Transient Energy Management Controller for Hybrid Diesel-Electric Marine Propulsion Plants using Nonlinear MPC

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Abstract: A Nonlinear Model Predictive Control (NMPC) scheme is proposed for the optimal transient power-split problem of a hybrid diesel-electric marine propulsion plant. The NMPC scheme directly controls the torque output of the diesel engine and the electric motor generator ensuring that certain constraints concerning the engine overloading are applied. In this way, fuel consumption and NOx emissions can be reduced. The modeling for the controller design was based on experimental data gathered from the hybrid plant and on first principles for the diesel engine behavior and battery charging. The controller was experimentally tested in real-time operation. Results showed that controller rejected successfully load disturbances and maintained the desired rotational speed of the powertrain as well as the desirable state of charge in battery within limits.

Keywords: Model predictive control, energy management system, hybrid diesel-electric propulsion, hybrid vessel.

1. INTRODUCTION

The interest in novel hybrid technologies for marine propulsion plants is increasing, as a result of the concerns about the environmental footprint of shipping and the prospect for higher overall efficiency of the vessel energy generation system. Hybrid propulsion is used mainly in ships with multivariable operation profile and vessels that operate in coastal areas and within ports where strict emission regulations are applied, such as offshore supply vessels (OSV), naval vessels, tugboats and passenger ships. Several marine applications have been developed and many hybrid topologies have been considered so far, Geertsma et al. (2017).

The power management problem in hybrid marine power plants, which is assessed in this work, remains an open issue. The high system complexity and the introduced extra degrees of freedom by the new systems, as far as the numerous system limitations increase the need for sophisticated controls for the Energy Management System (EMS) that lead to the optimal operation of the plant.

The various control concepts that are applied to marine hybrid propulsion power-split problems come mainly from the automotive sector, where several control methodologies have been proposed. A number of strategies for the power management of hybrid powertrains have been applied, including dynamic programming Gong et al. (2019), stochastic dynamic programming, equivalent fuel consumption minimization Kalikatzarakis et al. (2018), and model predictive control (MPC). Optimal transient load sharing for the minimization of fuel consumption of NOx

emissions in hybrid electric vehicles has been investigated by Sivertsson and Eriksson (2014) and Grondin et al. (2015).

Among the advanced control design methodologies, MPC seems the most promising, as is capable to handle at the same time multi-variable processes, satisfy constraints, deal with long time delays and utilize knowledge for plant disturbance response. Linear MPC has been used in a broad range of applications in engine control and has been integrated into mass production, Bemporad et al. (2018). On the other hand, Nonlinear MPC (NMPC) is inherently capable of dealing with nonlinear equations of physical systems. As such, the control system performance can be guaranteed over the entire operating range of the system.

So far NMPC has been applied to numerous problems such as engine control Albin et al. (2018); Huang et al. (2015); Kang et al. (2016), hybrid electric vehicles Yu et al. (2013), and hybrid vessel propulsion. In Haseltalab and Negenborn (2019) the optimal power sources management of an autonomous tug is calculated using trip information. Recently, strategies including Machine-Learning (ML) were introduced, in an effort to address the issue of computational effort of optimization algorithms online Moriyasu et al. (2019).

This work focuses on power split strategies during transient operation of parallel marine hybrid power plants with the use of NMPC in order to reduce the fuel consumption and NOx emissions. The designed NMPC control scheme directly controls the torque setpoints of the diesel engine and the electric motor ensuring that certain constraints concerning the engine overloading are applied. Here, tran-
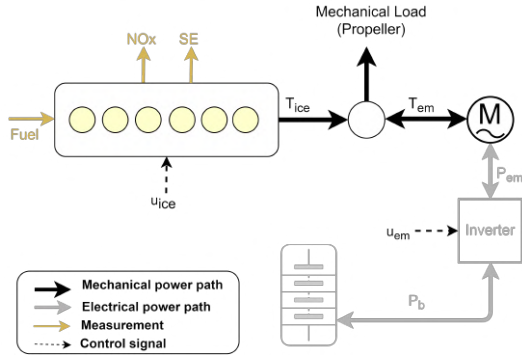
Fig. 1. Schematic representation of a parallel hybrid diesel electric powertrain.

sient dynamics of the diesel engine are suppressed and the engine behavior is quasi-static, while the electric motor is used to cope with the faster dynamics of the system. The modeling for the controller design was based on first principles for the diesel engine behavior and battery charging and fitted using data from the hybrid plant. The controller was experimentally tested in real-time operation in order to evaluate the NMPC performance at load disturbance rejection and maintaining the desired rotational speed of the powertrain and the desirable battery state of charge.

The rest of this work is organized as follows. In section 2, the modeling of the system is presented. The control system is formulated and the NMPC control strategy is developed in section 3. The experimental results are presented in section 4. Finally, section 5 contains the concluding remarks of this work.

2. HYBRID SYSTEM DESCRIPTION AND MODELING

A parallel marine hybrid propulsion plant that consists of an internal combustion engine (ICE) connected on the same shaft with an electric machine (EM) is depicted in Fig. 1. The EM is connected, through an inverter device to the energy storage. The mechanical and electrical power flow, the input signals of the system, as well as the measurements of interest are also shown in the schematic diagram.

For the design of the NMPC, a MIMO model of a parallel hybrid system powertrain is developed to be integrated in the controller. There are four dynamic components: the engine, the EM, the battery and the shaft. However, the system dynamics can be reduced to battery and shaft dynamics in order to simplify the NMPC implementation, as the torque generation time constants of the engine and EM are faster than the controllers computation intervals. As such, system inputs are selected the commands to the ICE (u_{ice}) and EM (u_{em}) for torque production and the load that is applied to the powertrain as disturbance (T_{load}) and system state variables are selected the shaft rotational speed (ω_{shaft}) and the battery state of charge (SOC). The internal model of the controller which describes the powertrain consists of four sub-models that are described below. In total, the system state $\mathbf{x}$ input $\mathbf{u}$ and disturbance input $\mathbf{u_d}$ vectors are the following

$$\mathbf{x} = [\omega \quad SOC]^T ; \ \mathbf{u} = [u_{ice} \quad u_{em}]^T ; \ \mathbf{u_d} = [T_{load}]^T \quad (1)$$

Rotational shaft dynamics The rotational dynamic behavior of the power plant is derived from the second Newton's law as follows

$$\frac{d\omega_{shaft}}{dt} = \frac{1}{J_{system}}(T_{ice} + T_{em} - T_{load}) \quad (2)$$

where ω_{shaft} is the shaft rotational speed, J_{system} is the powertrain moment of inertia, T_{ice} is the output torque of the engine at shaft, T_{em} is the output torque of the electric motor/generator (positive if the EM is motoring) and T_{load} is the torque load which is applied to the power-train.

Diesel engine The brake torque of the ICE depends on the torque command and the rotational speed of the engine. Therefore, it is modeled as a function of them using the following expression

$$T_{ice} = c_1 \cdot u_{ice} - (c_2 \cdot SE^2 + c_3 \cdot SE + c_4) \quad (3)$$

where u_{ice} is the torque command of ICE which is fed to engine ECU, and refers to the percentage of the maximum indicated ICE torque that can be produced, SE is the rotational shaft speed in rpm, (i.e. $SE = \frac{\omega_{shaft} \cdot 60}{2\pi}$) , c_i are coefficients which are fitted to the equation above, using experimental data. The second leg of this equation refers to torque losses due to shaft frictions, etc, Sivertsson and Eriksson (2014).

Electric machine The output torque of the EM is regulated via a frequency inverter. As the response time of the EM torque generation is neglected in the context of this work, the EM torque is modeled as the following static linear relation

$$T_{em} = c_{em} \cdot u_{em} \quad (4)$$

where u_{em} is the torque command as percentage of the maximum torque which is fed to the drive and c_{em} express the transformation to Nm.

The power consumption of the EM was modeled via the Willan's equation

$$T_{em} \cdot \omega_{shaft} = e^{\frac{P_m}{|P_m|}} \cdot P_m - P_0, \quad \text{(Motoring)} \quad (5)$$

where P_m is the power consumption/generation and e and P_0 are the Willan's coefficients. These were considered to be constant.

Battery model The battery was modeled via the widely used equivalent circuit, as described in Guzzella and Sciarretta (2012). The governing equation of the battery current is

$$I_b = \frac{U_{oc} - \sqrt{U_{oc}^2 - 4P_b \cdot R_i}}{2R_i} \quad (6)$$

where U_{oc} is the battery open circuit voltage, which was model as a linear function of state of charge, P_b is the power which is consumed/generated, R_i is the battery internal resistance which is considered constant.

The battery SOC can be calculated by the following equation

$$\frac{dSOC}{dt} = -\frac{I_b}{Q_{max}} \quad (7)$$

where Q_{max} is the maximum battery capacitance.

3. CONTROLLER DESIGN

The control concept is that the primary shaft mover is the diesel engine which is assisted by the electric motor during
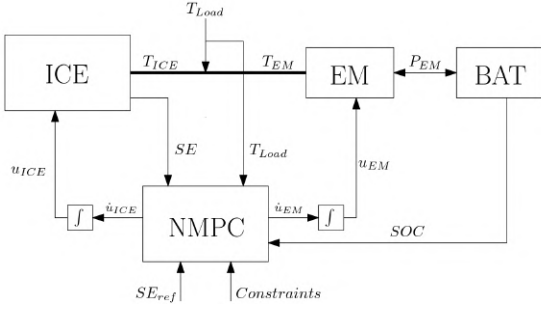
Fig. 2. NMPC architecture and experimental implementation.

transient operations. In that way, the engine operates in a way which resembles steady state operation. In engines fitted with after treatment systems (EGR, SCR), emissions are regulated by them with great efficiency. As such, there is little space for further reduction with the hybrid setup. In respect to the above, the primary object is the controller to maintain the speed reference, and secondary to keep the SOC reference, subject to various system constraints. The constraints in consideration and the controller tuning guarantee that T_{load} is mainly satisfied by the diesel engine in steady state operation, and the EM is used only in transient loads. This power-split strategy, which is called *phlegmatisation*, decreases the transient operation for the diesel engine and can achieve further emissions reduction, with minimum battery usage, Grondin et al. (2015). In order to achieve that, a real-time Nonlinear Model Predictive Controller (NMPC) was designed and implemented, using the *ACADO Toolkit* Houska et al. (2011). The control architecture and implementation is presented in Fig. 2.

For the present application, the structure of the NMPC consist of four differential states $\mathbf{x} = [SE, SOC, u_{ice}, u_{EM}]^T$ and three control variables $\mathbf{u} = [\dot{u}_{ice}, \dot{u}_{em}, \varepsilon]^T$. Also, the load torque T_{load} is fed to the controller as measured disturbance. As it can be noted, the system input variables are considered as differential states, and their derivatives as control inputs. In this way, the rate of change of the system inputs can be weighted and constrained in order to prevent oscillating behavior of the controller. Moreover, the slack variable ε is introduced as additional control input, in order to implement soft constraints, with which the limits violation within the prediction horizon is heavily penalized in the cost function. As such, the optimization problem remains feasible.

The cost function J, which is required to be minimized in order to solve the OCP is the following

$$
\begin{aligned}
J(u_{em}, &\dot{u}_{ice}, \dot{u}_{em}, SE, SOC, \varepsilon) = \\
&= \sum_{i=0}^{N-1} W_i \left[e_{SE,i}^2 \ e_{SOC,i}^2 \ u_{em,i}^2 \ \dot{u}_{em,i}^2 \ \dot{u}_{ice,i}^2 \ \varepsilon^2 \right] + \quad (8) \\
&\quad + W_N \left[e_{SE,N}^2 \ e_{SOC,N}^2 \right]
\end{aligned}
$$

where W_i is the stage cost matrix and W_N is the final cost matrix, $e_{SE} = SE_i - SE_{ref}$ and $e_{SOC} = SOC_i - SOC_{ref}$ are the speed and SOC reference tracking errors respectively. As it can be shown, the usage of the electric

Fig. 3. HIPPO-2 experimental testbed at LME/NTUA.

motor is only penalized in the cost function. This was chosen in order to avoid oscillations of the EM command, and during steady state operations the value of the EM command to be zeroed or such that the SOC to remain constant. The mathematical formulation is

$$
\min_{\dot{u}_{ice}, \dot{u}_{em}, \varepsilon} J(u_{em}, \dot{u}_{ice}, \dot{u}_{em}, SE, SOC, \varepsilon)
$$

$$
\begin{aligned}
s.t. \quad & \text{Equations (2)-(7)} \\
& SE_{min,hard} \leq SE \leq SE_{max,hard} \\
& SOC_{min,hard} \leq SOC \leq SOC_{max,hard} \\
& u_{em,min} \leq u_{em} \leq u_{em,max} \\
& 0 \leq u_{ice} \leq u_{ice,max}(SE) \qquad\qquad (9) \\
& \dot{u}_{ice,min} \leq \dot{u}_{ice} \leq \dot{u}_{ice,max} \\
& \dot{u}_{em,min} \leq \dot{u}_{em} \leq \dot{u}_{em,max} \\
& SE_{min,soft} - \varepsilon \leq SE \leq SE_{max,soft} + \varepsilon \\
& SOC_{min,soft} - \varepsilon \leq SOC \leq SOC_{max,soft} + \varepsilon \\
& \varepsilon \geq 0 \\
& U_{oc}^2 - 4P_b R_i \geq 0
\end{aligned}
$$

where $u_{ice,max}(SE)$ is the maximum ICE torque curve and the last equation refers to battery overloading.

By solving the above optimization problem over the prediction horizon, the appropriate commands for power split are calculated, in order to track the reference shaft speed and SOC.

4. EXPERIMENTAL TESTING

4.1 Experimental setup

For the evaluation of the NMPC behavior, various experiments were conducted on the hybrid propulsion powertrain HIPPO-2 experimental facility at Laboratory of Marine Engineering, NTUA (LME) (seen in Fig. 3). HIPPO-2 consists of an internal combustion engine (ICE) in parallel connection to an electric machine (EM). The prime mover is a 6-cyl. 9.3-liter, four-stroke, in-line diesel engine, with a rated power output of 261 kW at 1800-2200 rpm. The HIPPO-2 engine is fitted with an exhaust gas recirculation (EGR) system and an after-treatment unit for smoke and SCR catalytic NOx reduction. The EM is a 90 kW, 3-phase induction motor/generator, which is controlled by a frequency converter in torque control mode. The mechanical load is applied to the system by an electric brake dynamometer with power capacity of 315 kW. The testbed is controlled and monitored in real time by a dSpace MicroAutoBox II controller board, programmed under the Matlab/Simulink environment. The control and data acquisition of the whole facility is done through the engine and inverter CAN networks.
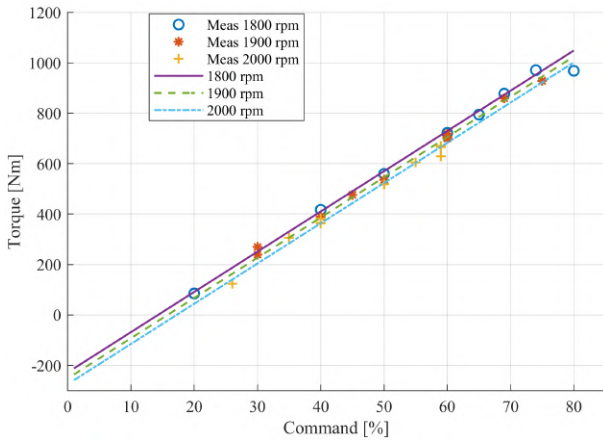
(a) Diesel-engine command to brake torque output mapping, Eq. (3).
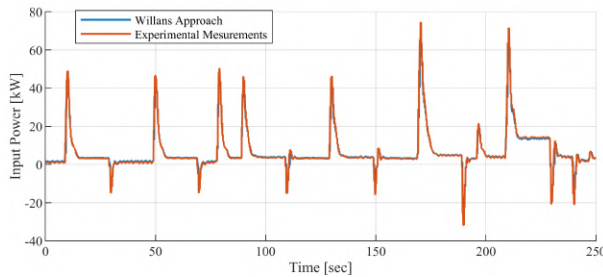
(b) Electric machine efficiency input power for torque production, Eq. (5) vs measurments.

Fig. 4. Identification results of the system behavior.

The experimental facility does not accommodate any battery set yet, and therefore a virtual battery simulation model was employed, which is considered to be charged/discharged by the electrical energy that is produced/consumed by the EM. The battery state of charge is simulated during the experiments. In order the experiment setup to be more realistic, a more complicated model than the one used for controller design was used, Liu et al. (2018). The selection of different battery models for SOC simulation and controller design was intentional, in order to evaluate the NMPC behavior with modeling inaccuracies.

Table 1. Parameters of the NMPC.

Parameter	Symbol	Value
Sample Time	T_s	0.1 s
Prediction Horizon	H_p	10 steps
Control Horizon	H_c	10 steps
Cost Matrix	W_i	$diag(10\ 100\ 0\ .1\ 5\ 0.5\ 10^9)$
Terminal Cost Matrix	W_N	$diag(10\ 100)$
	Constraints	
Soft SOC	SOC_{soft}	[25 75] %
Hard SOC	SOC_{hard}	[20 80] %
Soft SE	SE_{soft}	[1700 2000] rpm
Hard SE	SE_{hard}	[1600 2100] rpm
EM cmd	u_{em}	[-95 95] %
EM cmd rate	u_{em}'	[-50 50] %/s
ICE cmd rate	u_{ice}'	[-20 3] %/s

4.2 Experimental Results

For controller implementation, the coefficients of models (2)-(7) were calculated by fitting data from the tesbed and the manufacturer's test sheets. The validation results for ICE and EM are shown in Fig. 4a and 4b accordingly. The controller tuning was performed in simulation. The

numerical values of the tuning parameters, as well as the constraints of the NMPC problem, are presented in Table 1.

During experiments, step loading at constant speed as well as speed reference steps at constant load were tested. These scenarios resemble the ship power demand during ship maneuvering. NMPC behavior is evaluated against the operation of the conventional set-up, without operation of the EM, where the powertrain is controlled by the diesel engine ECU speed controller, which has its industrial calibration.

Torque steps Torque steps experiments included load steps of 15% of engine nominal torque amplitude from 300-500 Nm and 500-700 Nm. In the first subplot in Fig. 5, the total load of the powertrain and the split between the ICE and the EM is presented. Also with black dotted line, the response of the engine in the conventional setup, (i.e. without hybrid EM) is shown. As it can be seen, when the load is applied to the system, the NMPC reacts and the EM provides torque to the shaft to meet the total load and maintain the rotational speed. After the torque disturbance rejection, the controller regulates the ICE to take up the load slowly, according to the ICE loading rate constraint, until the EM is totally unloaded. At time 27 s where an unloading step is applied to the system the EM is engaged in the regenerating mode in oder to store energy in the battery and keep the desirable SOC. At time 55 s when the system reaches steady state condition after two serial torque step have been applied and the battery SOC has dropped to 46%, the EM is engaged in generating mode in order to charge the battery.

The performance of the diesel engine of the hybrid powertrain, as compared to the conventional setup (ICE only) in Fig. 6. It can be observed that the overshoots in the fuel consumption, which occurs at at time 7, 35 and 47 s in the conventional setup is avoided. At time 55-65 s the ICE has greater fuel consumption in the hybrid setup due to the fact that the diesel engine is used to charge the battery besides satisfying the load. Concerning the NOx emissions, it can be seen that at transients the overshoot due to the engine overloading is avoided, as the NMPC loads the ICE in a quasi-static way. This can also be seen in the subplot with the specific NOx content, the spikes which occur during transient loading of the conventional setup are minimized in the hybrid mode. Despite the fact that the NOx are reduced with the use of the engine EGR system in steady state operation, it lacks performance during transients.

The mean engine performance in the torque step experiment is presented in Table 2. In total the mean absolute NOx emissions were reduced 7.13% and the specific NOx emissions about 3.8% less. A minor reduction is observed for the fuel consumption, however in total 124.4 kJ electric energy is missing from battery at the end of the experiment.

Speed reference steps In this experiment, the speed reference step changes of 100 and 50 rpm were requested by the NMPC at constant torque load 400 Nm. As it can be seen in Fig. 7, at time 10, 35 and 75 s, when a step change in the speed reference is requested, the NMPC
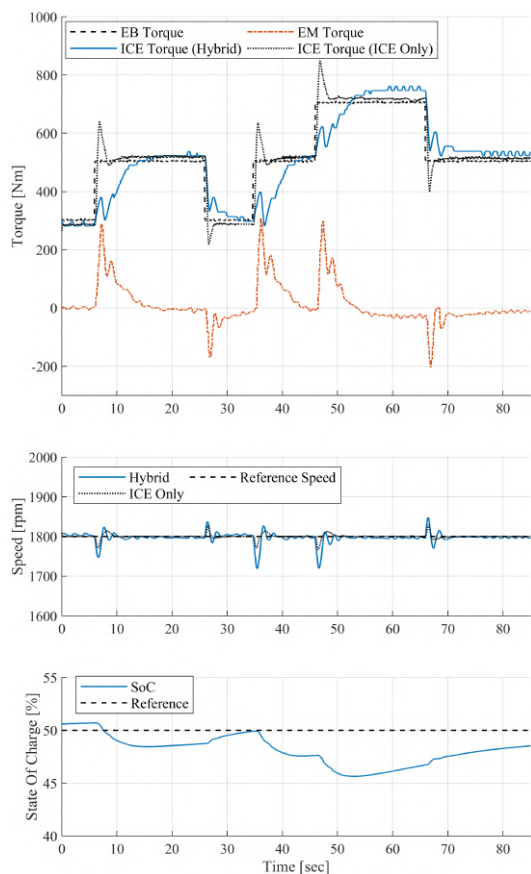
Fig. 5. Loading, power split, shaft speed and battery state of charge during torque steps experiment.
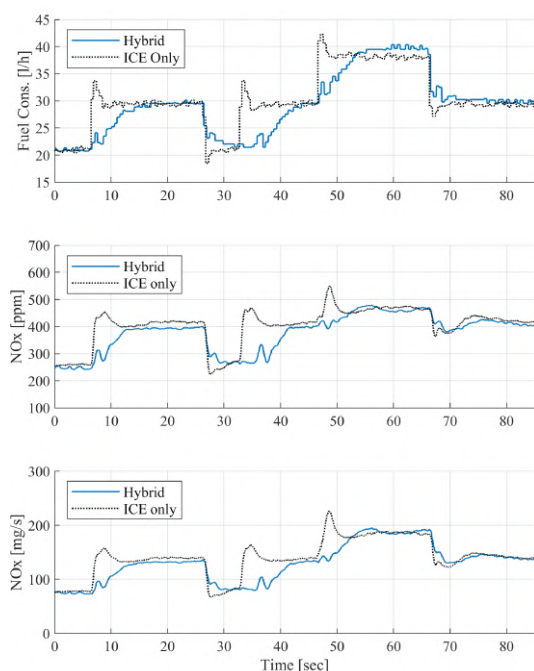

Fig. 6. Diesel engine performance during torque steps experiment.
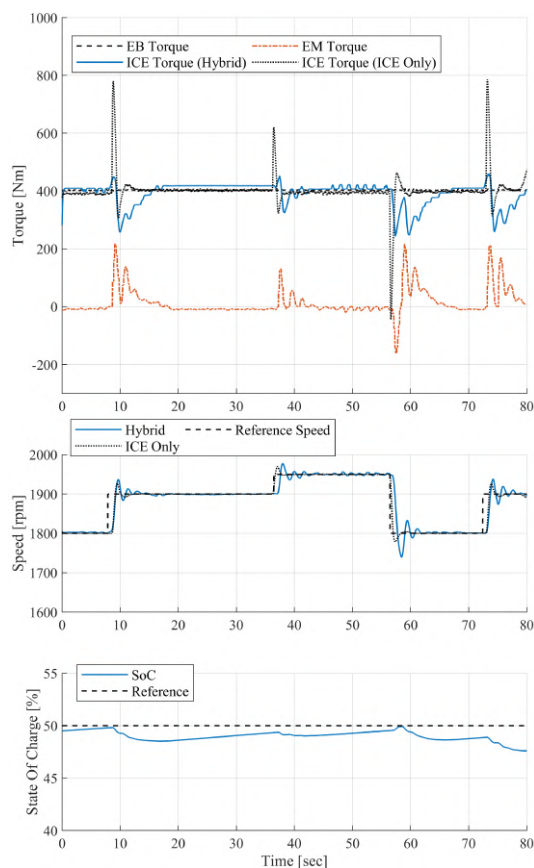

Fig. 7. Loading, power split, shaft speed and battery state of charge during speed reference steps experiment.

regulates the EM and the ICE in order to accelerate the shaft. The additional power that is needed in the higher rotational speed is initially produced by the EM and is taken up by the ICE progressively. In steady state, the ICE produces slightly more power and the EM generates electrical energy, which is stored to the battery. Moreover, at time 55 s, when a deceleration step is commanded, the EM is engaged to absorb kinetic energy from the system which charges the battery (regenerative braking). After that, both power sources are regulated in respect to the ICE loading rate constraint until the system reaches steady state operation.

In Fig. 8, the ICE performance in speed change experiments is presented. As it can be observed, the ICE behavior is smoothened during transients and the engine achieves almost steady state like performance. The fuel consumption and NOx emissions spike that not observed during hybrid operation, as compared to the conventional setup. As noted in Table 2, the hybrid plant under NMPC control achieved overall 5.8% and 6% reduction in NOx emissions and specific NOx emissions respectively during the experiment. The fuel consumption is slightly improved and 123.64 kJ of electric energy were consumed.

5. CONCLUSION

In this paper, a transient Energy Management Controller was proposed for the optimal power-split problem of parallel hybrid diesel-electric marine propulsion plants. The designed Nonlinear Predictive Controller directly regulates
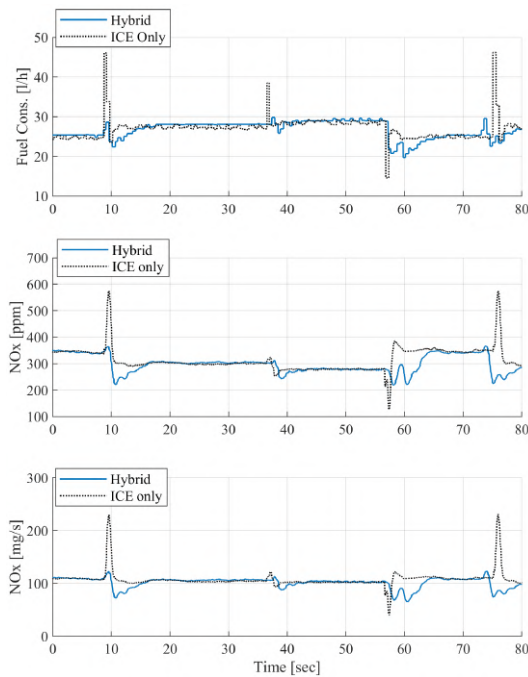
Fig. 8. Diesel engine performance during speed reference steps experiment.

Table 2. Experimental results analysis during step loading.

Quantities	Step Loading Experiment			Ref. Change Experiment		
	ICE only	Hybrid	Diff. (%)	ICE only	Hybrid	Difference (%)
Mean Em. NOx (mg/s)	140.89	130.85	-7.13	107.78	101.54	-5.79
(g/kWh)	5.109	4.914	-3.80	5.07	4.77	-5.99
Total Em. NOx (g)	11.98	11.12	-7.12	8.62	8.12	-5.79
Fuel Cons. (l)	0.715	0.696	-2.73	0.60	0.59	-1.57
El. Energy Cons. (kJ)	-	124.4	-	-	123.61	-
Bat. SOC Dif. (%)	-	-2.075	-	-	-1.3	-

the torque output of the diesel engine and the electric motor generator ensuring that certain constraints concerning the engine overloading are applied. In this way fuel consumption and NOx emissions are reduced. The modeling for the controller design was based on first principles and was fitted with data gathered from the hybrid plant. The controller was experimentally tested in real-time operation, where the controller coped with load disturbance rejection and maintaining the desired rotational speed of the powertrain and the desirable state of charge. In total the NMPC control scheme achieved 7.1% and 2.7% reduction in NOx emissions and fuel consumption respectively, and 6% reduction in mean specific NOx emissions.

Work in progress considers controller testing in cooperation with a load estimator during the application of propeller load during ship maneuvering and environmental disturbance.

ACKNOWLEDGEMENTS

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