input $\boldsymbol{u}_j = [u_{j,1}, u_{j,2}]^\top$ at timesteps $j=[1,N]$, N is the optimization horizon length in steps, $\boldsymbol{x}_0 = [\alpha_{0,1},\alpha_{0,2},\alpha_{0,3},\alpha_{0,4},\omega_{0,1},\omega_{0,2}]^\top$, $\boldsymbol{u}_0 = [u_{0,1},u_{0,2}]^\top$ and $\boldsymbol{P}_0 = [P_{0,1},P_{0,2}]^\top$ are the state, control and load vectors at optimization start time, and $\boldsymbol{P}_j = [P_{j,1},P_{j,2}]^\top$ is the expected load at timestep j.

The referred node angles α_i are not directly measurable, and thus not all elements of $\boldsymbol{x}_0$ are known. Instead, $\hat{\boldsymbol{x}}_0 = [\hat{\alpha}_{0,1},\hat{\alpha}_{0,2},\hat{\alpha}_{0,3},\hat{\alpha}_{0,4},\omega_{0,1},\omega_{0,2}]^\top$, where $\hat{\alpha}_{0,i}$ are estimated angles, can be used. A makeshift algebraic solution is obtained by setting $\hat{\alpha}_{0,4}=0$ as reference and assigning the remaining angles based on line power measurements. Observer design beyond this is not within the scope of this paper. Refer to Dahl et al. (2017, Eqs. 6 and 21).

The main load characteristics $\boldsymbol{P}_j$ at timesteps $j=[1,N]$, are assumed to be known ahead. This is realistic for vessels where heavy electric consumers notify the control system ahead of large load changes.

$J(\cdot)$ may represent a single control objective, or a synthesis of multiple objectives. The latter is how MPC accommodates for multi-objective control. Three objective functions for marine vessel power plants are proposed here:

Objective 1: Frequency Regulation. The genset electrical frequency should be kept at the reference, i.e.

$$\omega_i \to \omega_{\mathrm{ref}},\ \ i=1,2, \tag{6}$$

also in the event of load changes.

A quadratic stage cost function which penalises deviation from ω_{ref} is

$$J_1 = \sum_{j=1}^{N}(\boldsymbol{x}_j-\boldsymbol{x}_{\mathrm{ref}})^\top\boldsymbol{Q}(\boldsymbol{x}_j-\boldsymbol{x}_{\mathrm{ref}}), \tag{7}$$

where $\boldsymbol{x}_j\in\mathbb{R}^6$ is the state vector at timestep j, $\boldsymbol{x}_{\mathrm{ref}} = [0,0,0,0,\omega_{\mathrm{ref}},\omega_{\mathrm{ref}}]^\top$ holds the reference velocity and $\boldsymbol{Q} = \mathrm{diag}(0,0,0,0,q_5,q_6)$ is a diagonal weighting matrix. The summands of (7) represent stage costs. Since only the initial state vector $\boldsymbol{x}_0$ is given from (5a), the following states are obtained by integration along the model:

$$\boldsymbol{x}_j = \boldsymbol{x}_{j-1} + \int_0^{t_s}\dot{\boldsymbol{x}}(t,\boldsymbol{u}_{j-1})\,dt,\ \ j=[1,N], \tag{8}$$

where $\dot{\boldsymbol{x}}(\cdot,\cdot) = [\dot{\alpha}_1,\dot{\alpha}_2,\dot{\alpha}_3,\dot{\alpha}_4,\dot{\omega}_1,\dot{\omega}_2]^\top$ is the vector of state derivatives drawn from (1), and t_s is the step length.

Objective 2: Transient Load Sharing Control. An appropriate control input should not deviate unnecessarily.

Changes in load setpoint can be penalised by a quadratic cost:

$$J_2 = \sum_{j=1}^{N}(\boldsymbol{u}_j-\boldsymbol{u}_{j-1})^\top\boldsymbol{R}(\boldsymbol{u}_j-\boldsymbol{u}_{j-1}), \tag{9}$$

Table 1. MPC parameters

Prediction horizon	N	4	steps
Step length	t_s	0.5	[s]

Table 2. Optimization model parameters

Load damping	D_1	0.0001	[s/rad]
	D_2	0.0001	[s/rad]
Mechanical starting time	M_1	0.7833	[s]
	M_2	3.3667	[s]
Rated power	S_1	5	[MVA]
	S_2	30	[MVA]
Line reactance	X_1	0.0189	[pu]
	X_2	7	[pu]
	X_3	1.1667	[pu]

where $\boldsymbol{R} = \text{diag}\,(r_1, r_2)$ is a diagonal weighting matrix. A higher weight will reduce the amount of change for the corresponding genset, while a lower weight allows more change.

Objective 3: Bustie Power Control. Before opening a bustie breaker, i.e. disconnecting the edge between two nodes, the power flow through the breaker should be reduced. The power flow in the connection between nodes is available from the SPM, and can thus be included in the objective. To reduce the flow between nodes a and b, the objective function

$$J_3 = \sum_{j=1}^{N} q\left(\alpha_{j,a} - \alpha_{j,b}\right)^2, \tag{10}$$

where q is a weight for the bustie power flow, can be used.

3. SIMULATION

The system is simulated for 16 seconds for three different objective functions, in addition to a benchmark static droop controller. The initial load is $P_1 = 0.11$ pu and $P_2 = 0.69$ pu. A 500 kW load step warning for node 1 is given to the MPC at nine seconds. The actual step occurs after ten seconds, setting $P_1 = 0.13$ pu.

The power system simulation model is built with the Simscape Power Systems component library in Simulink (The MathWorks, Inc., 2015b). The genset parameters for this high-fidelity model are taken from The Marine Full Electric Propulsion Power System example (The MathWorks, Inc., 2015a). The simulation solver is ode45 (Dormand-Prince) running with a maximum step size of 0.00005 s.

The controller is implemented as a MATLAB function which solves (5) to determine new load setpoints at 2 Hz. The constrained nonlinear programming solver is fmincon with the SQP algorithm. Optimization parameters are given in Table 1.

The optimization model (1) is solved by ode15s (variable order method). Rated voltage is assumed throughout, i.e. $V_i = 1$ pu, $i = [1, 4]$. The system frequency is 60 Hz, and the velocity base ω^{B} is according to (2). The droop coefficient is $R = 0.05$ pu for both gensets. Remaining parameters are listed in Table 2.

The calculation time is determined subsequent to the simulation, by running only the optimization at each $\boldsymbol{x}_0$ considered during the simulation. This distinguishes the computational requirements of the controller from those of the plant simulator.

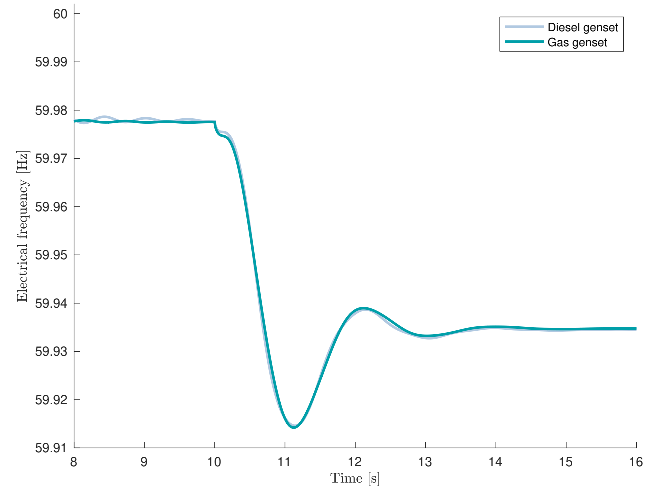


Fig. 2. Static droop: frequency under step load increase

The first eight seconds are not included in the following plots and calculation times. This interval is dominated by simulation initialization phenomena which are not of interest here.

3.1 Benchmark: Static Load Setpoint

The system response with static load setpoints $u_1 = u_2 = 0.8$ pu, is shown in Fig. 2.

When subjected to the step, the frequency droops. The transient response is smoothed by the generator inertias. Finally, the frequency settles at a value lower than the setpoint.

3.2 MPC: Frequency Regulation

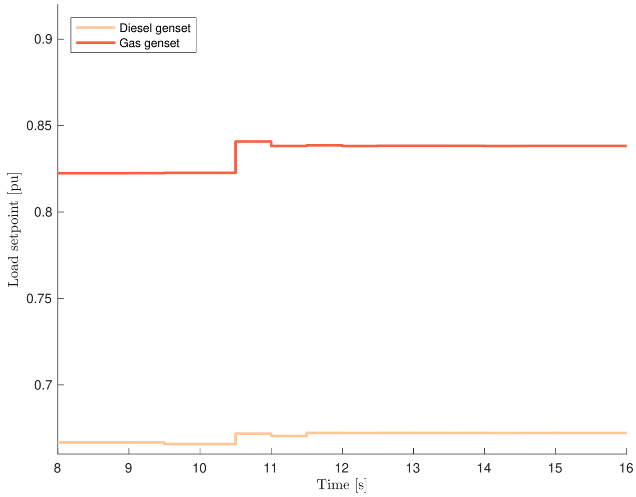
The MPC is allowed to freely adjust the load setpoints to maintain the 60 Hz reference frequency, by the objective function $J = J_1$. The reference is $\omega_{\text{ref}} = 1$, and the weights are $q_5 = q_6 = 10$.

The resulting load setpoints are seen in Fig. 3a. The large initial difference between the setpoints is due to their trajectories during initialisation. Contra-intuitively, the diesel genset initially decreases its setpoint before both gensets contribute to frequency restoration after the load step.

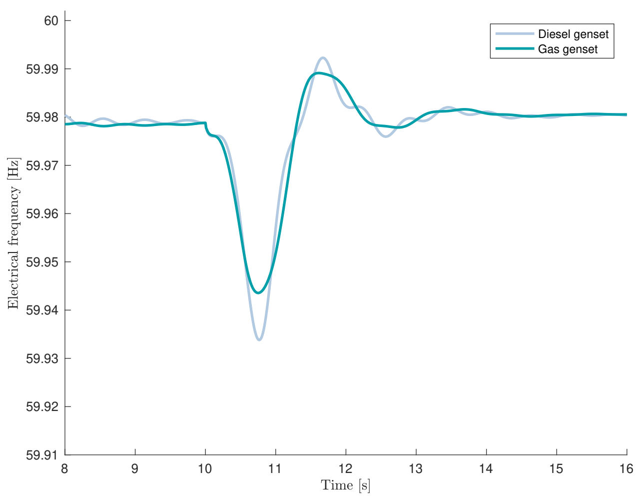
The resulting genset frequencies are shown in Fig. 3b. The initial steady state is a little below the setpoint. Transient effects are seen at the loadstep. These are, however, smaller in magnitude than for the benchmark case, and the initial frequency is regained after the transient.

3.3 MPC: Frequency Regulation and Transient Load Sharing Control

The MPC aims to maintain the reference frequency, while minimizing the changes in setpoint, by using the objective function $J = J_1 + J_2$. The weights are $q_5 = q_6 = 10$, $r_1 = 0.1$, and $r_2 = 0.2$.



(a) Load setpoints



(b) Generator frequencies

Fig. 3. MPC: Frequency regulation

The resulting load setpoints are shown in Fig. 4a. The variation in setpoint is significantly smaller and smoother than in the previous case. With this objective function, both engines increase their output ahead of the load step.

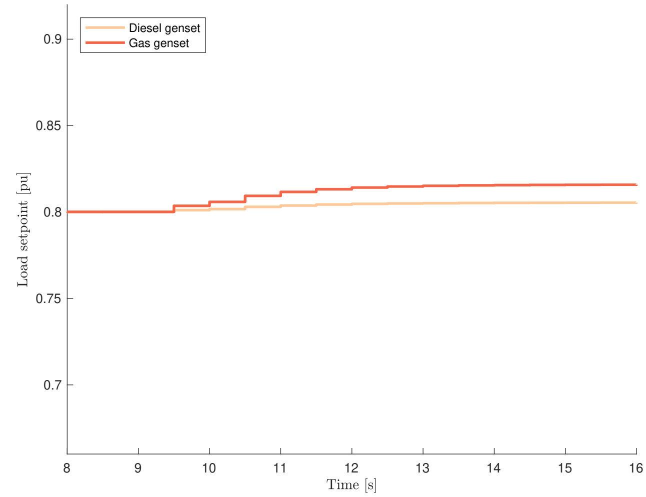
The corresponding generator frequencies are shown in Fig. 4b. As in the previous case, the initial steady state is a little below the setpoint. The frequency increases slightly in anticipation of the load, and dips less than in the previous case. Also, the machine frequency trajectories stay closer, indicating less oscillation in the power flow.

3.4 MPC: Frequency Regulation and Bustie Power Control

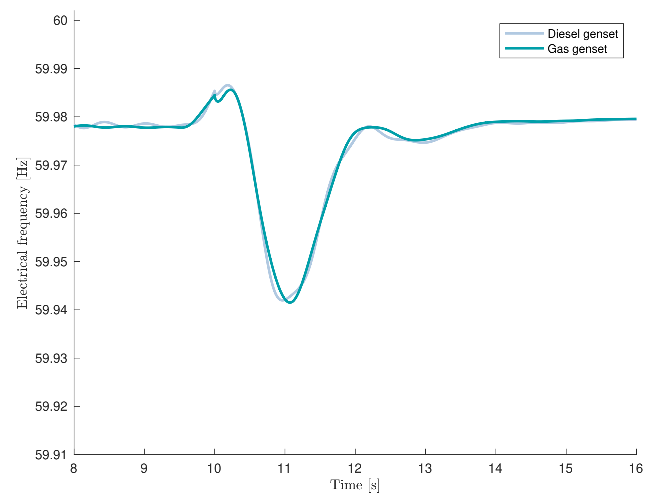
The MPC aims to maintain the reference frequency, while minimizing the power flow between nodes 1 and 2, by using the objective function $J = J_1 + J_3$. The weights are $q_5 = q_6 = 10$, and $q = 100$.

Fig. 5a illustrates how the load setpoint of the generator at the bus where the load step occurs is increased.

The resulting power through the bustie is plotted in Fig. 5c. For comparison, the power flow in the benchmark case is included. At the step, the flow is equal to the



(a) Load setpoints



(b) Generator frequencies

Fig. 4. MPC: Frequency regulation and transient load sharing control

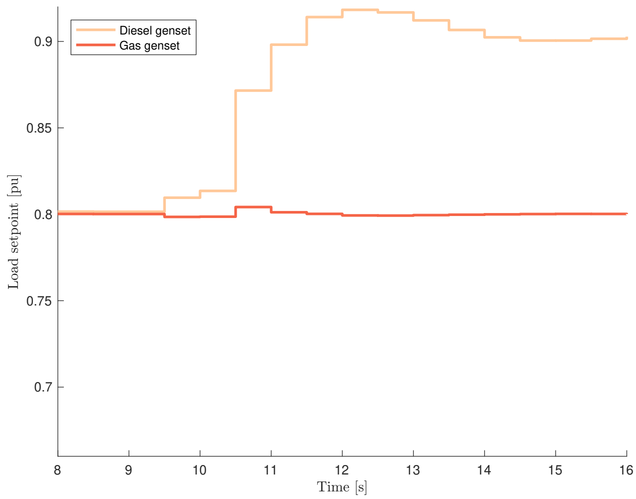
uncontrolled case: the electrical effects are much faster than the mechanical input from the generators. However, as the diesel engine catches up, the power through the bustie is reduced.

The genset frequencies, in Fig. 5b, are comparable to those of Fig. 3b: There are transient effects after which the initial steady state is regained. The trajectories are less smooth than for the previous objective function.

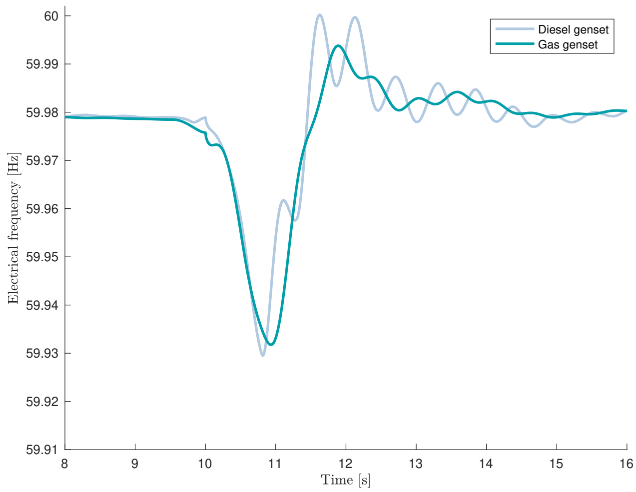
4. DISCUSSION

All the simulated control modes, including the benchmark, are well within acceptable deviation, ±5% of the rated frequency (Det Norske Veritas, 2015, Pt. 4, Ch. 8, Sec. 2, A200). In this regard, the MPC based on SPM is merely an alternative way to regulate the frequency for different loads. The same can be achieved by droop compensation (Johannessen and Mathiesen, 2009) and load feed-forward.

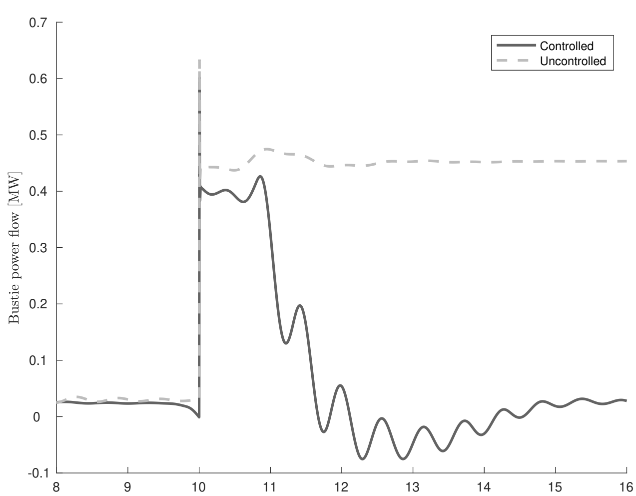
The benefit of MPC is that it can include supplementary considerations both in the form of constraints and additional cost objectives. As demonstrated, the energy flow and loading of the network is directly available for



(a) Load setpoints



(b) Generator frequencies



(c) Bustie power flow

Fig. 5. MPC: Frequency regulation and bustie power control

Table 3. Optimization calculation time and hardware

Objective function	Min. [s]	Mean [s]	Max [s]
J_1	0.18	1.79	7.06
$J_1 + J_2$	0.28	2.05	3.54
$J_1 + J_3$	0.15	5.13	12.09
Apple MacBook Pro 3 GHz Intel Core i7 processor 8 GB 1600 MHz DDR3 memory			

optimization through the SPM. Further, models for fuel consumption, emissions or even engine wear and tear can be added.

The computation time spent to solve (5) at each timestep is given in Table 3. The mean value is within the same order of magnitude but exceeds the 0.5 s timestep several fold. Connected to a physical plant, this would correspond to the optimization not completing in time, thus failing to apply the optimal setpoint. This study tackles the exceeding calculation time by pausing the high-fidelity plant simulation until the next setpoint has been found, thus allowing a proof of concept on a personal computer. Specialized optimization software and dedicated hardware can likely deliver sufficient speed.

MPC requires tuning to obtain proper weighting between objectives. The frequency oscillations of Fig. 3b were reduced by adding an actuation rate constraint. However, in Fig. 5b it seems that the flow objective poses a new challenge. Likely reducing the corresponding weight would reduce the oscillations, at the cost of the flow objective.

The recurrent steady state offset of about 0.04 % is likely due to losses that are not accounted for in the model. For instance, friction in gensets and ohmic losses in the cables are not included in (1). Although small, these deviations underline the MPC's vulnerability to modelling errors.

5. CONCLUSION

The performed simulations suggest that MPC with an optimization model based on SPM is viable for marine vessel power system control. For instance, objective functions can be formulated for frequency regulation, transient shaping and power flow control. Specifically for frequency regulation, the controller performance supersedes the benchmark.

The study strengthens the hypothesis that the SPM catches the main physical properties of the frequency dynamics of on-board power systems. As such it seems fit for control design research.

CODE AND DATA AVAILABILITY

The code and data of this study is published to promote reproduction and facilitate replication. Refer to Dahl (2018).

ACKNOWLEDGEMENTS

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