Power Quality Assessment in Shipboard Microgrids under Unbalanced and Harmonic AC Bus Voltage

Liu, Wenzhao; Tarasiuk, Tomasz; Gorniak, Mariusz; Savaghebi, Mehdi; Quintero, Juan Carlos Vasquez; Su, Chun-Lien; Guerrero, Josep M.

Published in:
I E E E Transactions on Industry Applications

DOI (link to publication from Publisher):
10.1109/TIA.2018.2867330

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

Citation for published version (APA):
Liu, W., Tarasiuk, T., Gorniak, M., Savaghebi, M., Quintero, J. C. V., Su, C.-L., & Guerrero, J. M. (2019). Power Quality Assessment in Shipboard Microgrids under Unbalanced and Harmonic AC Bus Voltage. *I E E E Transactions on Industry Applications*, *55*(1), 765-775. Article 8447296. https://doi.org/10.1109/TIA.2018.2867330

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

Power Quality Assessment in Shipboard Microgrids under Unbalanced and Harmonic AC Bus Voltage

Wenzhao Liu[1*], Tomasz Tarasiuk[2], Mariusz Gorniak[2], Mehdi Savaghebi[1], Juan C. Vasquez[1], Chun-Lien Su[3] and Josep M. Guerrero[1]
[1]Department of Energy Technology, Aalborg University, Aalborg, Denmark
{wzl, mes, juq, joz}@et.aau.dk
[2]Department of Marine Electrical Power Engineering, Gdynia Maritime University, Gdynia, Poland
{t.tarasiuk, m.gorniak}@we.am.gdynia.pl
[3]Department of Marine Engineering, National Kaohsiung University of Science and Technology, Kaohsiung, Taiwan.
cls@nkust.edu.tw

***Abstract*—Power quality (PQ) is becoming more and more critical issue in shipboard microgrid systems (SMG). Especially, the impact of voltage unbalance combined with harmonic distortions on the SMG behavior has not been fully investigated. In this paper, simple power quality assessment models and a series of controlled experiments are proposed and carried out in a real ship under sea-going conditions. The ship experimental results are presented and discussed considering non-linear bow thruster load and high power ballast pump loads under unbalanced and harmonic voltage conditions. In addition, the analysis of bow thruster current harmonic surges during the ballast pump start-up is presented. Furthermore, the voltage/current distortions of working generator, bow thruster and pump loads are analyzed. The paper provides a valuable analysis for coping with PQ issues in the SMG.**

Keywords*—*power quality; shipboard microgrid; unbalance; harmonic;

I. Introduction

Power Quality (PQ) issues for Shipboard Microgrid Systems (SMGs) are among the significant concerns with the power electronics applications onboard, especially concerning the wide use of variable frequency drives for loads such as: pump loads, fans, bow thruster motors and propellers [1].

SMGs usually include generators with limited power capacity as well as some nonlinear and high-power pulsed loads, which are always hard to control [2]. A typical ship operates under different working modes to suite specific exploitation conditions, with significantly varying PQ characteristics. In fact, SMGs are sensitive to unbalanced and harmonic voltages/currents, high magnitude of transient disturbances and frequency variations, which brings potential safety hazards to shipboard power services. Therefore, the PQ assessment and improvement for SMGs under unbalanced and harmonic voltage are of great importance.

However, analyzing detailed behaviors of whole SMGs is still quite complex, especially under unbalanced and distorted voltage conditions. In fact, most of the papers and maritime standards of International Association of Classification Societies (IACS) and its members clearly lack the requirements regarding voltage/current waveform unbalance, except IEEE Standard 45-2002, which requires that line-to-line voltage unbalance onboard should not exceed 3%[3]. Furthermore, the consequences of voltage unbalance on the diesel generators and other electrical devices onboard can be various. For instance, the damage of the auxiliary engines by unbalanced distortions may cause engine bearings malfunction and lead to the generator breakdown [4]. This may also cause overheating of the bearings when the generator cut in again [5] or significantly faster degradation of equipment insulation (thermal ageing), and result in failure and/or malfunctions in SMGs [6-8].

On the other hand, the operation of SMGs under unbalanced AC bus voltage is quite different form normal conditions. Voltage unbalances may have negative effects on bow thruster variable frequency drive (VFD). The unbalanced voltages lead to significant input current unbalances that stress the diode bridge rectifiers and protective devices such as fuses, contactors, and circuit breakers [9]. In addition, the unbalanced voltages typically inject a second harmonic ripple component into the dc bus, which increases the electrical stresses on the dc-bus choke inductor and capacitor. Furthermore, voltage unbalances can give rise to significant amounts of torque ripple in the VFD-controlled induction motor, increasing the mechanical and thermal stresses [10].

However, each SMG, even relatively small one, contains dozens or hundreds of electrical devices working at the same

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

time and supplied by a voltage with fluctuating frequency and magnitude, especially in pitching and rolling vessel [11], [12]. Therefore, the behavior of SMGs can be hardly determined and monitored by calculations only, since the PQ parameters change continuously over time and unpredictable number of interactions occurs, such as the impact of voltage unbalance on waveform distortions with high power non-linear loads. The problem of PQ assessment is recognized by IACS, which recommends determining the level of harmonic distortion experienced onboard by calculations, and verifying the results by experimental tests during sea trials [13]. However, the PQ assessment methods have not considered the actual impact of voltage unbalances and harmonics.

Therefore, the aim of this paper is to fill the aforementioned gap and investigate the particular SMG behaviors in presence of the voltage unbalance and waveform distortions occurring concurrently. The model methods were proposed to achieve quick PQ assessment in real time under such cases, the model methods only requires necessary parameters of the SMGs, which can be easily applied for ship industry. Thus, more information including experimental comparisons under various unbalanced and harmonic voltage conditions can be provided to the ship engineer and designer.

II. Shipboard Microgrid System

A. *Shipboard microgrid system description*

Typical characteristics of SMG includes the isolated power generations with limited capacities, varying voltage and frequency levels, high short-circuit impedance of the supply power network and the extensive use of high-power nonlinear/pulsed loads [14]. Based on these characteristics, the SMG is more prone to PQ issues, such as unbalanced or distorted voltage/current waveforms, high level of voltage/current distortions, transient disturbances and global frequency variations [15].

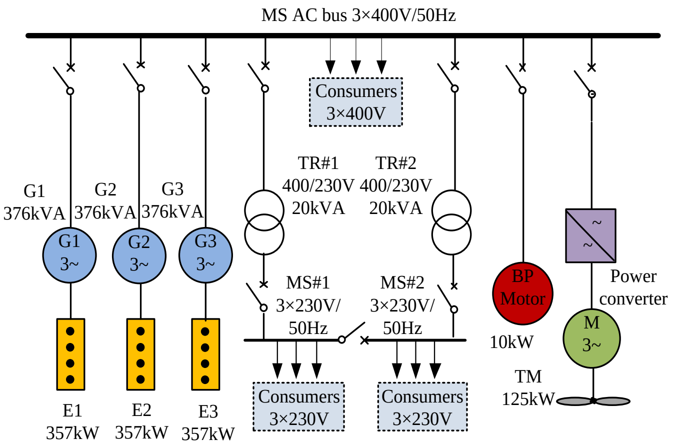


Fig.1. Simplified diagram of the investigated SMG (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engine; BT: bow thruster; TR: transformer; MS: main switchboard; BP: ballast pump motor)

The simplified diagram of the investigated SMG is shown in Fig. 1. The rated AC bus voltage is 400V and the system frequency is 50Hz. The SMG consists of three identical synchronous generators with the rated power of 376 kVA connected to the main switchboard directly. Each generator is driven by a four-stroke diesel engine with the rated power of 357 kW. The load with the greatest power onboard is the bow thruster motor (125kW), supplied by a variable frequency power converter.

In addition, mainly linear loads like the ballast pump and fresh water pump are also present. Ballast pump is in charge of balancing the ship and ensuring its stability and fresh water pump is used in main engine cooling system.

Different AC voltage levels for consumers such as lights or small hotel appliances onboard can be achieved through transformer conversions.

B. *Proposed assessment for bow thruster operation under unbalanced and distorted voltage condition*

In fact, even moderate unbalanced AC bus voltage has enormous impact on the uncontrolled rectifiers, which are typically a part of bow thruster drive onboard [16]. However, for such rectifiers, the voltage unbalances lead to the increase of total r.m.s line current and extra harmonics [16], [17].

On the other hand, double-phase and single-phase rectify modes appear when the loads decrease under unbalance cases, which cause drawing large unbalanced and harmonic currents from the generator [17]. The effect can be particularly deteriorating in weak AC grids such as the one in SMGs. So, the paper is focused on analyzing the bow thruster drive and the whole system operations under unbalanced and harmonic conditions. These investigations can be carried out analytically and/or experimentally in a real shipboard. The latter is necessary because there are many hard-to-control factors, which can influence the operations of the SMG.

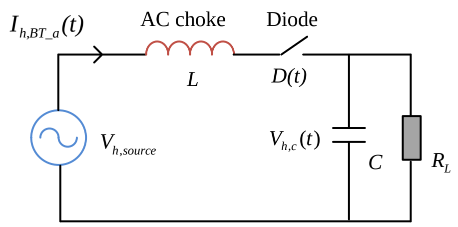


Fig.2. The one-phase equivalent rectifier circuit of bow thruster VFD

For a simplified analysis, a one-phase equivalent rectifier circuit of bow thruster VFD is shown in Fig. 2. The capacitor voltage of rectifier can be easily derived as

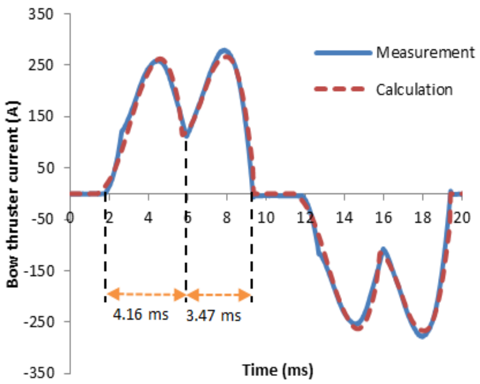
$$V_{h,c}(t) = V_{h,source} \quad if \begin{cases} I_{h,BT\_a}(t_1) = 0, \ \dfrac{dI_{BT\_s}(t_1)}{dt} > 0 \\ I_{h,BT\_a}(t_2) = 0, \ \dfrac{dI_{BT\_s}(t_2)}{dt} < 0 \end{cases} \tag{1}$$

The line current of bow thruster $I_{h,BT\_a}(t)$ can be approximated by solving second order differential equation expressed as follows

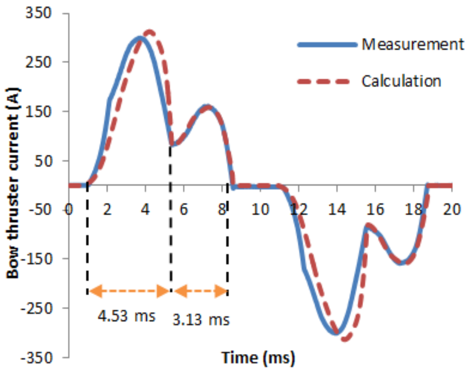
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

$$R_L \cdot L \cdot C \cdot \frac{d^2 I_{h,BT\_a}(t)}{dt^2} + L \cdot \frac{dI_{h,BT\_a}(t)}{dt} + R_L \cdot I_{h,BT\_a}(t) = V(t+t_1) + R \cdot C \cdot \frac{dV(t+t_1)}{dt} \quad (2)$$

It can be observed from (2) that $I_{h,BT\_a}(t)$ depends on the values of inductor L and capacitor C and load R_L. The voltage unbalance leads not only to changes of respective voltage values but also asymmetry between times t_1 and t_2 for the line current of bow thruster. It enables approximate assessment of bow thruster current distortions for various loads under quasi-balanced and unbalanced voltage conditions.



(a) Quasi-balanced voltage case (UF =0.39%)



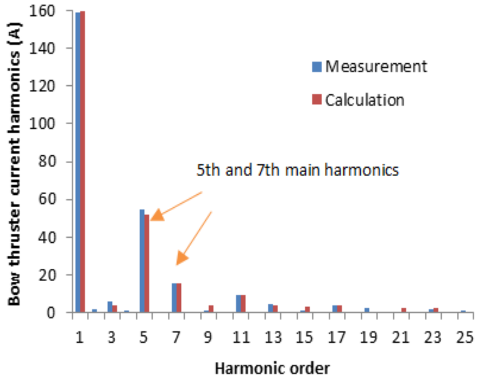
(b) Unbalanced voltage case (UF= 1.63%)

Fig.3. Line current of bow thruster under quasi-balanced and unbalanced voltage case

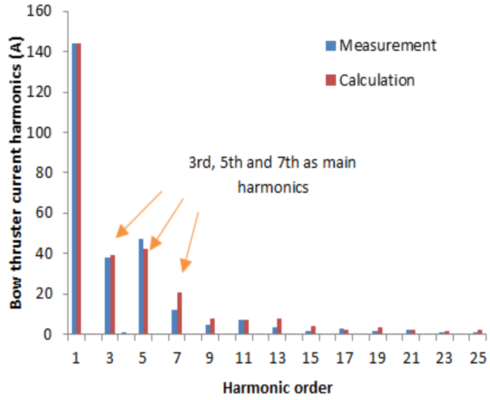
In addition, the comparison between current calculations and measurement of bow thruster load (109kW) under two cases, quasi-balanced and unbalanced, in the investigated ship can be found in Fig. 3. As can be seen in Fig. 3(a) and (b), the calculation of bow thruster current almost matches the measurement from the real ship. However, the differences between respective times and magnitudes show different results in the two cases.

In Fig. 3(a), for the quasi-balanced case with Unbalance Factor (UF) of 0.39%, the bow thruster current presents the characteristic of waveform contains main 5th and 7th harmonics. UF was calculated as ratio of voltage negative sequence component to positive sequence component expressed in percentage [8].

However, as shown in Fig.3 (b), for the unbalanced case with UF of 1.63%, the differences between conduction time of respective diodes increases and higher harmonics and also fundamental frequency negative sequence component will occurs obviously. It should be noted that the fundamental operating frequency of bow thruster drive remains almost the same under two cases.



(a) Quasi-balanced case (UF=0.39%)



(b) Unbalanced case (UF= 1.63%)

Fig.4. Harmonic analysis of bow thruster current under quasi-balanced and unbalanced voltage case

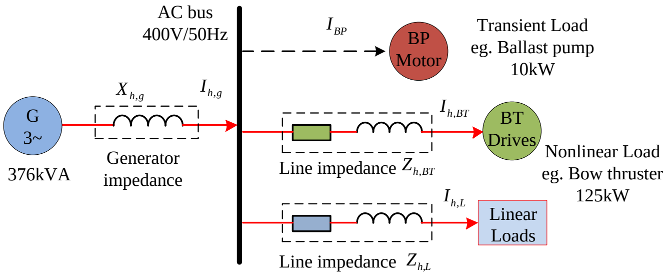
Fig.4 presents the harmonic analysis of bow thruster current (both calculated and measured) under the two cases. The calculations, voltages were performed using Fourier series up to harmonic of 49th harmonic order by DFT decomposition [18], following the requirement in the IACS maritime standards [8], [13]. As can be seen in Fig. 4(b), the 3rd harmonic value will increase obviously when voltage unbalances occur.

In a short conclusion, the behavior of the bow thruster VFD can be assessed by simple models under quasi-balanced and unbalanced cases. However, noted that its actual impact depends on the configurations of whole ship power system and characteristics of numerous large power loads (sometimes thousands) working concurrently. So, the resulted generator currents and AC bus voltage distortions still very hard to be calculated, especially under unbalanced conditions. The next section will present the analysis of generator and ballast pump currents measurements as well as the PQ assessment for the SMGs.

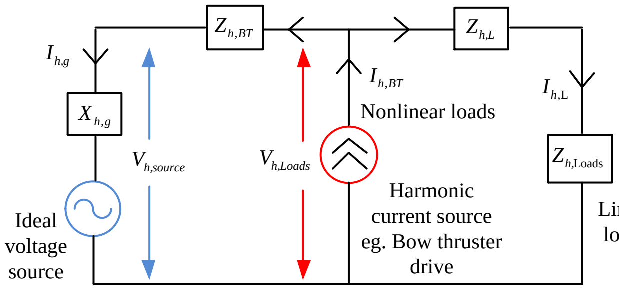
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

C. Proposed PQ assessment and harmonic analysis for SMG

For the harmonic analysis and SMG modeling, it is assumed that only one generator is operating. This can be considered as the worst case from the harmonic distortions point of view. Note that the bow thruster load with VFD is considered as the main harmonic source and the ballast pump is used to investigate the dynamic performance of SMG. The simplified SMG diagram for harmonic analysis is shown in Fig.5.



(a) Harmonic flow between the generator, nonlinear and linear loads



(b) Simplified SMG model with harmonic current flow

Fig.5. Simplified SMG model considering the main harmonic source onboard

In the system of Fig.5, the AC bus voltage harmonic distortions are mainly caused by the bow thruster VFD injecting harmonic current $I_{h,BT}$ to the generator and other linear loads. The harmonic current passes through the system impedance including the generator internal reactance $X_{h,g}$ and the line impedances $Z_{h,L}$, $Z_{h,BT}$.

The resulting voltage distortions on main AC bus depend on line impedances, which can be neglected due to short distance onboard, impedances of linear loads working concurrently (which cannot be fully controlled and assessed as constant value) and dq-axis transient and sub-transient reactance of the generator and the rotor angle [19].

The negative sequence and positive sequence harmonic voltages, V_h and V_{h+2} can be expressed as follows if neglecting the generator's resistance [19]:

$$\begin{bmatrix} V_h \\ V_{h+2} \end{bmatrix} = \begin{bmatrix} j\frac{h}{2}\cdot(X_q^{''}+X_d^{''}) & j\frac{h}{2}\cdot(X_q^{''}-X_d^{''})\cdot e^{-j2\delta} \\ j\frac{h+2}{2}\cdot(X_q^{''}-X_d^{''})\cdot e^{j2\delta} & j\frac{h+2}{2}\cdot(X_q^{''}+X_d^{''}) \end{bmatrix} \cdot \begin{bmatrix} I_h \\ I_{h+2} \end{bmatrix} \quad (3)$$

where $X_q^{''}$ is the generator quadrature-axis sub-transient reactance, $X_d^{''}$ is direct-axis sub-transient reactance of generator, h is harmonic order and δ is rotor angle. I_h and I_{h+2} represent the harmonic currents flow to the generator and mainly from the bow thruster.

On the other hand, the bow thruster current harmonics depend on the topology of VFDs [20]. The harmonic currents $I_{h,BT}$ of six-pulse diode-bridge VFD, which is common for many bow thruster drives, can be expressed as

$$I_{h,BT} = \begin{bmatrix} I_{h,BT\_a} \\ I_{h,BT\_b} \\ I_{h,BT\_c} \end{bmatrix} = \begin{bmatrix} \sum_h I_{h,BT\_a}\sin(h\omega t+\theta_{h,BT}) \\ \sum_h I_{h,BT\_b}\sin(h\omega t+\theta_{h,BT}-\frac{2\pi}{3}) \\ \sum_h I_{h,BT\_c}\sin(h\omega t+\theta_{h,BT}+\frac{2\pi}{3}) \end{bmatrix} \quad (4)$$

$$\forall h \in \{\, 6k \pm 1 \,|\, k = 1, 2, 3 ... \}$$

where I_{h,BT_a}, I_{h,BT_b} and I_{h,BT_c} represent the magnitude of each harmonic component of bow thruster in *abc* frame. ω and $\theta_{h,BT}$ are the angular frequency and the original phase shift of bow thruster respectively.

The magnitude of each current harmonic component is determined by the nature of loads, voltage unbalance factor and harmonics from main AC switchboard bus [21]. The short circuit fault current I_{sc} of generator connected to AC bus can be determined as:

$$I_{sc} = \frac{I_r}{\frac{1}{2}\cdot(X_q^{''}+X_d^{''})} \times 100 \quad (5)$$

where I_r represent magnitude of the generator rated current.

After neglecting effect of the generator cross couplings from negative-sequence harmonic currents to positive-sequence harmonic voltages and impact of other loads (see Fig. 5b) the equivalent AC bus voltage harmonic magnitudes generated by non-linear loads (mainly from bow thruster onboard) can be expressed as:

$$\begin{cases} I_{h,g} \approx I_{h,BT} \\ \tilde{V}_{h,g} \approx \dfrac{h \times V_g \times I_{h,g}}{I_{sc}} \end{cases} \quad (6)$$

where V_g is the rated voltage of generator and $I_{h,g}$ represents the harmonic current flow through the generator.

The total harmonic distortions of the AC bus voltage (THD_v %) can be calculated as

$$THD_v = \frac{\sqrt{\sum_h \tilde{V}_{h,g}^2}}{V_g} \times 100\% \quad (7)$$

Neglecting the effect of salient-pole generators cross couplings from negative-sequence harmonic currents h to positive-sequence harmonic voltages h+2 leads to rough results for respective voltage harmonics.

However, take (3)-(7) into account, the voltage THD can be determined quickly and detailed calculations are shown in Section III.

D. Definition of effective apparent power for three-phase unbalanced system based on IEEE Standard 1459-2010

In order to calculate the power flow under unbalanced voltage cases, IEEE Standard 1459-2010 [22] suggest using the definition of effective apparent power to maintain the active power loss constant, especially considering the actual

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

voltage unbalances in three-wire AC SMG. The effective apparent power S_e is defined as

$$S_e = 3 \times V_e \times I_e \tag{8}$$

where for three wire AC systems [18]:

$$\begin{cases} V_e = \sqrt{\left(V_{ab}^2 + V_{ac}^2 + V_{bc}^2\right)/9} \\ I_e = \sqrt{\left(I_a^2 + I_b^2 + I_c^2\right)/3} \end{cases} \tag{9}$$

In addition, this standard also defined active harmonic power to separate active power components as

$$P = P_1 + \tilde{P}_h = V_1 I_1 \cos\theta_1 + V_0 I_0 + \sum_{h \neq 1} \tilde{V}_h \tilde{I}_h \cos\theta_h \tag{10}$$

Considering the distorted and unbalanced voltage/current waveforms onboard, the active powers for AC system are calculated as the sum of respective powers and can be easily measured based on two-watt meter method [23].

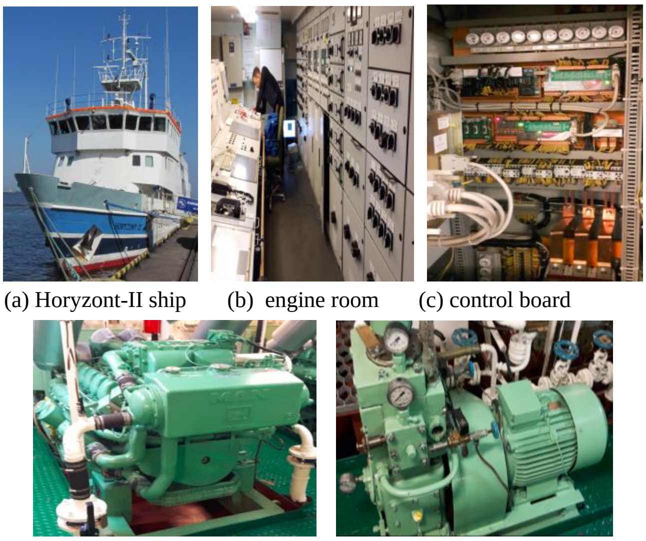
The fundamental reactive power is defined as [22-24]:

$$Q_1 = \frac{\omega}{nT} \int_{\tau}^{\tau + nT} I_1 \left(\int V_1 \cdot dt \right) \cdot dt = V_1 I_1 \sin\theta_1 \tag{11}$$

In addition, according to IEEE standard 1459-2010, the so-called non-active power Q_N is defined for the reactive power assessment under non-sinusoidal waveform conditions as follows

$$Q_N = \sqrt{S_e^{\,2} - (P_1 + \tilde{P}_h)^2} \tag{12}$$

III. Experimental Results and Comparisons



(a) Horyzont-II ship (b) engine room (c) control board

(d) diesel generator (e) pump load

Fig.6. Horyzont-II ship test environment [25], [26].

For the experimental tests, a research-training ship called Horyzont-II was employed as shown in Fig.6. It is designed to improve the knowledge and practical skills of navigators, mechanics and electricians, serving on merchant ships and also to conduct specialized marine research and regularly cruises to Polar Regions [26]. The ship power system architecture is shown in Fig.1.

In the tests, voltage and current samples were registered by the controller (NI PXIe-8106) equipped with three DAQs (NI PXIe-6124) and anti-aliasing filters (LTC-1564). The coils (PEM LFR 06/6) and (LEMs CV3-1500) were used for electrical signals conditioning [27]. The cut-off and sampling frequencies of anti-aliasing filters were 10 kHz and 30 kHz, respectively.

The SMG parameters are shown in Table I.

TABLE I. Ship Microgrid System Parameters

Ship microgrid	parameters	Value
Main AC bus voltage	Vabc [V_{rms}]	400
	f [Hz]	50
	Uf [%]	1.5-1.8
Diesel generator	V_g [V_{rms}]	400
	P_g [kW]	357
	X_d'' [%]	7.6
	X_q'' [%]	18.8
	$\cos\phi_g$	0.85
Ballast pump motor	$V_{m\text{-}abc}$ [V_{rms}]	400
	P_m [kW]	10
	$\cos\phi_m$	0.85
	k	6
	m	1
Bow thruster load	$V_{t\text{-}abc}$[V_{rms}]	400
	P_t [kW]	125
Fresh water pump load	$V_{f\text{-}abc}$ [V_{rms}]	400
	P_f [kW]	11
Heater load	$V_{h\text{-}abc}$ [V_{rms}]	400
	P_h [kW]	90

A. SMG under unbalanced and harmonic AC bus voltage

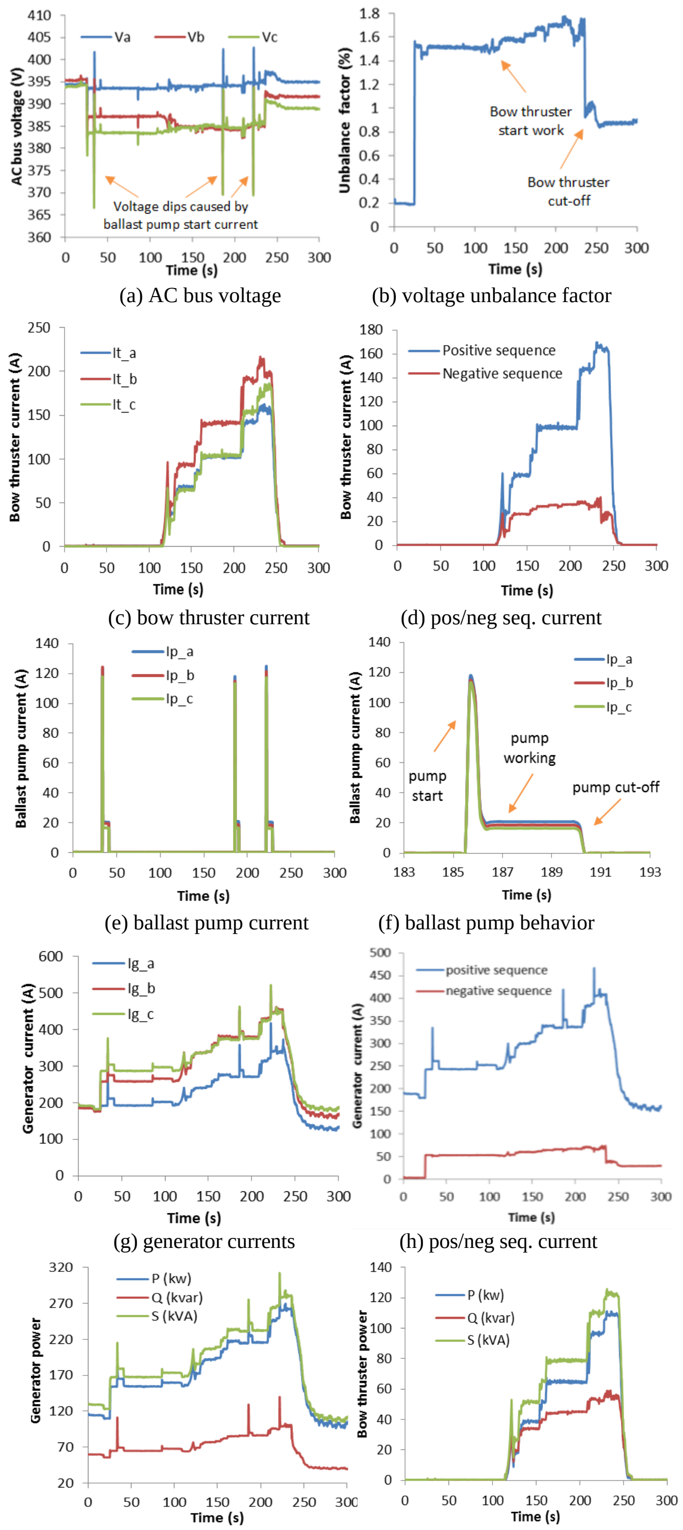
For the specific harmonic analysis of the investigated SMG, experimental tests have been carefully designed for the worst case studies during the ship sea-going. The behavior of the SMG was monitored detailed as follows：

The bow thruster power has changed up to full load while only one generator is enabled. A 90kW heater load with phase A disconnected and phases B and C connected, was used for fuse blowing emulation causing AC bus voltage unbalance. Next, the ballast pump onboard started three times to generate transient voltage dips to test the dynamic performances of the investigated SMG. This test represents typical behavior of SMG and includes transient impact in the systematic PQ assessment [25-29].

However, it should be noted that the investigated SMG contains hundreds of electrical devices working at the same time, harmonic components may also come from other

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

electronic devices, but the main harmonic source in this case is bow thruster drive load.



(a) AC bus voltage (b) voltage unbalance factor

(c) bow thruster current (d) pos/neg seq. current

(e) ballast pump current (f) ballast pump behavior

(g) generator currents (h) pos/neg seq. current

(i) generator powers (j) bow thruster powers

Fig.7. Experimental results of SMG under unbalanced and harmonic AC bus voltage

Figs. 7 (a) and (b) show the rms values of AC bus voltage and its UF, respectively. The UF was increased to 1.75% with the bow thruster power increase. Next, the ballast pump started three times and generated voltage dips, because it draws a large amount of current in a very short time. As can be observed in Figs. 7(e) and (f), the ballast pump starting current can exceed 120A containing slight unbalances. Sometimes this current can even reach 148 A (about 7 times of the rated working current level of ballast pump) within only 0.3s [29].

On the other hand, the generator current surges, Fig. 7(g), only occurs at the fundamental positive sequence component and does not affect the fundamental negative sequence component as shown in Fig. 7(h) because the ballast pump current contains very small negative components with quite limited capacity to disturb the negative sequence current from the working generator.

It can be seen in Figs.7 (c)-(h) that the generator and bow thruster currents are severely unbalanced with the sudden transient surges for generator current. For instance, considering the third voltage dip, the active power of generator reached 300 kW (below rated value) and transient currents reached values I_{g_a}=441 A and I_{g_c}=548 A. The difference between phases is 107A, which is about 20 % of generator rated current (542.7 A). Sometimes, the difference between respective line currents reached even 120 A (22% of generator rated current), which may trigger the overcurrent protection devices for higher unbalance and/or minor overload, and possibly endanger ship voyage operations. The detailed settings of overcurrent devices in the investigated ship were as follow:

(1) 115 % of rated current and 20 seconds delay.
(2) 130 % of rated current and 10 seconds delay.
(3) 150 % of rated current and 1 second delay.

Moreover, the maximum r.m.s current is higher than the respective value in the normal conditions, which means unequal thermal stress for generator windings under unbalanced voltage conditions. On the other hand, the unbalanced voltage affects the operation of ship automatic voltage regulator, which sets only highest line-to-line voltage to about rated voltage.

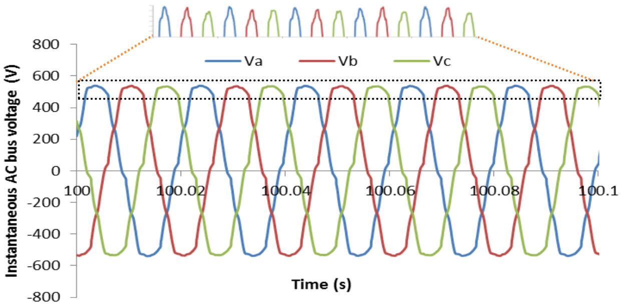
B. Harmonic analysis of SMG under quasi-balanced and unbalanced voltage conditions

For the comparative harmonic analysis of SMG under normal and unbalanced AC bus voltage conditions, two cases were selected. First case was SMG under normal operations and the second case was faulty heater load operation, which created voltage unbalance, UF additionaly increased by bow thruster power increase and its power converter operation under unbalanced supply voltage.

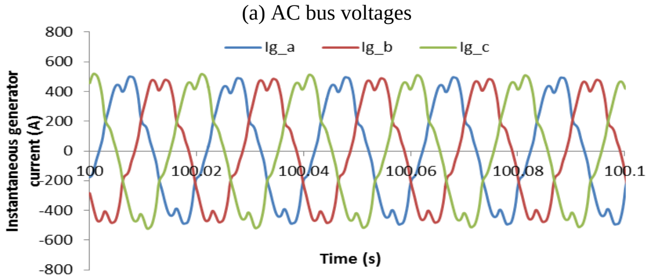
For the quasi-balanced voltage conditions, the UF of AC bus voltage can be determined as only about 0.35% under the bow thruster full load conditions. The operation of SMG under quasi-balanced conditions was almost the same as the described in the previous case study, but without the faulty heater load.

a) Bow thruster full loaded under quasi-balanced voltage conditions

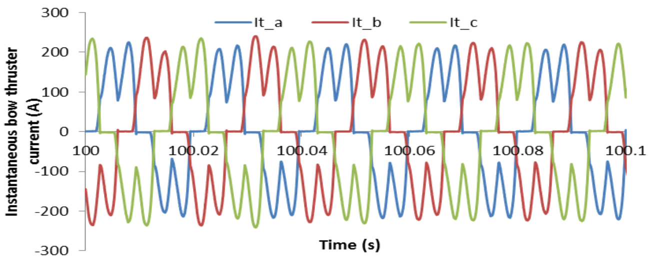
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications



(a) AC bus voltages



(b) generator currents

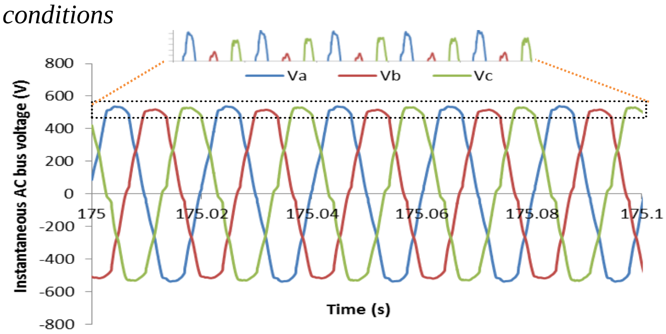


(c) bow thruster currents

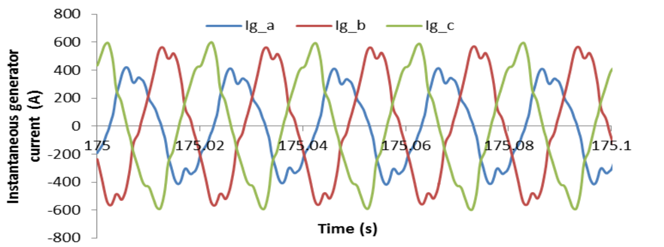
Fig.8. Instantaneous values of (a) AC bus voltage, (b) generator current and (c) bow thruster current under quasi-balanced voltage conditions

Fig. 8 shows the instantaneous values of the voltage as well as generator and bow thruster currents under normal grid conditions as an example. These results were recorded for bow thruster full load operation. The voltage THD changed from 1.1% (bow thruster switched off) up to 6.7% (bow thruster full load) and remained roughly the same for all line-to-line voltages. Accordingly, the distortions of generator and bow thruster currents were symmetrical, mainly containing 5^{th}, 7^{th}, 11^{th} and 13^{th} harmonics. Generator current THD changed from 1.5% (bow thruster switched off) up to 12.8% (bow thruster full load). Bow thruster current remained highly distorted (THD up to 39.6% for full load) but balanced.

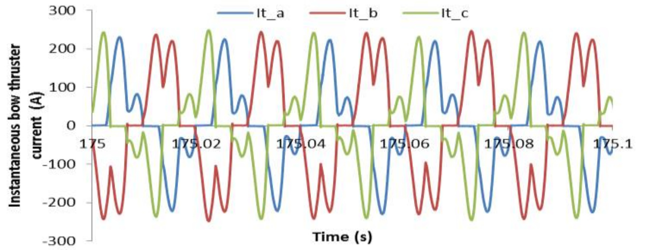
b) Full Load Bow thruster under unbalanced voltage conditions



(a) AC bus voltage



(b) generator current

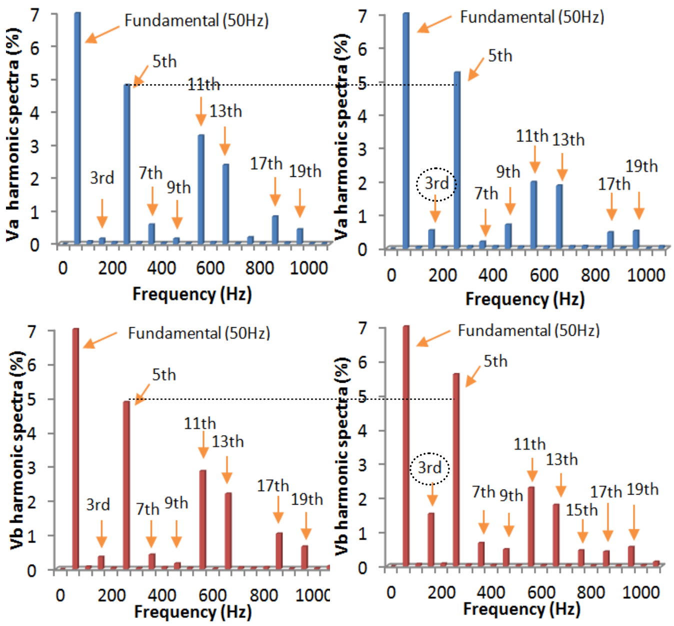


(c) bow thruster currents

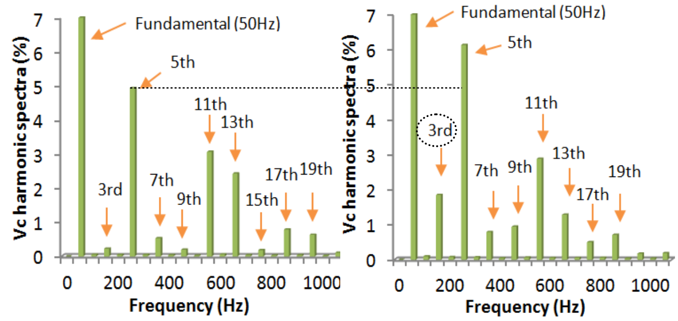
Fig.9. Instantaneous values of (a) AC bus voltage, (b) generator current and (c) bow thruster current under unbalanced voltage conditions

Fig. 9 shows the instantaneous values of the voltage as well as generator and bow thruster currents under unbalanced grid voltage for the bow thruster full load as an example. It should be noted that for the same bow thruster load, its current THD increases for two phases and harmonic current can reach even 77 A for the particular case, which is increased in comparison to 57 A for balanced condition. Also, THDs of the line-to-line voltages differs even with this moderate unbalance with UF equal to 1.75%, which means that harmonic problem can be more critical onboard under unbalanced conditions.

c) Harmonic and THD calculations for the bow thruster and AC bus voltage



This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications



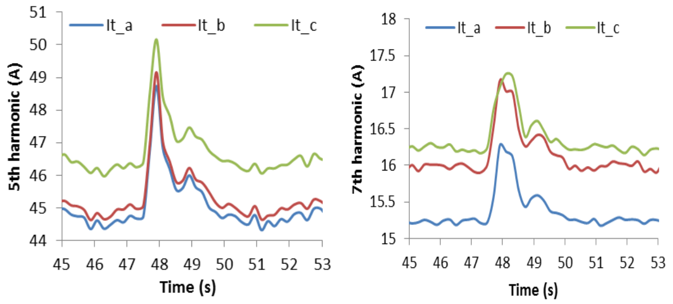
(a) quasi-balanced conditions (b) unbalanced conditions

Fig.10. Harmonic spectra of AC bus voltages up to 25th harmonic under full load of bow thruster

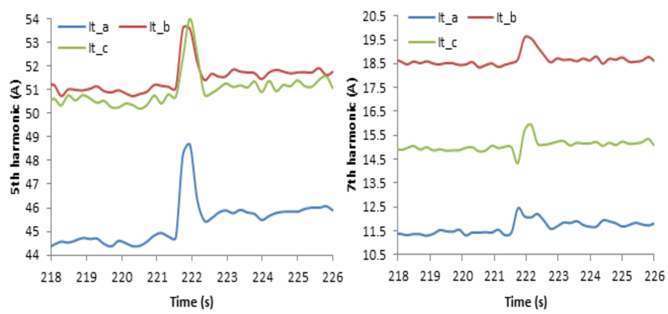
As it can be seen in Figs. 10(a) and (b), the spectra of AC bus voltage harmonics change when unbalances are considered, e.g. 5th harmonic content increases, even beyond 6% of the fundamental component in comparison to approximately 5 % under balanced condition.

On the other hand, the significant value of 3rd harmonics appears obviously due to the actual unbalances. However, the higher order harmonics (e.g. 11th, 13th, 17th, 19th...) are almost unchanged compared with the SMG working under the normal voltage conditions.

It should be noted that harmonic analysis should not be limited to steady state conditions. The frequent dynamic behavior of SMG will cause transient impact on the harmonic and THD calculations that is also very important for the PQ assessment in real time.



(a) Transient 5th and 7th harmonics of bow thruster current (AC bus quasi-balanced voltage UF=0.35%)

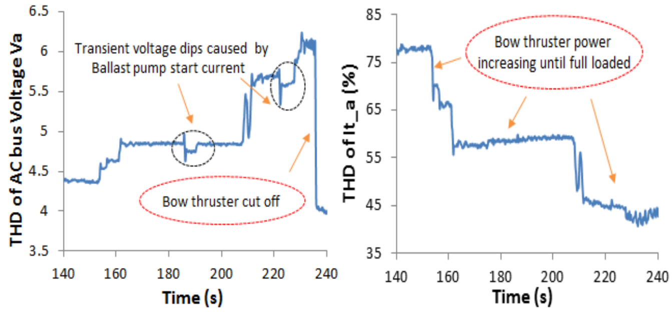


(b) Transient 5th and 7th harmonics of bow thruster current (AC bus unbalanced voltage UF=1.75%)

Fig.11. Impact of ballast pump starts on bow thruster current harmonics

As an example, Fig.11 (a) shows the transient impact on the 5th and 7th harmonics of bow thruster current due to the ballast pump start, which will also lead to the AC bus voltage transient dip and generator current surge [27]. It can be seen that these harmonic components increase in the voltage dip intervals.

Furthermore, for the higher power levels and unbalanced voltage case (e.g. voltage unbalance factor is 1.75% in Fig.11 (b)), more harmonics appeared around the individual current harmonic components of the bow thruster. In fact, the individual current harmonics more easily affect the stability of SMG, especially under unbalanced voltage cases [30], [31]. However, the stability analysis of ship power system is beyond the main scope of this paper.



(a) THD of AC bus voltage (b) THD of bow thruster current

Fig.12 THD of the AC bus voltage and bow thruster current

Fig.12 shows the THD calculations of AC bus voltage and bow thruster current under unbalanced voltage. It can be obviously seen that THD of bow thruster current decreased with the power level increase. However, the THD of AC bus voltage increased from 4.45% to 6.08% with the bow thruster power increase to full load. It means that the bow thruster is the main harmonic source onboard.

Furthermore, the transient voltage dips caused by the ballast pump starts caused short-term variations of THD, which can even reach 1%.

d) Power quality assessment for the SMG under quasi-balanced and unbalanced conditions

For more comparable power quality assessment under bow thruster full load conditions, the main parameters, which describe the SMG operation under quasi-balanced and unbalanced conditions, are presented in Table II.

It can be seen in Table.II that AC bus voltage unbalance leads to increse in harmonic power flow in the system for the same active power of nonlinear load. Combined with increase in nonactive power and unbalanced currents, it means additional losses in the generators, transformers and cables. In addition, the unequal currents of generator and pump motors also mean uneven thermal stress on the machines windings, which can lead to accelerated thermal aging onboard.

On the other hand, for the fresh water pump, active power was above 6 kW for both quasi-balanced and unbalanced cases, but harmonic active powers were only 6 W and 12 W for quasi-balanced and unbalanced conditions respectively, which means the assumption that harmonic current of non-linear load flows mostly through generator in (6) is reasonable.

Other calculations for PQ assessment in SMG are based on suggestions from IEEE Standard 1459-2010 [22].

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TIA.2018.2867330, IEEE Transactions on Industry Applications

TABLE II. COMPARISONS AND PQ ASSESSMENT FOR SMG UNDER QUASI-BALANCED AND UNBALANCED VOLTAGE CONDITIONS

Network parameters		Shipboard microgrid: Quasi-balanced AC bus voltage	Shipboard microgrid: Unbalanced AC bus voltage
Main AC bus bars voltage unbalance factor		0.35%	1.75%
Main AC bus bars voltages measurement	Va [V]	395.2	394.9
	Vb [V]	396.3	385.2
	Vc [V]	393.9	385.9
Main AC bus bars voltage distortion factors [calculations from Eq.(6), (7) and real generator current harmonics]	THD_va [%] measurement	6.43	6.08
	THD_va [%] calculation	6.74	6.38
	THD_vb [%] measurement	6.23	6.60
	THD_vb [%] calculation	6.66	6.41
	THD_vc [%] measurement	6.44	7.26
	THD_vc [%] calculation	6.59	7.24
Generator parameters calculations [Eq (10)-(12)]	Active power [kW]	234.7	253.2
	Harmonic active power [kW]	-0.53	-0.62
	Nonactive power [kvar]	106.8	100.0
	Ia [A]	371.0	341.3
	Ib [A]	373.9	455.9
	Ic [A]	385.4	447.7
	THD_ia [%]	11.99	14.92
	THD_ib [%]	12.11	10.13
	THD_ic [%]	11.41	13.31
Bow thruster parameters calculations [Eq (10)-(12)]	Active power [kW]	110.1	109.0
	Harmonic active power [kW]	-0.99	-1.26
	Nonactive power [kvar]	48.32	57.88
	Ia [A]	172.1	160.0
	Ib [A]	177.1	213.3
	Ic [A]	177.7	172.4
	THD_ia [%]	35.41	42.9
	THD_ib [%]	34.88	29.81
	THD_ic [%]	35.46	47.38
Fresh water pump parameters calculations [Eq (10)-(12)]	Active power [kW]	6.46	6.32
	Harmonic active power [W]	6	12.4
	Nonactive power [kvar]	4.17	4.42
	Ia [A]	11.00	13.35
	Ib [A]	11.61	11.34
	Ic [A]	11.08	9.34
	THD_ia [%]	15.69	15.68
	THD_ib [%]	14.97	13.76
	THD_ic [%]	15.81	24.93

Futhermore, the calculation of maximum voltage THD based on the SMG and the proposed models under quasi-balanced and unbalanced voltage conditions can be found in Table III.

TABLE III. COMPARSIONS FOR MEASURED AND CALCULATED VOLTAGE THD CONSIDERING GENERATOR AND BOW THRUSTER LOAD-109KW

Parameter			Quasi-balanced voltage case (UF=0.39%)	Unbalanced voltage case (UF=1.63%)
THD assessment of AC bus voltage	Based on generator harmonics	measured value[%]	6.47	7.18
		[1]calculation value[%]	6.69	7.56
	Based on bow thruster harmonics	[2]calculation value[%]	8.32	7.55
		[3]calculation value[%]	8.38	8.56

1- based on real generator current harmonics, 2- based on real bow thruster current harmonics 3- the proposed model of (2),(6),(7)

The THD assessment of AC bus voltage can be detemined by current harmonics from gernerator or bow thruster side The presented results in Table III leads to the conclusion that the proposed model based (6) and (7) enables accurrate assessment of voltage THD in the case of salien pole generators. Also noted that neglecting the impact of other loads may lead to THD overestimation, but these loads were impossible to be determined one by one in a real ship. So, the experimental results confirmed the validity of the proposed models for quickly PQ assessment in ship.

IV. CONCLUSIONS

This paper provides valuable investigations about real SMG operations under various unbalanced and harmonic voltage conditions. The proposed model methods can be easily applied to assess PQ parameters in the ship power system.

The PQ analysis and experimental research leads to some practical conclusions:

(1) Permissible voltage unbalances should be tied with the voltage distortions for PQ assessment in real time, which means more flexible threshold of the unbalance factor and/or harmonic should be adopted in future maritime standards. (2) Transient voltage dips caused by load starts (eg. ballast pump) can lead to fundamental and harmonic generator current surges, which may endanger the operation of the SMG.

(3) The differences between critical parameters under quasi-balanced and unbalanced conditions are different. THD increases for some line-to-line voltages, which can adversely affect the operation of sensitive loads, which must be taken into account by the system operator.

Finally, it can be stated that the proposed calculations may led to overestimation of voltage THD but the experimental results verified the proposed models for quick PQ assessment in a real ship power system.

ACKNOWLEDGMENT

This work was partly supported by the National Science Centre, Poland under Grant DEC-2012/07/E/ST8/01688. More information related to maritime microgrid can be found in www.maritime.et.aau.dk.

REFERENCES

[1] Skjong, E., Volden, R., Rødskar, E., Molinas, M., Johansen, T.A. and Cunningham, J. Past, Present, and Future Challenges of the Marine Vessel's Electrical Power System. *IEEE Transactions on Transportation Electrification*, vol.2. no.4, pp.522-537. 2016.

[2] Shariatzadeh, F., Kumar, N. and Srivastava, A.K., Optimal Control Algorithms for Reconfiguration of Shipboard Microgrid Distribution System Using Intelligent Techniques. *IEEE Transactions on Industry Applications*, vol.53.no.1, pp.474-482. 2017.

[3] IEEE Standard 45-2002, IEEE Recommended Practice for Electrical Installations on Shipboard.

[4] MAIB (2011), Marine Accident Investigation Branch, Report on the investigation of the catastrophic failure of acapacitor in the aft harmonic filter room on board RMS Queen Mary 2 while approaching Barcelona on23September2010.http://www.maib.gov.uk/publications/investigation_reports/2011/qm2.cfm (last access 20.11.2017).

[5] Gnacinski, P., Windings Temperature and Loss of Life of an Induction Machine Under Voltage Unbalance Combined With Over or Under voltages, *IEEE Transactions on Energy Conversion*, vol. 23, no. 2, pp. 363-371. 2008.

[6] T. Tarasiuk, J. Mindykowski, An extended interpretation of THD concept in the wake of ship electric power systems research, *Measurement*, vol. 45, no 2, pp. 207-212, 2012.

[7] Chin, Hai-Ming, Chun-Lien Su, and Chi-Hsiang Liao. "Estimating Power Pump Loads and Sizing Generators for Ship Electrical Load Analysis." *IEEE Transactions on Industry Applications* ,vol.52, no. 6 pp: 4619-4627.2016.

[8] DNV DL. Casualty information for unbalanced engine forces and vibration on board ships, *Det Norske Veritas*, DTP 245.

[9] Agamloh, E.B. and Peele, S., Operation of variable frequency drive motor systems with source voltage unbalance. *IEEE Transactions on Industry Applications*, vol. 53, no. 6, pp. 6038-6046. 2017.

[10] Kevin Lee, Thomas M. Jahns, Thomas A. Lipo, Giri Venkataramanan, and William E. Berkopec, Impact of Input Voltage Sag and Unbalance on DC-Link Inductor and Capacitor Stress in Adjustable-Speed Drives. *IEEE Transactions on Industry Applications*, vol. 44, no. 6 , pp. 1825-1833. November/December 2008.

[11] Gnacinski, P, Tarasiuk, T, Energy-efficient operation of induction motors and power quality standards, *Electric Power Systems Research*, vol. 135, pp. 10-17, June 2016.

[12] Bruzzese, C., T. Mazzuca, and M. Torre. "On-line monitoring of mechanical unbalance/misalignment troubles in ship alternators by direct measurement of split-phase currents." *In Electric Ship Technologies Symposium (ESTS), IEEE*. pp. 379-386., 2013.

[13] *International Association of Classification Societies*, Requirements Concerning Electrical and Electronic Installations, *IACS Req*. 2016.

[14] Giannoutsos, Spyridon V., and Stefanos N. Manias. "A systematic power-quality assessment and harmonic filter design methodology for variable-frequency drive application in marine vessels." *IEEE Transactions on industry applications*.vol 51, no. 2.pp: 1909-1919,2015.

[15] Skjong, Espen, Jon Are Suul, Atle Rygg, Tor Arne Johansen, and Marta Molinas. "System-wide harmonic mitigation in a diesel-electric ship by model predictive control." *IEEE Transactions on Industrial Electronics*.vol. 63, no. 7. pp: 4008-4019, 2016.

[16] Seung-Gi Jeong, Ju-Yeop Choi, Line Current Characteristics of Three-Phase Uncontrolled Rectifiers Under Line Voltage Unbalance Condition. *IEEE Transactions on Power Electronics*, vol. 17, no. 6, November 2002, pp. 935-945.

[17] Zhi-Jian Fang, Tao Cai, Shan-Xu Duan, Changsong Chen, Cheng-Da Ren, Performance analysis and capacitor design of three-phase uncontrolled rectifier in slightly unbalanced grid. *IET Power Electronics*, 2015, vol. 8, no. 8, pp. 1429–1439.

[18] T. Tarasiuk, "Angular frequency variations at microgrids and its impact on measuring instruments performance," IET Generation,Transmission and Distribution, vol. 10, no 13,pp. 3234-3240, 2016.

[19] Dinh, Nhut-Quang, Arrillaga, Jos, "A Salient-Pole Generator Model for Harmonic Analysis", IEEE Transactions on Power Systems, vol. 16, no. 4, November 2001, pp. 609-615.

[20] Cuzner, Robert, Daniel Drews, and Giri Venkataramanan. "Power density and efficiency comparisons of system-compatible drive topologies." *IEEE Transactions on Industry Applications* vol. 51, no. 1 pp: 459-469, 2015.

[21] IEC Standard for Testing and Measurement Techniques Power Quality Measurement Methods, *IEC Std*. 61000-4-30, 2015.

[22] IEEE Standard definitions for the measurement of electric power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions, IEEE Standard 1459-2010, March 2010.

[23] Qin, Wenping, Peng Wang, Xiaoqing Han, and Xinhui Du. "Reactive power aspects in reliability assessment of power systems." *IEEE Transactions on Power Systems.* vol. 26, no. 1, pp: 85-92.2011.

[24] Herrera, Reyes S., Patricio Salmeron, and Hyosung Kim. "Instantaneous reactive power theory applied to active power filter compensation: Different approaches, assessment, and experimental results." *IEEE Transactions on Industrial Electronics.* vol 55, no. 1,pp: 184-196.2008.

[25] Liu, Wenzhao, Josep M. Guerrero, Mehdi Savaghebi, etc. "Impact of the Voltage Dips in Shipboard Microgrid Power Systems." *In 43rd Annual Conference of IEEE Industrial Electronics Society.* pp.2287-2292. IEEE Press, Nov. 2017.

[26] Liu, Wenzhao, Tomasz Tarasiuk, Mariusz Gorniak. Josep M. Guerrero, Mehdi Savaghebi, Juan.C Vasquez Quintero and Chun-Lien Su. "Power Quality Assessment in Real Shipboard Microgrid under Quasi-balanced and Unbalanced Voltage Conditions." *In 33rd IEEE Applied Power Electronics Conference and Exposition* (APEC). pp.521-527, IEEE Press, Mar. 2018.

[27] T. Tarasiuk, M. Gorniak. "Load Sharing in Ship Microgrids under Nonsinusoidal Conditions–Case Study." *IEEE Transactions on Energy* Conversion . vol .32,no.2, pp.810-819. June, 2017.

[28] Yang, Haoyuan, and Shu-Yuen Ron Hui. "Nonintrusive Power Measurement Method With Phase Detection for Low-Cost Smart Meters." *IEEE Transactions on Industrial Electronics* .vol 64, no. 5 pp: 3962-3969.2017.

[29] Su, Chun-Lien, Ching-Jin Chen, and Ching-Cheng Lee. "Fast Evaluation Methods for Voltage Sags in Ship Electrical Power Systems." *IEEE Transactions on Industry Applications*,vol.49 no.1. pp: 233-241. 2013.

[30] Sulligoi, Giorgio, Andrea Vicenzutti, Vittorio Arcidiacono etc.. "Voltage stability in large marine-integrated electrical and electronic power systems." IEEE Transactions on Industry Applications 52, no. 4,pp: 3584-3594.2016.

[31] Javaid, Uzair, Francisco D. Freijedo, Drazen Dujic, and Wim Van Der Merwe. "Dynamic Assessment of Source–Load Interactions in Marine MVDC Distribution." IEEE Transactions on Industrial Electronicsvol, 64, no. 6, pp: 4372-4381.2017.