Analysis of Data-Driven Modeling of Cycloconverters for Efficient Electromagnetic Transient Simulations of Electrified Ship Propulsion Systems

Seyyedmilad Ebrahimi* and Juri Jatskevich
Department of Electrical and Computer Engineering, The University of British Columbia, Vancouver, Canada
Email: ebrahimi@ece.ubc.ca (S.E.), jurij@ece.ubc.ca (J.J.)

***Abstract*—Simulation studies of modern electrified ship propulsion systems using the discrete switching models of cycloconverters are very time-consuming and require expertise and accuracy in modeling all the details of the ship's electric power system. Alternatively, data-driven models of cycloconverter-based Variable-Frequency-Drive (VFD) systems are proposed, which may simplify the modeling and improve simulation efficiency and speed. The data-driven models can be established based on several measurements or a few runs of the detailed simulations, but their subsequent use enables very fast and efficient system-level studies. In this paper, the data-driven models of cycloconverter-based VFDs are analyzed in terms of their accuracy and numerical efficiency with respect to their detailed switching model counterparts for harmonic studies of an example ship propulsion system. The advantages and drawbacks of both modeling techniques are demonstrated through time-domain and frequency-domain electromagnetic transient simulations conducted in MATLAB/Simulink using the Simscape Electrical toolbox.**

***Index Terms*—Cycloconverter, data-driven, modeling, ship propulsion, simulation, switching**

I. INTRODUCTION

Modern ships often utilize electric motors for their propulsion rather than diesel engines [1]. The electrifying of marine propulsion systems reduces fuel consumption and greenhouse emissions. In [2], approaches are presented for the optimal selection of the size and capacity of renewable sources. In addition to their increased efficiency, electrified propulsion systems produce less vibration and noise while offering superior dynamic performance, e.g., faster maneuvering and/or smoother positioning [3].

Due to the variable speed of the vessel while cruising or maneuvering in the sea, the frequency of the voltages/currents of the electric propulsion motors cannot be constant. Therefore, marine propulsion systems are equipped with Variable-Frequency Drives (VFDs) to control the electric motors efficiently in a wide range of speeds and torques. In [4, 5], various VFD configurations have been presented for modern electric ship propulsion systems. Specifically, the VFDs provide voltages/currents with amplitude/frequency that correspond/match with the speed of the vessel (which also depend on the number of magnetic poles of the propulsion electric motors, and are typically lower than grid frequency, e.g., ~30 Hz and below at lower vessel speeds). In [6–8], various techniques are presented for control of electric motors in VFD applications.

The MW-level VFD systems that are used in marine systems may be realized using the AC-AC cycloconverters, which can convert ac voltages with constant frequency/amplitude to ac voltages with variable frequency/amplitude. In [9, 10], the application and implementation of cycloconverters for VFD applications were demonstrated.

Cycloconverters are realized using thyristor-controlled switches and are capable of handling very high-power levels in addition to being simple, reliable, and durable [11, 12]. However, the discrete switching operation of cycloconverters results in distortion of the ac voltages and currents (i.e., produces harmonics). The harmonic characteristics of cycloconverters were analyzed in [13]. Depending on the level of harmonics injected, the main ac bus with normally sinusoidal voltages and currents established by the ship generators may be significantly distorted. When the voltages of the main ac bus become distorted, the quality of the electric power delivered to other non-propulsion loads of the vessel (e.g., the communication and control-center devices, etc.) is also affected, which can adversely influence their proper functioning.

Harmonic filters are typically installed at the propulsion bus to mitigate the distortions caused by the operation of cycloconverters [14]. The selection and design of appropriate filter configurations, sizes, and parameters require a comprehensive analysis of the system's power quality under different operating conditions for the propulsion motors and cycloconverters. Computer simulations are often essential in such system harmonic analyses, which in turn require accurate and

Manuscript received March 26, 2024; revised May 20, 2024; accepted July 10, 2024.
*Corresponding author

doi: 10.18178/ijeetc.13.6.503-509

numerically efficient models of various components, including electric machines. Various models of electrical machines were presented in [15, 16] for Efficient Electromagnetic Transient (EMT) simulations. It is also imperative to consider the overall efficiency of the ship powertrain when selecting different configurations and parameters, which also requires extensive computer studies and analysis, as shown in [17].

Also, the appropriate choice of models for cycloconverters significantly impacts the simulations' accuracy and efficiency, which is essential because such models may be run many times. The so-called detailed switching models of cycloconverters can be established using discrete models for thyristor switches, which are typically available as standard library components in most commercially available EMT simulation programs, e.g., PSCAD/EMTDC, MATLAB Simscape Electrical toolbox [18], etc. Using detailed switching models of cycloconverters can provide accurate prediction of the distorted waveforms by considering the discrete operation of the converters similar to the actual hardware.

However, such switching models are numerically expensive (i.e., they require extensive computations) and excessively slow down the simulations. This becomes a challenge, especially when the computer simulations need to run multiple times (often in loops) to design harmonic filters and/or tune their parameters.

A so-called Average-Value Model (AVM) for cycloconverters was developed in [19] and for voltage source converters in [20], for numerically efficient and fast simulations. Although allowing orders of magnitude faster simulations, the switching phenomena (and the ac harmonics) are neglected in AVMs, and only the fundamental-frequency components of the ac waveforms are captured. Therefore, such AVMs are unsuitable for harmonic analysis of cycloconverter-based marine propulsion systems.

Alternatively, data-driven models of cycloconverters are often utilized in the industry. Such simplified models consider the cycloconverter as sources/injectors of harmonics; thus, modeling the cycloconverter as harmonic current sources. In addition to offering numerical efficiency (i.e., faster simulations), this also allows the use of data recorded from measurements to run the simulations for harmonic analysis. This significantly simplifies computer studies compared to conventional computationally-expensive detailed models because detailed modeling requires complete knowledge of all the system components and their parameters and takes a very long time to simulate. However, this may come at the cost of reduced accuracy.

To the best of the authors' knowledge, the switching models in [18] are state-of-the-art for modeling the AC-AC cycloconverters. This paper proposes and analyzes the data-driven model of cycloconverter-based VFDs in terms of accuracy and numerical efficiency compared to the detailed switching model counterpart for harmonic studies of an example ship propulsion system. The advantages and drawbacks of both modeling techniques are demonstrated through time- and frequency-domain EMT simulations in MATLAB/Simulink, Simscape Electrical toolbox.

II. Modeling of Ship Propulsion System

A simplified schematic of an electrified ship propulsion system is shown in Fig. 1. Therein, a synchronous generator (as the primary source of electric power) is connected to the propulsion ac bus. Two synchronous motors are used at the port and starboard (STBD) sides of the vessel for propulsion. The motors are fed through cycloconverters and transformers. The propulsion transformers are typically configured as start-delta (YΔ) and delta-delta (ΔΔ) (for primary and three secondaries) to provide quasi-harmonic cancellation (mainly at 5th and 7th harmonics). A (cluster of) filter(s) is also installed at the ac bus for harmonic mitigation. The AC-AC cycloconverters also often have full-bridge configuration (i.e., each comprises 36 thyristor switches).

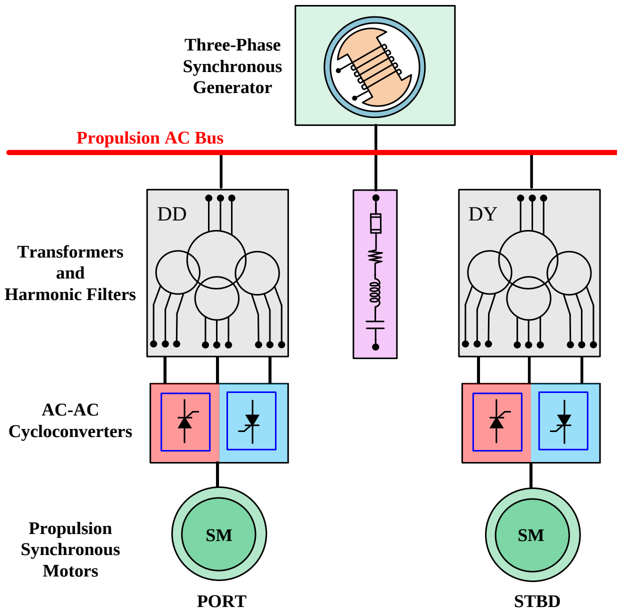

Fig. 1. Simplified schematic of a ship propulsion system with AC-AC cycloconverters on port and starboard sides.

A. *Modeling of Propulsion Generators and Motors*

For modeling the synchronous generators and propulsion motors, the machine models expressed in quadrature (*q*) and direct (*d*) rotor magnetic axes, with included zero (0) sequence, are typically used to predict the dynamic behavior with possible unbalanced operation [21]. Such models are referred to in the literature as *qd*0 models [21] and have the order corresponding to the total number of equivalent windings. However, such full-order models typically require significant computations and are numerically expensive.

For steady-state harmonic analysis, which is the focus of this paper, it may be sufficient to represent the synchronous machines by a simplified Thevenin equivalent circuit, also referred to as the Voltage-Behind-Reactance (VBR) model [22], as shown in Fig. 2. Therein, the stator of the machine is modeled as an *RL* impedance in series with sinusoidal voltages representing the back

Electromotive Forces (emfs) of the machine. The values of the back emfs are controlled to maintain the desired voltage at the stator output terminals under different operating conditions; thus, modeled as controlled voltage sources in Fig. 2.

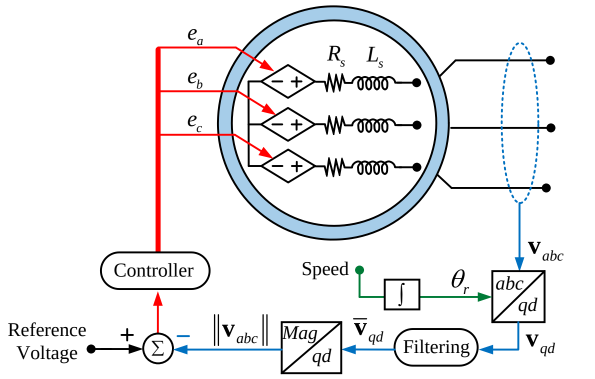

Fig. 2. Simplified representation of the synchronous machines modeled as voltage-behind-reactance, including their automatic voltage regulator.

B. *Modeling of Propulsion Transformers and Harmonic Filters*

For harmonic analysis, the propulsion transformers can be modeled as ideal transformers in series with the impedances of the windings (i.e., resistance and leakage inductances of the windings, which are typically provided as per-unit values).

It is noted that although including all the non-idealities (e.g., the magnetizing and losses of the core, saturation, etc.) improves the accuracy of the transformer models, it increases the computational burden for simulations accordingly.

For harmonic mitigation in ships, passive filters, which are composed of inductive and capacitive elements, are typically preferred; thus, their modeling is straightforward. In this paper, a series RLC filter is considered, as shown in Fig. 1.

C. *Modeling of Cycloconverters*

A full-bridge AC-AC cycloconverter with 36 thyristor-controlled switches is considered in this paper, as shown in Fig. 3. As seen, the AC-AC cycloconverter is made up of six blocks of 6-pulse ac–dc thyristor-controlled rectifiers, which are connected back-to-back. From an input ac voltage with frequency f_i and line-to-line voltage $V_{\mathrm{LL}}^{\mathrm{in}}$, the cycloconverter establishes output ac voltage with frequency f_o and line-to-line voltage $V_{\mathrm{LL}}^{\mathrm{out}}$. This is done by sinusoidal modulation of the firing angle of the thyristor switches. The relation between the magnitude of the input and output voltages of the cycloconverter can be expressed as

$$V_{\mathrm{LL}}^{\mathrm{out}} = \left(\frac{3\sqrt{3}}{\pi}\right) M V_{\mathrm{LL}}^{\mathrm{in}}, \tag{1}$$

where M is the so-called modulation index, and $0<M<1$ [11].

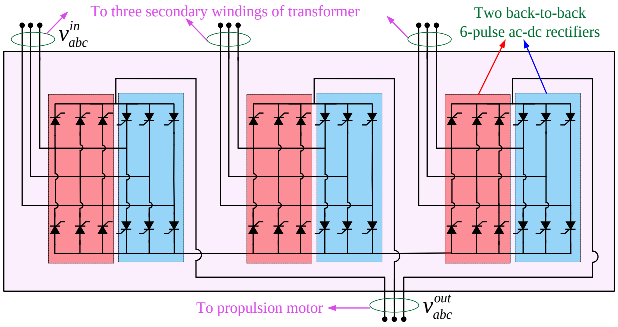

Fig. 3. Configuration of full-bridge AC–AC cycloconverters with 36 thyristor switches.

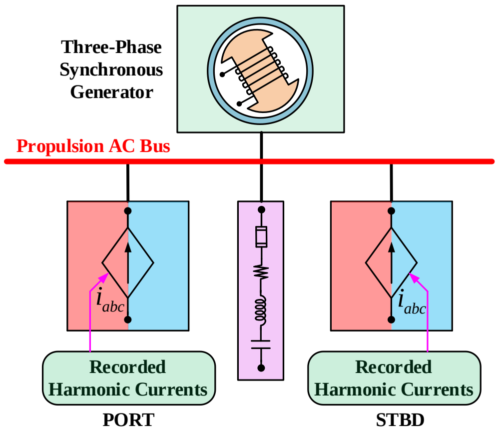

Fig. 4. Simplified schematic of the ship propulsion system in Fig. 1 when modeling the AC–AC cycloconverters as data-driven current sources.

The detailed switching model of the cycloconverter considers the discrete operation of all the (36, in case of full-bridge configuration as shown in Fig. 3) switches (i.e., their timing for turning on/off, etc.) individually. This increases the fidelity of the models; however, it results in very slow simulations.

The data-driven model assumes that the cycloconverter is represented as a source of harmonic currents injected into the propulsion bus. Therefore, it is modeled as controlled current sources, driven by the data recorded from experimental measurements or brief simulations of the detailed switching model under different loading conditions. This approach simplifies the modeling of the ship propulsion system significantly and increases the numerical efficiency (i.e., simulation speed) because the cycloconverters, together with their connecting transformers and propulsion motors, are all lumped into harmonic current sources, as illustrated in Fig. 4, handling which requires fewer computations. Specifically, the recorded current waveforms can be stored in lookup tables and fed as inputs to the controlled current sources. Therefore, at each simulation time step, the program just needs to find the appropriate value of the current from the lookup tables, which requires only some interpolations.

III. Performance Verification of Cycloconverter Models

Here, the accuracy and the numerical efficiency of the data-driven modeling of cycloconverters are investigated and compared to their detailed switching modeling [18]. For this purpose, the ship propulsion system in Fig. 1 is considered for study. Specifically, two cases are considered: In the first case, the system is implemented with the models of all the components in the system, as discussed in Section II, and detailed discrete switching models of the switches in the cycloconverters (as in Fig. 3); and the system model is labelled as "detailed switching model." In the second case, the cycloconverters are represented using sources of harmonic currents, and the system is implemented according to Fig. 4; and the system model is labelled as the "data-driven model." For the "data-driven model," currents obtained from simulations with the "detailed switching model" without filter are recorded and used for the controlled sources.

The synchronous generator produces 50 Hz voltages and is controlled by its automatic voltage regulator (AVR), as shown in Fig. 2, to maintain the voltage of the propulsion ac bus at 690 V under various loading conditions. It is assumed that the propulsion synchronous motors operate with constant flux; thus, the amplitude of their back emfs changes proportionally to their speed/frequency and can be formulated as

$$\left|e_{\mathrm{LL}}^{\mathrm{rms}}\right| = k_1 f_o, \tag{2}$$

where f_o is the frequency of the motor back emf voltages (which is also proportional to the speed of the vessel and the number of magnetic poles of the motor), $\left|e_{\mathrm{LL}}^{\mathrm{rms}}\right|$ is their line-to-line rms value, and k_1 is a constant. Here, it is assumed that 1400 V is induced at 15 Hz; thus, k_1=93.33 V/Hz. It is also assumed that the active power required by the propulsion motors varies as a cubic function of the speed/frequency and can be formulated as

$$P_o = k_2 \left(f_o\right)^3, \tag{3}$$

where P_o is the active power of each propulsion motor. Also, k_2 is a constant, and it is assumed that 600 kW is required at f_o = 15 Hz; thus, k_2=0.18 kW/Hz3.

The cycloconverters are also assumed to be controlled (through their modulation index) to maintain the reactive power of the propulsion motors at zero while satisfying their active power demand and output frequency.

The harmonic filter shown in Fig. 1 and Fig. 4 is tuned to have a resonance frequency at 600 Hz (i.e., 12th-order harmonic of input 50 Hz fundamental frequency) with a quality factor of Q=20. The values of all system parameters are summarized in Table I.

TABLE I: PARAMETERS OF THE SYSTEM FOR CASE STUDY SIMULATIONS

Generators	$r_s = 1.4$ mΩ	$L_s = 85.4$ μH	
Propulsion Motors	$r_s = 15$ mΩ	$L_s = 1.5$ mH	
Transformers	690:1000	$L_l = 50$ μH (referred to primary)	
Harmonic Filters	$r_f = 8.8$ mΩ	$L_f = 46.91$ μH	$C_f = 1.5$ mF

Three different loading conditions are assumed for the propulsion system: 1) high power/speed with f_o = 15 Hz, 2) medium power/speed with f_o = 12 Hz, and 3) low power/speed with f_o = 9 Hz. In each condition, the power quality is investigated once without the harmonic filter and once, assuming the filter is installed for harmonic mitigation. The individual and total harmonic distortion (THD) of the voltage at the main propulsion ac bus is then calculated using detailed switching and data-driven models for each scenario. The THD is defined as

$$\mathrm{THD}\,(v) = \frac{\sqrt{\sum_{j\neq 1} V_j^{\,2}}}{V_1}, \tag{4}$$

where V_j is the amplitude of the jth harmonic order of the voltage v.

The propulsion ac bus voltage profiles under the three considered loading conditions are shown in Fig. 5 when the filter is not connected. As can be observed, the voltages are distorted, and the amounts of harmonics/distortions increase by increasing the propulsion power (i.e., THD of the voltage is 13.53%, 8.53%, and 4.05% for high power/speed, medium power/speed, and low power/speed, respectively). This requires the installation of harmonic filter(s) to reduce the distortions.

The profiles of the propulsion ac bus voltage under the same three loading conditions, when the filter is installed are depicted in Fig. 6. As seen in Fig. 6, compared to the waveforms in Fig. 5, the voltages are less distorted, and THD of the voltage is reduced to 8.87% (from 13.53%), 5.74% (from 8.53%), and 2.67% (from 4.05%) for high power/speed, medium power/speed, and low power/speed, respectively; as calculated by the detailed switching model.

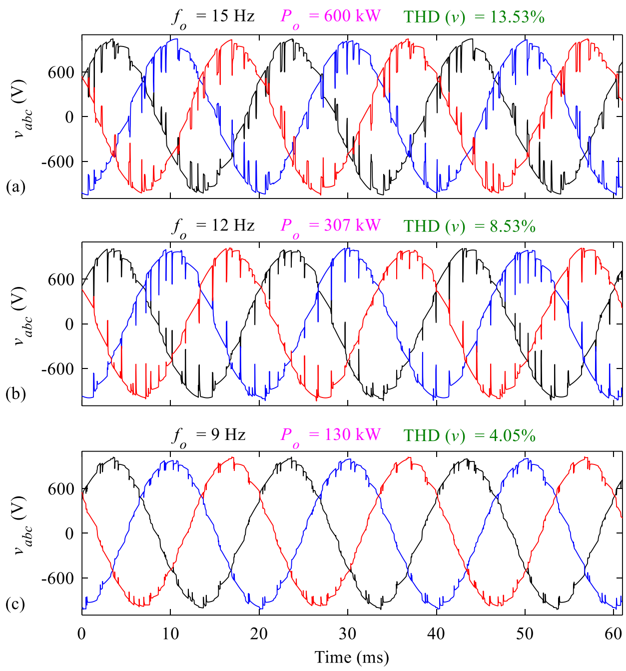

Fig. 5. Simulation results for the profile of the ship main ac bus without the harmonic filter when (each of the two) cycloconverters and propulsion motors operate at: (a) high speed/power with frequency f_o=15 Hz and power P_o=600 kW, (b) medium speed/power with f_o=12 Hz and P_o=307 kW, (c) low speed/power with f_o=9 Hz and P_o=130 kW.

It is also observed in Fig. 6 that, although the waveforms obtained by the data-driven model are generally very close to those obtained from the detailed switching model, the amount of their distortions slightly differ. Specifically, the data-driven model predicts slightly lower THD for the ac bus voltage, i.e., 6.80% (instead of 8.87%), 4.31% (instead of 5.74%), and 2.45% (instead of 2.67%) for the three loading conditions.

To analyze the inaccuracy of the data-driven model, the harmonic spectrum of the ac bus voltage (under medium power/speed) is shown in Fig. 7, calculated for individual harmonics (up to order 20) by the subject models, with/without harmonic filters.

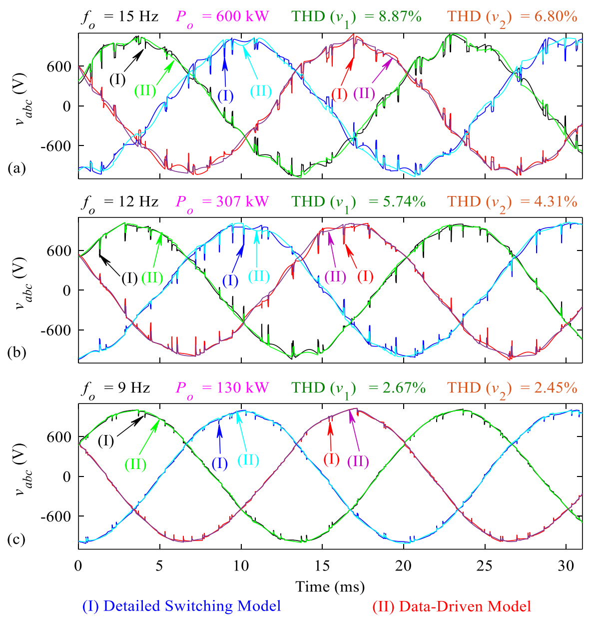

Fig. 6. Simulation results obtained by the two subject models for the profile of the ship main ac bus with harmonic filter when (each of the two) cycloconverters and propulsion motors operate at: (a) high speed/power with frequency f_o=15 Hz and power P_o=600 kW, (b) medium speed/power with f_o=12 Hz and P_o=307 kW, (c) low speed/power with f_o=9 Hz and P_o=130 kW.

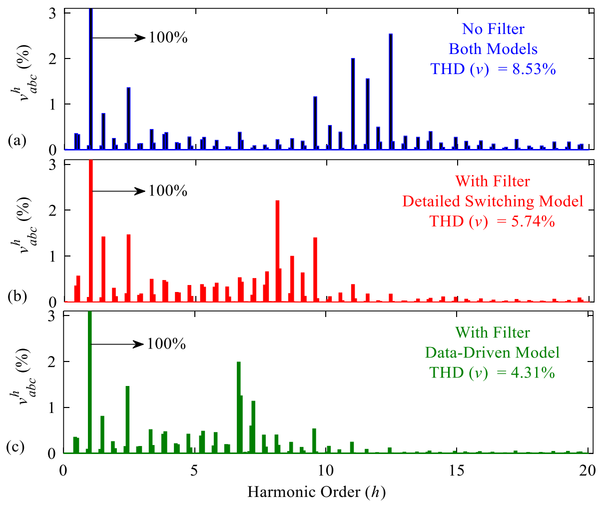

Fig. 7. Harmonic spectrum of the ship main ac bus voltage when (each of the two) cycloconverters and propulsion motors operate at medium speed/power with f_o=12 Hz and P_o=307 kW, as obtained by the subject models assuming: (a) no filter connected, (b) filters connected obtained with detailed switching model, (c) filters connected obtained with the data-driven model.

As seen in Fig. 7 (b) and (c), the harmonic components predicted by the data-driven model are slightly different from the ones obtained by the detailed switching model. This has resulted in somewhat different THDs. This is due to the fact that the harmonic currents of the system depend on the switching pattern of the thyristor switches, which will be impacted by installing the harmonic filter. However, the data-driven model is not sensitive to this because it uses the data (for harmonic currents) obtained from the switching model when there is no filter in the system, thus causing some inaccuracy.

It is also worth noting that, comparing the harmonic components without a filter shown in Fig. 7 (a) to the ones when there is a filter in Fig. 7 (b), the components around ~7th harmonic are amplified. This can be explained by analyzing the impedance characteristic of the system based on Fig. 4. Specifically, for the harmonic components, the effective impedance would be equal to the parallel combination of the impedance of the generator (Z_g) and the impedance of the filter (Z_f). The frequency characteristics of these impedances are shown in Fig. 8. As seen in Fig. 8, the impedances of the generator and the filter resonate at around ~7th harmonic, which results in the amplification of those components in the ac bus voltage, as observed in Fig. 7 (b) and (c).

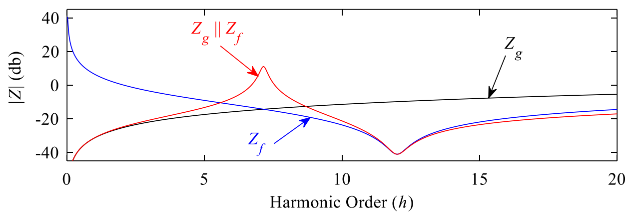

Fig. 8. Frequency characteristics of the impedance of the generator (Z_g), the impedance of the filter (Z_f), and their effective parallel combination (Z_g || Z_f).

The THD of the propulsion ac bus voltage under various loading conditions with filtering is summarized in Table II. As seen, despite the slight inaccuracy of the data-driven model, it still provides a rough/useful estimate of the power quality of the system under various loading conditions.

TABLE II: THD OF THE PROPULSION AC BUS VOLTAGE UNDER VARIOUS LOADING CONDITIONS WITH HARMONIC FILTER AS OBTAINED BY THE SUBJECT MODELS

Loading condition	Detailed switching model	Data-driven model
High power/speed	8.87 %	6.80 %
Medium power/speed	5.74 %	4.31 %
Low power/speed	2.67 %	2.45 %

To compare the numerical efficiency (simulation speed) of the data-driven model against the detailed switching model, the CPU times taken to run the 3 s simulation with each model are summarized in Table III. Simulations are run in MATLAB 2021a using Simscape Electrical toolbox on a PC with processor Intel® Core™ i7-9750H @2.60GHz. Also, a fixed time-step of 2 µs is used with a discrete solver.

TABLE III: THE CPU TIME TAKEN BY THE SUBJECT MODELS FOR THE 3-SECOND SIMULATION STUDY UNDER VARIOUS LOADING CONDITIONS

Loading Condition	Detailed Switching Model	Data-Driven Model
High power/speed	452 s	7.4 s
Medium power/speed	453 s	7.5 s
Low power/speed	451 s	7.3 s

As seen in Table III, the same 3 s simulation study that takes ~452 s (i.e., ~7.5 mins) to run with the detailed switching model takes only ~ 7.4 s to run with the data-driven model. The main reason for this substantial computational efficiency (i.e., being 61 times faster) of the data-driven model is due to avoiding the computations needed for handling the discrete operation of the 72 switches (36 per cycloconverter) in the system. The computational superiority offered by the data-driven model should be considered a compromise with its slight numerical inaccuracy simplifies computer studies. The choice of the proper model for simulations should depend on the application, the desired accuracy of the simulations for power quality assessments, the amount of time required/allowed for the simulation studies, and the expertise in establishing models of various components of the system, especially the AC–AC cycloconverters.

IV. CONCLUSION

This paper presented the data-driven model of AC–AC cycloconverters used in a ship propulsion system. The accuracy and numerical efficiency of the data-driven model are then compared to the conventional detailed switching models for analyzing the power quality and effect of harmonic filters on an actual ship propulsion system. It was demonstrated that the data-driven model offers significant computational efficiency (i.e., ~61 times faster) over its switching model counterpart, mainly due to avoiding the excessive computations required to handle the discrete operation of the (many) switches. However, this comes at the cost of slight inaccuracy due to the model being insensitive to the exact switching pattern of the converter switches. The selection of an appropriate model for harmonic analysis would be a compromise between the desired accuracy, the acceptable time for simulations, and the user's expertise in modeling the ship propulsion system, especially the AC–AC cycloconverters.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Seyyedmilad Ebrahimi contributed to the work through conceptualization, methodology, investigation, analysis, simulations, writing the original draft. Juri Jatskevich contributed to the work through conceptualization, methodology, investigation, analysis, supervision, reviewing and editing the paper. All authors had approved the final version.

FUNDING

This work was funded by the Natural Sciences and Engineering Research Council (NSERC) of Canada under the Alliance grant.

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Seyyedmilad Ebrahimi received the B.Sc. and M.Sc. degrees in electrical engineering from Sharif University of Technology, Tehran, Iran, in 2010 and 2012, respectively, and the Ph.D. degree in electrical and computer engineering from The University of British Columbia (UBC), Vancouver, BC, Canada, in 2019. He is currently a postdoctoral teaching and research fellow with the Department of electrical and Computer Engineering, UBC. His research interests include modeling and analysis of power electronic converters and electrical machines, application of power electronics to power systems, modeling and control of power systems, and simulation of electromagnetic transients.

Juri Jatskevich received the M.S.E.E. and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, IN, USA, in 1997 and 1999, respectively. Since 2002, he has been with The University of British Columbia, Vancouver, BC, Canada, where he is a professor with the Department of Electrical and Computer Engineering. His research interests include power electronic systems, electrical machines and drives, modeling, and simulation of electromagnetic transients. Dr. Jatskevich was an Associate Editor for IEEE TRANSACTIONS ON POWER ELECTRONICS (2008–2013), the Editor-in-Chief of IEEE Transactions on Energy Conversion (2013–2019), and the Editor-in-Chief At-Large for IEEE Power and Energy Society (IEEE PES) journals (2019/2020). He also chaired the IEEE PES Task Force on Dynamic Average Modeling (2007–2022). He was the recipient of the 2022 IEEE PES Cyril Veinott Electromechanical Energy Conversion Award and the 2023 Nagamori Award.