Efficient Load Management in Electric Ships: A Model Predictive Control Approach

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***Abstract*—This paper introduces a Model Predictive Control (MPC) approach for the Shipboard Power System (SPS) management under stressful high power loads. As part of the proposed approach, an optimization problem is formulated to mitigate the effects of a high power electrical load in the ship system and improve the overall system performance with respect to operating constraints. The nonlinear MPC also guarantees asymptotic stability of the closed-loop system by including a final cost in the objective function and a terminal inequality constraint. Moreover, a comparison of the controller performance under three different cases of load prediction, i.e. perfect prediction, no prediction and ARIMA prediction with different delays, is presented. In the case studies, a nonlinear model of Medium-Voltage DC shipboard power system is used for the control purpose. Simulation results illustrate the effectiveness of the presented MPC-based load management approach.**

***Index Terms*—Shipboard Power System (SPS), Pulsed Load, Medium-Voltage DC (MVDC), Model Predictive Control (MPC).**

I. Introduction

Shipboard Power System (SPS), as an islanded microgrid, is an independent network which provides electrical energy to the service loads, propulsion motors and weaponry loads on a ship [1], [2]. Since many electric components are tightly coupled in a small space and there is no other relatively stronger network to support the system in case of an emergency, SPS is more sensitive to unanticipated disturbances and physical damages when compared to conventional terrestrial power systems. Therefore, the effective operation of this system needs an appropriate control management framework with well-defined objectives to achieve the desired performance.

In this paper, we use a Medium Voltage DC (MVDC) distribution system which is a trending technology for the next-generation naval warships. The MVDC has significant advantages and improvements in comparison with the conventional AC-based distribution in a shipboard power system [3]–[6]. For instance, no phase angle synchronization is needed between sources and loads which facilitates the connection of different types of generators, loads and storage devices. In addition, the size and weight of generators are reduced due to the removal of frequency constraints. Moreover, the fuel consumption is decreased since variable speed prime movers are used [7]–[9]. A complete architecture of a notional MVDC next generation integrated ship power system is given in [10]. However, in this research, we use the MVDC SPS model dynamics described in [11] to apply the presented MPC-based load management algorithm.

Effects of high power electrical loads such as pulsed loads and the necessity of controlling such loads in the power system have been studied thoroughly in the literature [12]–[15]. In the shipboard power system, weaponry loads including electromagnetic launch systems, electromagnetic guns, and free electron lasers are known as high power pulsed loads. These loads draw very high short-time current from system which can drop the voltage in the whole microgrid, for a short period of time. In shipboard power systems, a large and prolonged voltage (or frequency) drop may shut down the propulsion system or make other sensitive loads offline [16]. Due to the size and weight constraints, it is infeasible to add more conventional generators to support the system for high power loads. Moreover, since shipboard power system is an independent network, there is no external generation support available if necessary. Energy storage systems such as batteries, ultra-capacitors and flywheels are one of the effective remedies for this problem [17], [18]. Other methods may consider pulsed load as an unknown or a known disturbance to the power system and then apply appropriate controller to reject disturbance [12], [19]–[22].

During the past few decades, Model Predictive Control (MPC) has attracted a considerable interest from both industry and academic research community because of its advantages in the practical applications. For instance, MPC can systematically handle physical limitations imposed on the control inputs and system states. It can also deal with different types of system models (linear and nonlinear models), and it is easily reconfigurable and can handle run-time modifications of control objectives [23]–[26]. The general problem formulation of an MPC consists of a system model, environment prediction model, objective function, and system constraints on states and inputs. Research studies on the stability analysis of MPC approach has almost reached a mature stage [27]. Four different approaches are taken in the literature to ensure stability of the MPC design [27]:1- terminal equality constraint [28], 2- terminal cost function [29], 3- terminal constraint set [30], 4- terminal cost and constraint set [31]. In this paper, the closed-loop stability of the nonlinear MPC is considered by including a terminal cost in the objective function as well as an additional terminal state

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TABLE I: A list of representative state variables of MVDC model

Symbol	Description
v_{dc}	DC bus voltage
i_{gen1}	Current of generator 1 (MTG)
i_{gen2}	Current of generator 2 (ATG)
$\omega_{r_{1,2}}$	Rotor speed of gas turbine (MTG & ATG)
$SG_{1,2}$	State of speed governor (MTG & ATG)
$FS_{1,2}$	State of fuel system (MTG & ATG)
$v_{fd_{1,2}}$	Field winding excitation voltage (MTG & ATG)
v_s	Ship speed
ω_m	Rotor speed of propeller
i_{LC}	Induction motor current
λ_{rd}	Rotor d-axis flux linkage in induction motor
λ_{rq}	Rotor q-axis flux linkage in induction motor
λ_s	Stator flux linkage

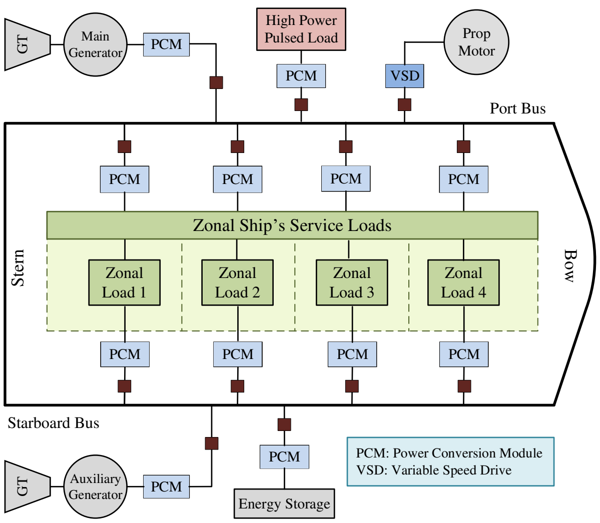

Fig. 1: MVDC SPS architecture

inequality constraint. Due to many applications of MPC in the various real world problems [32]–[38], recently MPC has attracted the interest of researchers in the field of shipboard power system applications [39]–[41]. This paper presents an MPC-based power management approach for mitigating the effects of stressful high-power loads such as weaponry loads in the electric ships.

The reminder of the paper is organized as follows: Section II introduces the nonlinear MVDC SPS model which we use in this paper. Section III presents a complete description of the proposed power management algorithm based on a model predictive control approach. Section IV presents the closed-loop stability analysis of the nonlinear MPC approach. Simulation results of two different cases for a nonlinear MVDC SPS system are given in Section V. Finally, the concluding remarks are presented in Section VI.

II. MVDC Shipboard Power System Model and Formulation

In this paper, we consider the general dynamics of a nonlinear MVDC ship power system as follows:

$$\dot{x}(t) = f(x(t), u(t), t), \quad x(0) = x_0 \tag{1}$$

where $x(t) \in \mathbb{R}^n$ is the state vector and $u(t) \in U \subset \mathbb{R}^m$ is control input, at time t. x_0 denotes a vector of initial values for state variables. The system described by equation (1) can be sampled and written in discrete time by sample time k, for the purpose of prediction and control, as:

$$\begin{aligned} x(k+1) &= f(x(k), u(k), k) \\ x(0) &= x_0. \end{aligned} \tag{2}$$

Here, we use $x(t)$ and $x(k)$ to refer to the state of the continuous-time model and the discrete-time model, respectively.

The considered system contains one Main Turbine Generator (MTG), one Auxiliary Turbine Generator (ATG), four zonal service loads, one propulsion motor which is connected to the DC bus via Variable Speed Drive (VSD), one energy storage device and a high power pulsed load like free electron lasers or electromagnetic guns. This nonlinear MVDC SPS model includes 37 state variables. Table I lists most of the important variables involved in the state space description of the system and Fig. 1 shows the general architecture of the MVDC SPS used in this research. The full mathematical interpretation of the considered MVDC ship model is omitted here due to the limited space and more information can be found in [11].

In the following section, we present the basics of the model predictive control approach and then explain the main results for the power management of an MVDC SPS.

III. The Model Predictive Control Approach

Model predictive control is a model-based approach that solves an optimization program over a given horizon h subject to operation and system constraints and uses a model and its operation environment for the system future trajectory prediction. Even though an optimal control sequence is generated for the whole prediction horizon h, only the first control input is given to the system [23], [24]. MPC can handle a variety of cost functions including non-linear ones as well as several objective functions subject to system constraints. The basic structure of MPC is depicted in Fig. 2.

The overall MPC objective function is expressed as follows:

$$J = \sum_{k=0}^{N-1} L(x(k+1), u(k)) \tag{3}$$

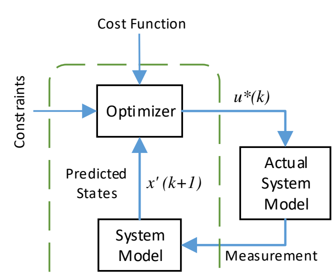

Fig. 2: The basic structure of MPC

where L denotes a nonlinear function with respect to x and u and N is the final time step. In every time step k, predictions and optimal control sequence are computed over a finite prediction horizon h. So, the following cost function is minimized in every time step k:

$$J_k = \sum_{i=1}^{h} L(x(k+i), u(k+i-1)) \tag{4}$$

subject to state constraints $\Psi(x(k)) < 0$, control inputs constraints, and the system's dynamic constraints (2). Here, the following set-point cost function is used:

$$\begin{aligned} L(x(k), u(k-1)) =& \|(x(k) - x^*(k))\|_Q^2 + \|u(k-1)\|_R^2 \\ &+ \|\Delta u(k-1)\|_{R^*}^2 \end{aligned} \tag{5}$$

where $\|\cdot\|$ denotes the Euclidean norm. Q, R and R^* are weighting matrices, $\Delta u(k)$ denotes the changes in the control inputs, and $x^*(k)$ is the desired value of state variable in time step k. The MPC optimization problem is solved over the prediction horizon h at each time step k. The objective of the MPC controller is to meet desired performance by driving system state to the defined $x^*(k)$ while minimizing the cost of control inputs as well as the variations in control inputs $\Delta u(k)$ using a permissible trajectory defined by the state and control constraints. Using the computed optimal control sequence, the first element of the control sequence, $u^*(k)$, is given to the system at time k and the rest are discarded.

The health of the electric shipboard power system is adversely affected by high power loads, particularly, without the presence of any appropriate control methods. In case of large pulsed-type loads, short-time power demand may significantly exceed the power rating of all the installed generators. In a shipboard power system, war specific loads such as electromagnetic guns, or free electron lasers that draw very high short-time current are known as pulsed loads. Such current surges can drop the voltage in the entire microgrid, or shut down the propulsion system, or perhaps throw the underlying loads themselves offline.

To efficiently manage stressful pulsed loads in SPS, we implemented an MPC controller for the nonlinear MVDC SPS described by (2). The goal of optimization problem is to meet voltage performance by maintaining it in the desired value and minimize the changes of the control inputs Δu with respect to states and control inputs constraints. Therefore, the objective function is defined as follows:

$$J(x, u) = \sum_{k=0}^{N-1} \left(q \cdot (v_{dc}(k) - v_{dc}^{ref}(k))^2 + \|\Delta u(k)\|_{R^*}^2 \right) \tag{6}$$

subject to control inputs and states constraints, and system's dynamic constraints (2). q is the weighting factor for the voltage tracking objective. In the case study, the reference DC bus voltage, v_{dc}^{ref}, is 5 kV. The control inputs are the droop gain and the power reference for each generator (MTG & ATG). The droop gain in the voltage controller is employed to control the power share between energy sources. It has indirect effects on the output power of generators and can control DC bus voltage to improve the power quality on the microgrid.

To efficiently handle uncertain load conditions, Autoregressive Integrated Moving Average (ARIMA) prediction method is used to predict load changes in the system with a predefined T_d delay. The ARIMA prediction is a time series method and a generalization of an Autoregressive Moving Average (ARMA) method which is widely used in uncertainty forecasting [42], [43].

In the simulation results, a comparison is presented for different cases of prediction, namely, no prediction, perfect prediction, and ARIMA prediction with different prediction delay values. To quantify the effectiveness of the proposed control approach, we introduce the following Improvement Factor (IF):

$$IF = \frac{1}{N} \sum_{k=1}^{N} \frac{\|v_{dc}(base\ line) - v_{dc}(no\ prediction)\|}{\|v_{dc}(base\ line) - v_{dc}(ARIMA)\|} \tag{7}$$

where $v_{dc}(base\ line)$ is the value of DC bus voltage when we have perfect prediction of a pulsed load event. $v_{dc}(no\ prediction)$ and $v_{dc}(ARIMA)$ are the values of DC bus voltage when we have no prediction, and ARIMA prediction of a pulsed load event in the MPC controller.

In the next section, the closed-loop stability problem of the nonlinear MPC for an MVDC SPS system is discussed.

IV. Stability Analysis

This section presents a nonlinear MPC approach that ensures the closed-loop stability of the considered MVDC SPS system. Based on the method introduced in [31], the objective function includes a finite horizon cost as well as a terminal cost subject to state and input constraints, system dynamics (1), and an additional inequality constraint on terminal state. The terminal state inequality constraint guarantees that the system state will lie within a predefined terminal region, Ω, at the end of the finite prediction horizon. Based on this method, we first obtain the Jacobian linearization of the nonlinear MVDC system (1) around the reference values, leading to the following linear model:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{8}$$

Then, the considered optimization problem setup with guaranteed stability is as follows:

$$J(x, u) = \int_t^{t+T_p} \left(\|x(\tau)\|_Q^2 + \|u(\tau)\|_R^2\right) d\tau + \|x(t+T_p)\|_P^2 \tag{9}$$

or, if the objective is reference tracking,

$$\begin{aligned} J(x, u) = \int_t^{t+T_p} & \left(\|x(\tau) - x_{ref}\|_Q^2 + \|u(\tau)\|_R^2\right) d\tau \\ & + \|x(t+T_p) - x_{ref}\|_P^2 \end{aligned}$$

subject to system's dynamic constraints, state constraints, control input constraints and an additional finite state constraint ($x(t+T_p) \in \Omega$) which requires the states at the end of the finite horizon to be in an assigned terminal region Ω. Q and

R are symmetric positive-definite weighting matrices which are selected for desired performance. T_p is a finite prediction horizon and P is a symmetric and positive-definite terminal penalty matrix.

In this method, the terminal penalty matrix, P, and the terminal region, Ω, are calculated offline to be used in the objective functions and constraints of the online MPC optimization problem. The first step is to determine a linear state feedback $u = Kx$ such that $\bar{A} = A + BK$ is asymptotically stable. Then, a terminal penalty matrix P of the terminal cost is determined based on the solution of the following Lyapunov equation:

$$(\bar{A} + \kappa I)^T P + P(\bar{A} + \kappa I) = -Q^* \tag{10}$$

where P is a unique positive-definite and symmetric matrix, $Q^* = Q + K^T RK$, and a $\kappa \geq 0$ is chosen such that:

$$\kappa < -\lambda_{max}(\bar{A}), \tag{11}$$

where $\lambda_{max}(\bar{A})$ denotes the largest real part of the eigenvalues of the matrix $\bar{A}$. So, by choosing a constant κ satisfying (11) and solving Lyapunov function (10), we determine a unique terminal penalty matrix P.

The second step is to determine a terminal region Ω. We are looking for a neighborhood of the origin, Ω_α, defined as

$$\Omega_\alpha := \{x \in R^n | x^T Px \leq \alpha\} \tag{12}$$

for some constant α. Note that the linear feedback controller should satisfy the constraints in Ω_α. The following optimization problem should be solved for several iterations until the maximum value is non-positive:

$$\max_x \ \left\{x^T P\phi(x) - \kappa \cdot x^T Px | x^T Px \leq \alpha, Kx \in U\right\} \tag{13}$$

with

$$\phi(x) = f(x, Kx) - \bar{A}x. \tag{14}$$

If there exists a suitable value for α, the region Ω_α is used as a terminal region in the online MPC optimization problem. Accordingly, the new optimization problem setup includes the terminal inequality constraint. Note that both the terminal cost and terminal constraint are computed offline and even though the design process starts with linearization, the operation, prediction, and optimization of the MPC does not rely on linearization. The complete discussion on the terminal cost and terminal inequality constraint can be found in [31].

V. Simulation Results

Two case studies are presented in this section to validate the presented MPC method for the nonlinear MVDC SPS system under a high power pulsed load. We use the model architecture described in the section II. The model consists of two generators, one propulsion module, four zonal service loads, one high power pulsed load and one energy storage. This nonlinear MVDC model includes 37 state variables and 4 control inputs. The objective of the MPC controller is to meet voltage performance requirement of maintaining the bus voltage in 5 kV as well as having minimal variations in the control inputs. The control inputs are chosen as the droop gain and the power reference for each generator. The control input constraints are as follows:

$$0.01 < K_{droop_1} < 0.09$$
$$0.01 < K_{droop_2} < 0.09$$
$$21.15 \times 10^6 < P_{ref_{Gen1}} < 25.85 \times 10^6$$
$$2.97 \times 10^6 < P_{ref_{Gen2}} < 3.63 \times 10^6$$

The nominal values (initial values) for the power references in the main and auxiliary generators are set at 23.5 MW and 3.3 MW, respectively, but this setting can be changed. The weighting factor for the voltage tracking objective in (6) is defined as $q = 1$. The weighting matrix R^* for minimizing changes in the four control inputs is defined as follows:

$$R^* = \begin{bmatrix} 10 & 0 & 0 & 0 \\ 0 & 5 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

This section provides the simulation results of two cases with different prediction delays to validate the proposed MPC method under a pulsed load with 2 MW amplitude in the system. The horizon for MPC-based controller is 2. The sampling time T_s is $0.01s$, the control interval T_c is $0.1s$ and the desired voltage V_{dc}^{ref} is 5 kV. Here, *fmincon* solver in the MATLAB is employed for the nonlinear optimization problem in the MPC controller. The simulation is done on a PC with Core i7-7700K CPU and 32.0 GB of RAM running on MATLAB R2016a.

The following two subsections present the results of applying the MPC controller under no prediction, perfect prediction and ARIMA prediction with two different prediction delays.

A. ***Case I.***

In this case, the prediction delay T_d in ARIMA prediction is set to 10 T_s. The pulsed load starts at $t = 2\ s$ with $2MW$ amplitude and 2 s duration as depicted in Fig. 3. The control inputs are shown in Fig. 4 for this case with three different predictions. Fig. 5 depicts the bus voltage of the MVDC system. In these figures, the red line shows the results when no pulsed load prediction is used. The green and blue lines show the results for ARIMA and perfect prediction of pulsed load in the MPC, respectively. Perfect prediction (base line) represents the results when MPC has complete information of the pulsed load event including amplitude, start time and end time for the prediction. In case I, the improvement factor described in (7) is 4.0899.

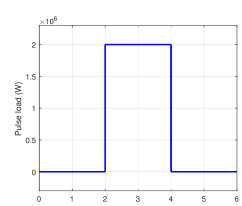

Fig. 3: Pulse load with 2 MW amplitude

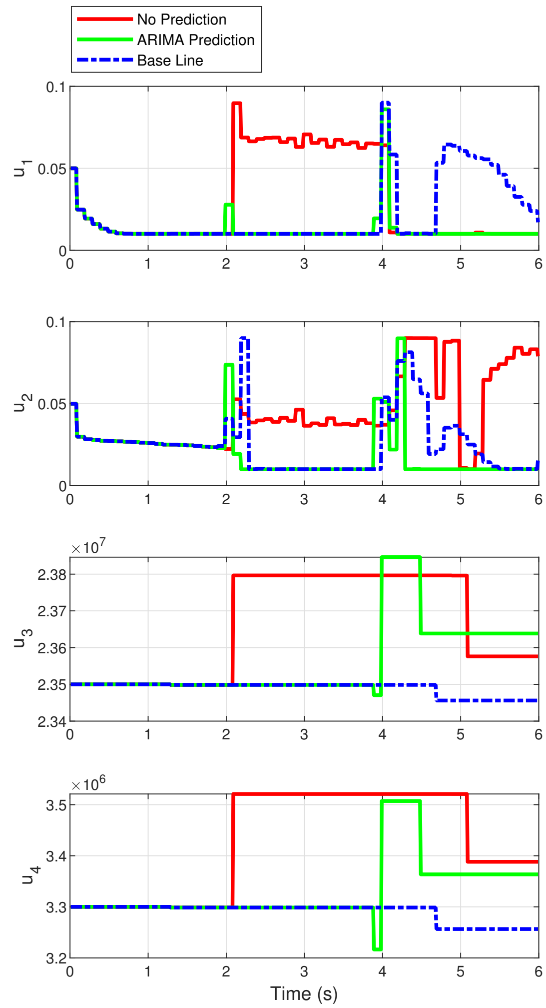

Fig. 4: Control Inputs of of Case I: $u_1 : K_{droop1}$, $u_2 : K_{droop2}$, $u_3 : P_{ref_{Gen1}}$, $u_4 : P_{ref_{Gen2}}$

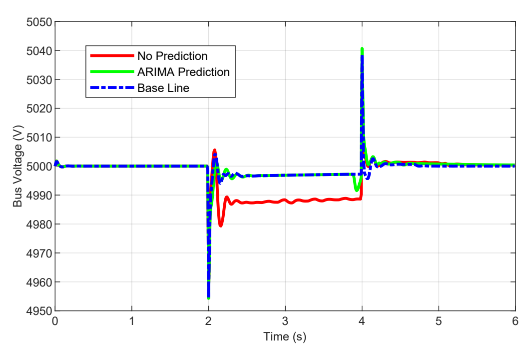

Fig. 5: DC Bus Voltage (V) of Case I

B. *Case II*

In this case, the prediction delay T_d in ARIMA prediction is set to 30 T_s. The pulsed load starts at $t = 2$ s with $2MW$ amplitude and 2 s duration. Fig. 6 show the control inputs for this case with three different predictions. Fig. 7 depicts the bus voltage of the MVDC system. Since there is more prediction delay in this case, the larger error is observed in the bus voltage near the start time and end time of the pulsed load (2s and 4s) in comparison with the previous case. These changes are obvious in Fig. 7. In case II, the improvement factor is 1.6739.

A summary of the simulation outcome for these two cases is shown in table II. Accordingly, the simulation results verify the effectiveness of the presented MPC-based controller to mitigate the effects of a high power pulsed load event in the MVDC SPS.

TABLE II: Simulation information

	Case I	**Case II**
Sampling Time (T_s)	0.01 s	
Control Interval (T_c)	0.1 s	
Reference DC Bus Voltage	5000 V	
Pulse Load Amplitude	2 MW	
Prediction Delay (T_d)	10 T_s	30 T_s
Improvement Factor	3.9768	1.8938

Stability Analysis Discussion: The stability guarantee, as described in Section IV, is added to the simulation to compare the performance of approaches. The objective function is extended to include terminal cost and an additional terminal state inequality constraint. The terminal penalty matrix, P, is obtained based on the solution of the Lyapunov equation (10) and linearization of (1).

At first, the Jacobian linearization of the nonlinear MVDC system (1) is obtained, and then, a linear state feedback $u = Kx$ is designed such that $\bar{A} = A + BK$ is asymptotically stable. This linear state feedback is just used to find a terminal penalty matrix, P, and a terminal region offline. Based on $\lambda_{max}(\bar{A})$ and the condition (11), we choose a constant κ which yields the unique solution for the Lyapunov equation (10). Then, the following optimization problem

$$\max_{x} \left\{ x^T P\phi(x) - \kappa.x^T Px | x^T Px \le \alpha, Kx \in U \right\}$$

is solved by reducing α from α_1 until the optimal value is nonpositive, where α_1 is the largest possible value such that $Kx \in U$ for all $x \in \Omega_{\alpha_1}$. Finally, an $\alpha = 0.024$ is obtained from this process which specifies a region Ω_α in the form of (12) in which the following inequality is satisfied:

$$x^T P\phi(x) \le \kappa x^T Px \tag{15}$$

The region Ω_α can then serve as a terminal region in the online MPC optimization problem. Here, the output simulation signals are almost similar to the previous section and the response will not be repeated for the sake of brevity. However, it is observed that for the case of no prediction, the stability guarantee improves the performance of the system. Even though the MPC controller can work without the added stability constraints, there is no guarantee that the controller will perform suitably with any initial condition or different sampling time or control interval. There is no significant difference in terms of computation time between controllers with stability guarantee and without it; however, the latter case usually requires longer prediction horizons. In general, it is recommended to impose stability conditions to the controller to guarantee the stability of the closed loop system under different conditions.

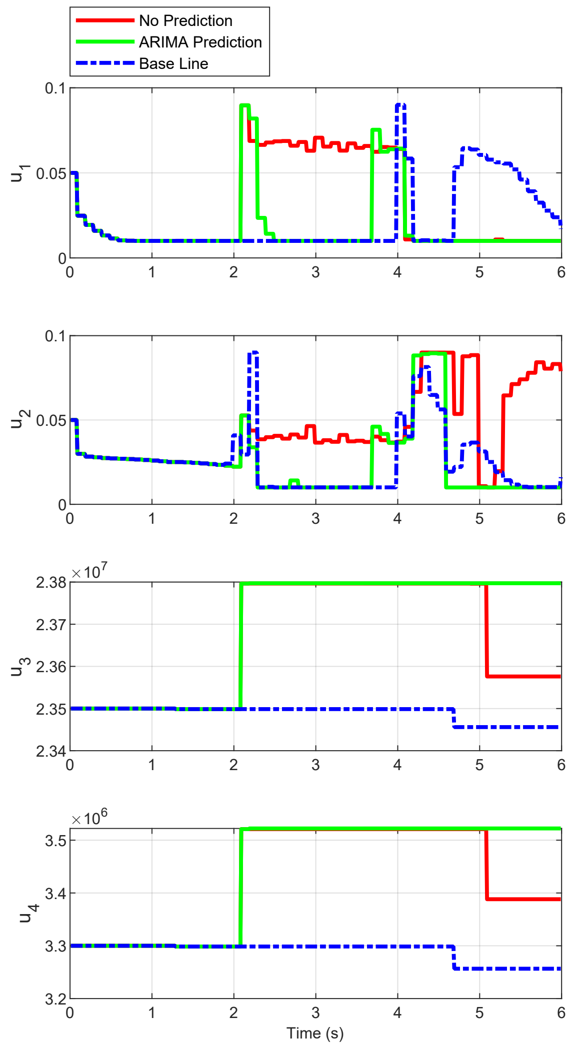

Fig. 6: Control Inputs of of Case II: $u_1 : K_{droop1}$, $u_2 : K_{droop2}$, $u_3 : P_{ref_{Gen1}}$, $u_4 : P_{ref_{Gen2}}$

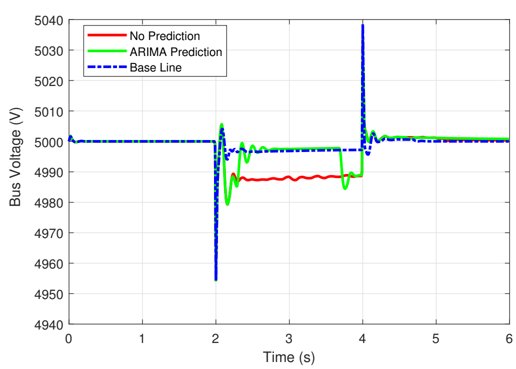

Fig. 7: DC Bus Voltage (V) of Case II

VI. Conclusion

This paper presents a model predictive control approach for the effective shipboard power system load management. An MPC controller is designed to control the MVDC SPS system under high power pulsed load used for, for example, free electron lasers under battle condition. The optimization goal is to meet voltage performance with minimal variations in the control inputs with respect to operating constraints. The closed-loop stability of the nonlinear MPC for an MVDC SPS system is also guaranteed by adding a terminal cost in the objective function and considering an additional terminal state inequality constraint. A terminal penalty matrix and a terminal region are obtained offline. The validity of the presented MPC-based algorithm is shown in the simulation results. Moreover, an improvement factor is introduced to quantify the effectiveness of the presented control approach under three different cases of prediction.

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