Modeling and Power Quality Assessment in Shipboard Microgrids

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BY
WENZHAO LIU

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AALBORG UNIVERSITY
DENMARK

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DENMARK

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CV

Wenzhao Liu received the B.S. and M.S. degrees in electrical engineering and power electronics from Yanshan University, Qinhuangdao, China, in 2012 and 2015, respectively. He is currently working toward the Ph.D. degree in power electronics and power system at Aalborg University, Aalborg, Denmark. He has been a guest Ph.D. student in Gdynia Maritime University, Gdynia, Poland, in 2017. His research interests include distributed generation systems and shipboard microgrid.

ENGLISH SUMMARY

With the growing development of power electronics technology onboard, ship power systems can be seen as shipboard microgrids (SMGs), which shows specific features such as higher torque-dense electric propulsion system, large-power pump motor loads, and smart power management and monitoring devices. In this background, power quality issues onboard are of a significant concern caused by the wide application of variable frequency drives such as bow thruster drives, large power pumps loads, fans and propellers.

This project provides PQ assessment methods for SMGs under both unbalanced and harmonic AC bus voltage conditions. The impact of voltage unbalance combined with harmonics on the SMG behaviors are analyzed, some models and controllable experimental research are proposed and carried out in a real ship under sea-going conditions. The experiments are presented considering real non-linear bow thruster load and high power ballast pump loads at steady and transient conditions. In addition, the transient impact of voltage dips has been carefully analyzed based on maritime standards methods. The research work done proposed modelling methods based on the critical ship system parameters, which can be easily applied for PQ assessment onboard. Moreover, voltage dips caused by pump loads can lead to generator unbalanced fundamental current and harmonic current surges, which also have been analyzed.

On the other hand, an interesting evaluation method for voltage dips is proposed to estimate the expected severity of voltage dips and generator current transient surges due to the onboard motor start-ups under real ship sea-going conditions. The PQ assessment model is based on the Riemann-summation-principle evaluation method. The methods are validated by measurement data gathered from the practical SMG during the ballast pump motor starts, which can provide engineers with necessary information of the actual magnitude/depth of voltage dips and transient peak value of generator current. In addition, the maximum allowable capacities of power motors can be estimated, which is beneficial to determine proper motor starter designs and improve the PQ in real SMGs.

It is worth noting that power quality issues are still challenging for SMGs systemically analysis. However, the proposed methods are able to obtain simplified models allowing quick analysis and accurate PQ assessment in practical ships, especially under unbalanced and harmonic voltage conditions.

DANSK RESUME

Med den voksende udvikling af strømelek troniksteknologi om bord kan skibesystemerne ses som typiske mikrofonterminaler (SMGs), som viser specifikke funktioner som højere drejningsmoment elektrisk fremdriftssystem, storpumpemotorbelastning og smart strømstyring og overvågningsenheder. I denne baggrund er strømkvalitetsproblemer om bord et væsentligt problem, der skyldes den brede anvendelse af frekvensomformere såsom baugpropellerdrev, kraftpumper, fans og propeller.

Dette projekt giver PQ vurderingsmetoder til SMG under både ubalancerede og harmoniske AC busspændingsforhold. Påvirkningen af spændingsbalance kombineret med harmonikere på SMG-adfærd analyseres, nogle modeller og kontrollerbar eksperimentel forskning foreslås og udføres i et rigtigt skib under havgående forhold. Eksperimenterne præsenteres i betragtning af reel ikke-lineær buepropelbelastning og ballastpumper med høj effekt ved stabile og forbigående forhold. Derudover er den transiente effekt af spændingsdykninger blevet omhyggeligt analyseret ud fra maritime standardmetoder. Arbejdet foreslog modelmetoderne baseret på kritiske skibssystemparametre, som let kan anvendes til PQ-vurdering og forbedring om bord. Desuden kan spændings dybningerne forårsaget af pumpeladninger føre til generatoren ubalancerede grundlæggende og harmoniske strømstigninger, som også er analyseret.

På den anden side foreslås en interessant evalueringsmetode til spændings dybninger for at estimere den forventede sværhedsgrad af spændingsdykninger og generatorstrøm forbigående stigninger på grund af startmotorerne ombord under egentlige skibsvejeforhold. PQ vurderingsmodellen er baseret på Riemann-summation-princippet evalueringsmetode. Metoderne er valideret af måledata indsamlet fra den praktiske SMG, når ballastpumpens motor starter, hvilket kan give ingeniører nødvendige informationer om den faktiske størrelse / dybde af spændingsdykninger og forbigående topværdi af generatorstrøm. Desuden kan de maksimale tilladte kapaciteter af motorer anslås, hvilket er en fordel at bestemme rigtige motorstarterdesign og forbedre PQ i reelle SMG'er.

Det er medtaget, at strømkvalitetsproblemer stadig er udfordrende for systematisk analyse af skibet. Imidlertid er de foreslåede metoder blevet forenklet og nemme at implementere til hurtig analyse og præcis PQ-vurdering i praktisk skib, især under ubalancerede og harmoniske spændingsforhold.

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The Ph.D. study, entitled ‘Modeling and Power Quality Assessment in Shipboard Microgrids’, is carried out from November 2015 until November 2018, under the supervision of Prof. Josep M. Guerrero, from the department of Energy Technology, Aalborg University (AAU), Denmark. I would like to thank the department for the financial support during the period of my study.

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1-Oct-2018

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CHAPTER 1. INTRODUCTION

BACKGROUND AND MOTIVATION

1.1.1 SHIPBOARD MICROGRID CONCEPT

The ship electrical power system can be considered as a typical islanded microgrid when the ship is out in the sea, which also can operate as a grid-connected microgrid when connected to the shore power at berth, as shown in Fig. 1.1. So that many ideas and concepts from traditional land-based microgrids can be converted and adapted in the ship power system, as so called shipboard microgrid (SMG) [1-6]. Nevertheless, with the development of all electric ship equipped with more power electronic devices, power quality (PQ) issues have been an increasingly serious challenge for ships [7-12]. This is because the ship system stability under failures is in general more critical than that in terrestrial microgrids, and onboard failures and/or blackouts that cannot be fixed automatically and cannot be repaired by the maintenance crew in a very short time during the ship sea-going. Those situations brought potential risks for the crew and passengers onboard [13-15].

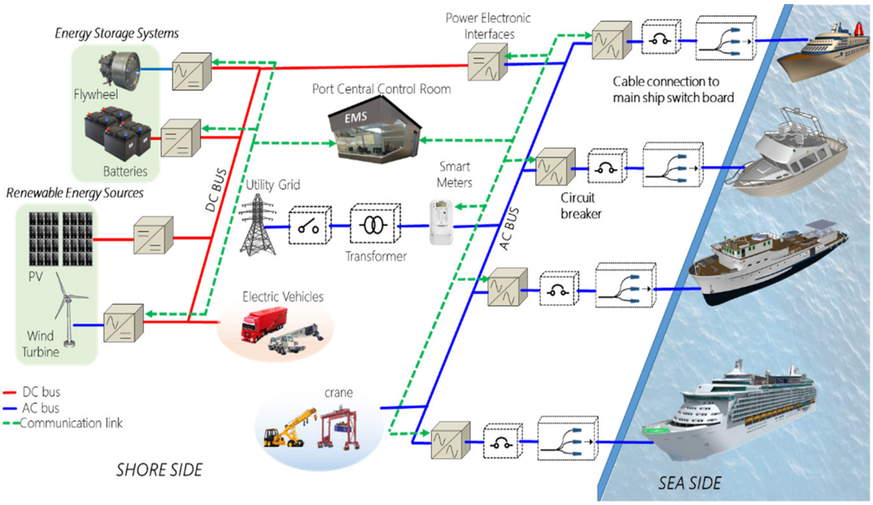


Fig.1.1. Typical shipboard microgrids connected with land-based microgrids

1.1.2 MOTIVATION

The main motivation of this thesis is to present several solutions and real study-cases for solving the pressing problems of energy efficiency and power quality in the ship. This project provides a PQ analysis of the SMGs and justifies the necessity of PQ improvement considering unbalanced voltage/currents, transient frequency variations, distorted waveforms, and power oscillations in ships. Furthermore, expectations and challenges of PQ can be considered for next generation of intelligent and electrical ships.

In fact, the development of ships electrification has been started from the early 20th century. Ships including integrated power system were popular for their outstanding features, such as less fuel consumption, higher torque dense electric propulsion, and increased availability and survivability [16-21]. A paradigmatic example was the Queen Elizabeth II (QEII) whose steam turbines were replaced with a diesel-electric propulsion plant in 1986 [17]. As shown in Fig. 1.2, the QEII uses an integrated power system, and its propulsion loads are fed by a high voltage (HV-10kV) distribution system and service loads such as fans, heaters, lights are fed by a LV distribution system. The LV bus is fed from the main switchboard HV-AC bus though a step down transformer.

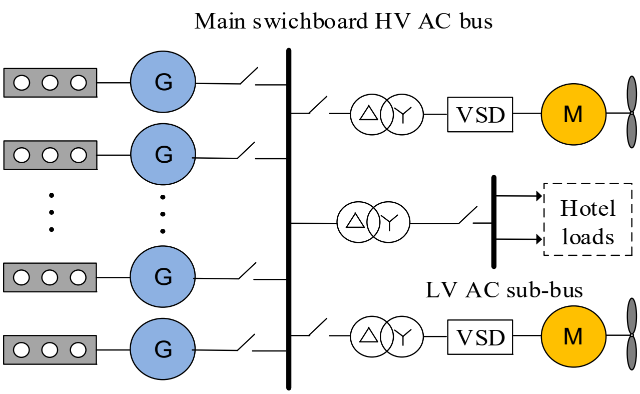


Fig.1.2. Queen Elizabeth II cruise ship power system

After 1980s, with the fast development of power electronic converter technologies, the variable frequency converters (variable speed drive, VSD) plays an important role in the electric propulsion or thruster system, often implemented in AC ship systems [22-24], the power electronic converter system generates variable voltage and frequency output from the fixed frequency and voltage power supply [25], [26]. Normally, the power conversion can be achieved by using direct AC-AC converters such as cyclo-converters [27], matrix converters [28], or AC-DC-AC converters with a dc-link obtained from a rectifier-inverter combination [29-30]. In addition to the propulsion and thruster drive systems, power electronics still play an important role in energy storage integration, generation and conversion [31-35].

However, at the same time, power electronics can create some problems related to power quality issues. Strong voltage and frequency variations, distorted waveforms, power oscillations, inaccurate load sharing among parallel generators as well as transient disturbances are generally produced due to the extensive use of nonlinear power electronic devices and high power loads with fast dynamic response demand in SMGs [8-11], [36-40]. These PQ issues can also lead to unwanted power losses in generators, unpredictable harmonics, and even malfunction or failures in vital propulsion systems.

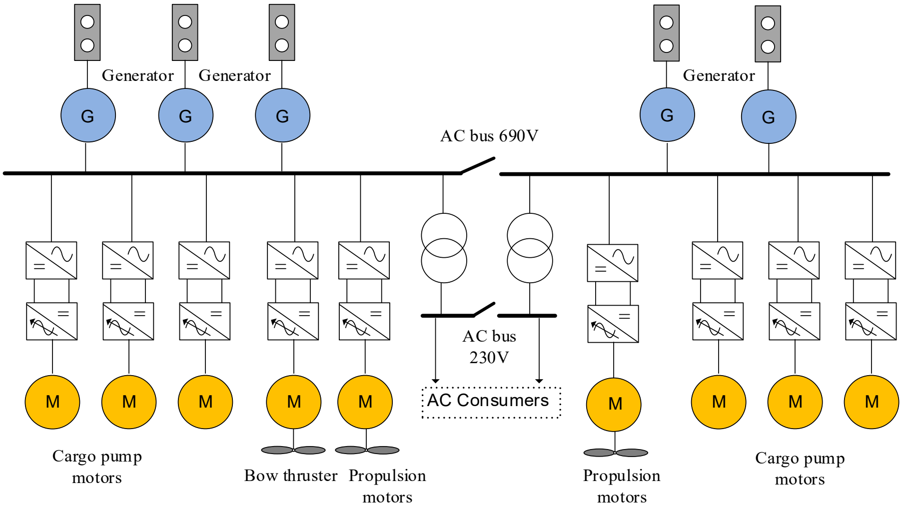


Fig.1.3. An example of AC SMG architecture (Siemens 2017)

Fig. 1.3 shows an example of classical radial AC distribution system, corresponds to the most common structure for typical industrial AC ships [41]. It can be seen that every generator onboard is generally driven by a diesel engine, and bow thrusters and propulsion motors are supplied by variable frequency power electronic converters. The AC bus is also divided into two buses linked with bus-tied switches, which is beneficial to isolate buses in case of faults. The sub-bus is then fed from the main switchboard through step-down transformers to supply other AC consumers, similarly as in the QEII. In fact, most ships are using the AC system in the marine industry due to more mature technologies.

In the case of three-phase AC SMGs, during the ship propulsion motor start-up and brake, sudden and severe bus voltage and frequency fluctuations caused by extensive use of high power loads may result in power system contingencies and eventually blackouts [42], [43]. The application of large capacity power electronics devices and some heavy energy consumers based on switches actions leads to the large harmonic currents pushed into the power system because of the highly inductance network impedance [44-46]. Furthermore, since SMGs are autonomous and flexible networks, due to the power flow through ship electric wire, voltage and current harmonics are not only causing energy waste but also affecting the communications and management systems of the electrical equipment onboard [47-50]. In addition, the harmonic currents are mainly produced by the connection of non-linear loads such as power electronic propulsion thrusters, the harmonic currents flow through the main AC bus that cause voltage distortions, and finally affects the whole power supply system onboard. However, there are still quite few challenging to analyze the whole ship system with different maritime standards [51-59]. This requires complex approach, starting from the ship design stage, involving power quality assessment and management to achieve the aim of International Maritime Organization (IMO): “safe, secure and efficient shipping systems on clean oceans” [60]. Therefore, coping with PQ issues is becoming more and more important for the shipping industry.

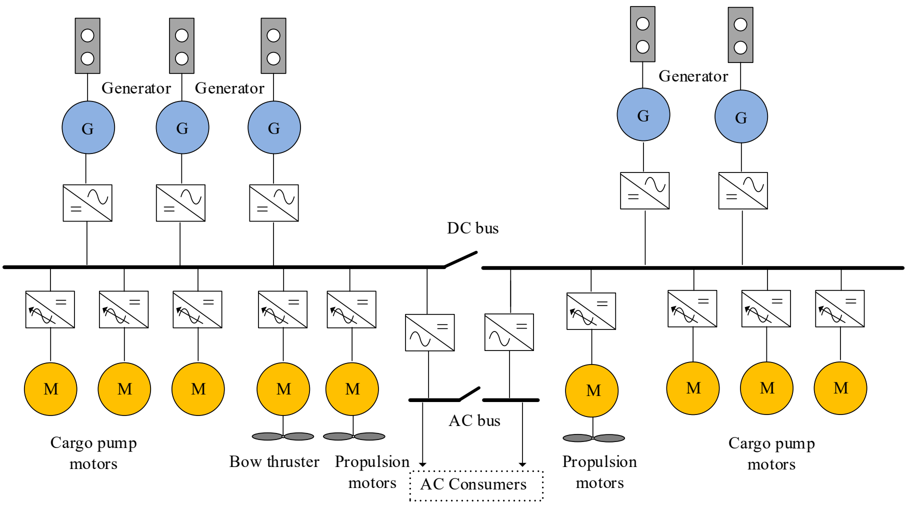


Fig.1.4. An example of DC SMG architecture (Siemens 2017)

Following the recent interests in research on DC grids, developments in power electronics, renewable energy and its storage systems are supporting the growth of DC SMGs [61-65]. An example of DC SMG architecture is shown in Fig. 1.4 [41]. Several rectifiers in the VFDs for motor control purposes have been removed, which is beneficial to reduce the system weight and volume. The DC bus is generated by rectified power sources. Moreover, the AC sub-bus is fed by the DC bus through inverters to supply the required power to consumers.

Compared to the AC SMG, in terms of power stability and quality aspects, DC systems have no frequency nor reactive power, making easy to control the power flow and increase the power stability [66-68]. On the other hand, DC-based power distribution systems can reduce the impact of harmonic distortion and increase power quality onboard [69], [70].

However, it should be noted that the maintenance cost of a DC SMG is much more expensive than the traditional AC one due to the fact of more complex power management and higher requirement of power electronics devices are installed onboard [71-73]. The rectifiers connected with generators directly also need more control to maintain the DC bus voltage constant and to help power-sharing functionalities.

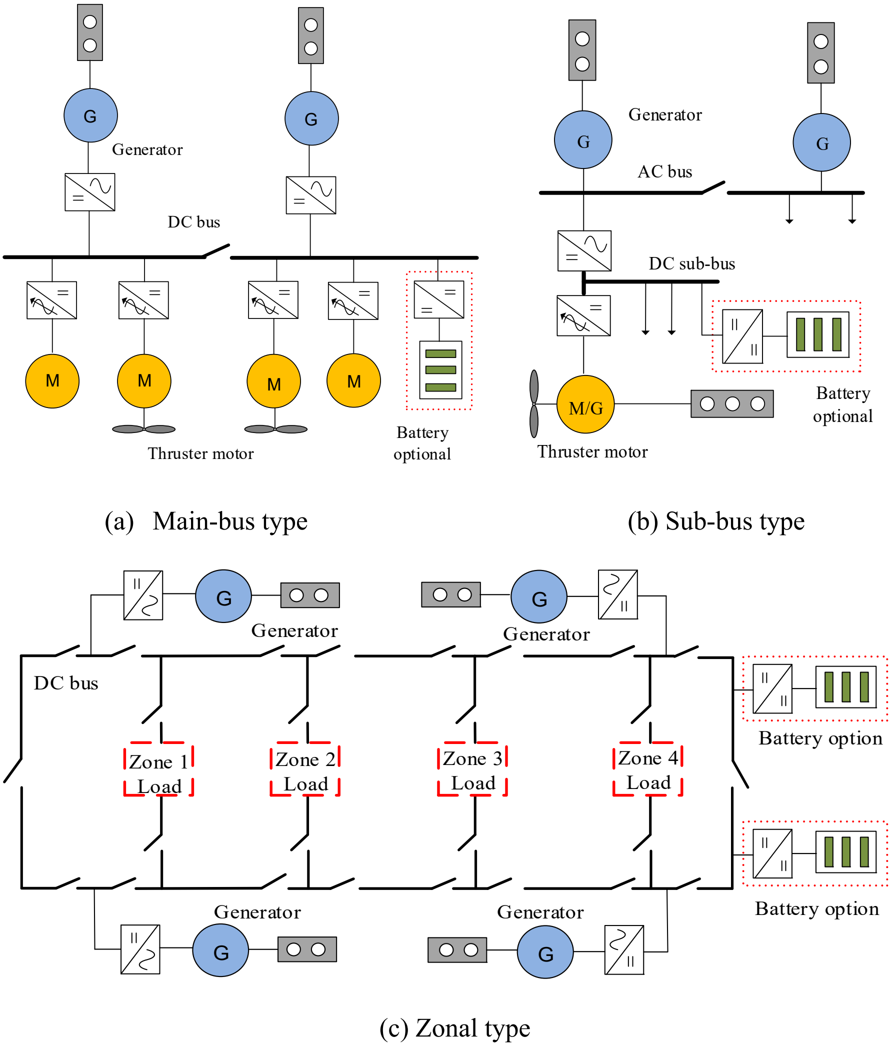


Fig.1.5. Different types of DC SMG

Furthermore, DC SMGs can be divided into main-bus type, sub-bus type and zone type [74], [75] as shown in Fig. 1.5. The main-bus type and sub-bus type are still common with two-split buses and applied to different ships based on their power requirements. In addition, in the zonal type, all loads in a compartment receive power from its zone or DC bus, which improve the survivability as it can prevent the spread of power damages. Therefore, the system is with higher redundancy, and has been applied to some naval ships [76], [77], which may also in combination with the battery control and management system to improve the energy efficiency and power quality onboard [78-80]. In other words, the DC SMGs technologies can also be seen as improved power quality solutions for future ships.

1.2. THESIS OBJECTIVES

Until now, for the ship industry, AC SMGs are still the most common structures. Therefore, the research objectives mainly considered the PQ issues in the AC SMGs. This project's objectives are listed as follows.

- To review previous studies on power quality aspects for shipboard power system and to determine their challenges and achievements.
- Since high-power pump motors start draw a large amount of power in short time, they cause significant frequency and voltage transients onboard. To propose new evaluation methods for voltage dips and assess the maximum allowable motor capacity onboard.
- To study and analyze the industrial ship operations under quasi-balanced and unbalanced voltage conditions and to compare with the PQ parameters based on maritime standards.
- To model and analyze the transient AC bus voltage dips, and to analyze its actual impact on generators and bow thruster motors.
- To verify the main harmonic sources in ships and to propose power quality assessment methods to analyse their impact.
- To study the PQ aspects on main architecture of SMGs.

1.3. THESIS OUTLINE

The outcomes of this project are documented in this Ph.D thesis, including an introduction of the project and a collection of the relevant articles published through the entire study period. In addition, the thesis is organized as follows:

Chapter .1 presents an introduction of the project background, motivation and objectives.

Chapter 2 presents the first paper, submitted to the *IEEE Transactions on Industrial Electronics*, which introduces an evaluation method for voltage dips in a shipboard microgrid under quasi-balanced and unbalanced voltage conditions. The proposed method can provide ship electrical engineers the necessary information about the actual magnitude/depth of voltage dips. Accordingly, the maximum allowable capacities of high-power motors can be estimated, which is beneficial to determine proper motor starter designs and to improve the power quality in real SMGs. Furthermore, two selected study-cases are carefully presented in order to analyze the SMG operations under sea-going conditions.

Chapter 3 presents the second paper, published in *IEEE IECON 2017*, which introduces deals with highlighting the actual impact of the voltage dips caused by starting high power pump motors in a real ship called Horyzont II. These adverse impacts are part of the power quality assessment, which includes the SMG frequency deviations, diesel generator current transient surges, bow thruster current harmonic components, and short-term disturbances. Furthermore, the paper presented the recent maritime electric standards, measurement methods and potential power quality improvement solutions for ship power systems.

Chapter 4 presents the third and fourth papers, published in *IEEE Transactions on Industry Applications* and *IEEE APEC 2018,* respectively. In this chapter, a simple power quality assessment models are proposed, while several controlled experiments are carried out in a real SMG. The assessment mainly considers non-linear bow-thruster drive motor and other pumps as the main harmonic sources onboard under unbalanced voltage conditions. Furthermore, the voltage/current distortions of working generator, thruster and pump loads are carefully analyzed and calculated based on the proposed models. This paper provides a valuable analysis for coping with PQ issues in the SMG.

Chapter 5 concludes the thesis contents and introduce the future works.

1.4. LIST OF PUBLICATIONS

A list of papers during the Ph.D. study, which are published or accepted until now, is given as follows.

Journal paper

J1. Wenzhao Liu, Tarasiuk Tomasz, Gorniak Mariusz, Mehdi Savaghebi, Juan Carlos Vasquez, Chun-Lien Su, and J. M. Guerrero, "Power Quality Assessment in Shipboard Microgrids under Unbalanced and Harmonic AC Bus Voltage," *IEEE Transactions on Industry Applications* 2018, (Accepted for publication – IEEE Early Access).

J2. Wenzhao Liu, Tarasiuk Tomasz, Chun-Lien Su, Gorniak Mariusz, Mehdi Savaghebi, Juan Carlos Vasquez, and J. M. Guerrero, "An Evaluation Method for Voltage Dips in a Shipboard Microgrid under Quasi-balanced and Unbalanced

Voltage Conditions," *IEEE Transactions on Industrial Electronics* 2018, (Accepted with minor revision, in fourth review).

J3. Guo Xiaoqiang, **Wenzhao Liu**, and Zhigang Lu, "Flexible power regulation and current-limited control of the grid-connected inverter under unbalanced grid voltage faults," *IEEE Transactions on Industrial Electronics,* vol. 64, no. 9, pp. 7425-7432. 2017.

J4. Guo Xiaoqiang, **Wenzhao Liu**, Xue Zhang, Xiaofeng Sun, Zhigang Lu and Josep M. Guerrero, "Flexible control strategy for grid-connected inverter under unbalanced grid faults without PLL," *IEEE Transactions on Power Electronics.* vol 30, no. 4. pp: 1773-1778. 2015.

Conference paper

C1. **Wenzhao Liu**, Josep M. Guerrero, Mehdi Savaghebi, Juan C. Vasquez, Tomasz Tarasiuk, and Mariusz Gorniak. "Impact of the voltage dips in shipboard microgrid power systems." In Industrial Electronics Society, IECON 2017-43rd Annual Conference of the IEEE, pp. 2287-2292, 2017.

C2. Wenzhao Liu, Tomasz Tarasiuk, Mariusz Gorniak, Josep M. Guerrero, Mehdi Savaghebi, Juan C. Vasquez, and Chun-Lien Su. "Power quality assessment in real shipboard microgrid systems under unbalanced and harmonic AC bus voltage." In-Applied Power Electronics Conference and Exposition (APEC), 2018 IEEE, pp. 521-527. IEEE, 2018.

C3. Wenzhao Liu, Xiaoqiang Guo, Giorgio Sulligoi, Y. J. Guan, Xin Zhao, B. Z. Wei, Mehdi Savaghebi, and Josep M. Guerrero. "Enhanced power quality and minimized peak current control in an inverter based microgrid under unbalanced grid faults." In Energy Conversion Congress and Exposition (ECCE), IEEE, pp. 1-6. 2016.

C4 . **Wenzhao Liu**, Xiaoqiang Guo, Mehdi Savaghebi, and Josep M. Guerrero. "Fault Ride Though Control of Photovoltaic Grid-connected Inverter with Current-limited Capability under Offshore Unbalanced Voltage Conditions." In Offshore energy & storage symposium (OSES) 2016.

C5. Josep M. Guerrero, Zheming Jin, **Wenzhao Liu**, Muzaidi B. Othman, Mehdi Savaghebi, Amjad Anvari-Moghaddam, Lexuan Meng, and Juan C. Vasquez. "Shipboard microgrids: maritime islanded power systems technologies." In PCIM Asia, pp. 1-8., 2016.

C6. Wei, Baoze, **Wenzhao Liu**, Josep M. Guerrero, and Juan C. Vásquez. "A power sharing method based on modified droop control for modular UPS." In Industrial Electronics Society, IECON 43rd Annual Conference of the IEEE, pp. 4839-4844. IEEE, 2017.

CHAPTER 2.

AN EVALUATION METHOD FOR VOLTAGE DIPS IN A SHIPBOARD MICROGRID UNDER QUASI-BALANCED AND UNBALANCED VOLTAGE CONDITIONS

This Section is based on the work done in paper 1, which has been submitted to IEEE Transactions on Industrial Electronics. More detailed information can be found in the attached publications of the Appendix.

SUMMUARY OF THE CONTRIBUTION

High power motor loads are widely applied to the shipboard microgrids (SMGs), which consuming about 70% of generated electrical power onboard [81]. Voltage dips caused by the starting current of high power motors are one of the main causes of onboard sensitive electrical equipment dropout [82], [83]. This phenomenon should be carefully considered in design of SMGs to comply with several maritime standards such as IEC61000-4-30 [84].

In this chapter, a fast evaluation method is proposed to estimate the expected severity of voltage dips due to the onboard motor start-up operation. The evaluation results are validated by measurements gathered from the ballast pump motor start-up in the SMG under real sea-going conditions. In addition, the SMG operations under quasi-balanced and unbalanced AC bus voltage cases were carefully selected to present the actual impact of the voltage dips in real SMG. The structure of the investigated ship can be seen in Fig.2.1.

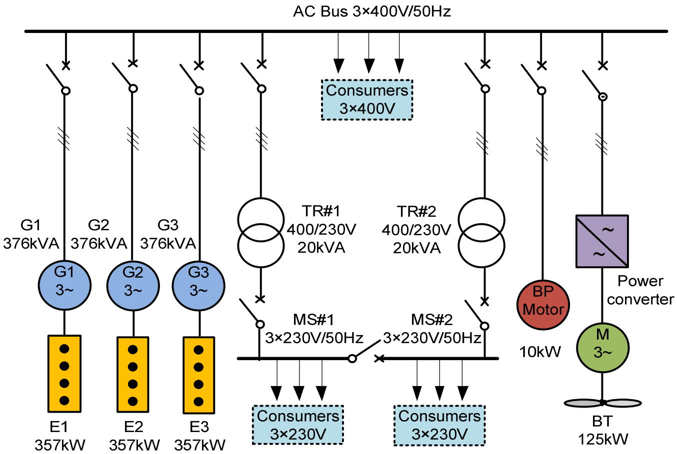


Fig.2.1. Simplified diagram of the investigated SMG [85]

The proposed method can provide ship engineers with necessary information about the actual magnitude/depth of voltage dips. Accordingly, the maximum allowable capacities of high power motors can be estimated, which is beneficial to determine proper motor starter designs and improve the power quality in real SMGs.

PROPOSED PUMP MOTOR STARTING MODEL AND EVALUATION METHOD

For the sake of modeling and analysis simplicity, the voltage dips caused by the starting-up action of pump motor in a SMG, by considering only one generator and a ballast pump motor, as shown in Fig. 2.2. The main harmonic source is the bow thruster drive. It should be noted that the situation in which only one generator is working can be considered as a worst-case from the harmonic distortions point of view in the onboard real ship [85], [86].

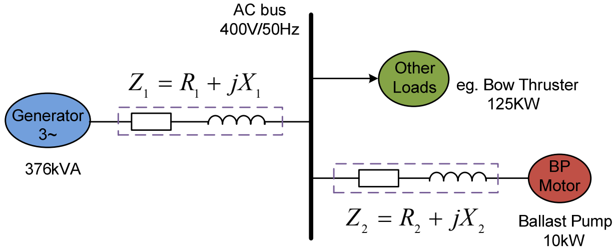


Fig. 2.2. Simplified diagram for the PQ analysis when the pump motor is starting in the SMG

In Fig. 2.2, in order to calculate the voltage dip magnitude at the AC bus during the starting-up process of a large motor, such as the ballast pump, the impedances between the generator and the ballast pump, Z_1 and Z_2, must be identified. Z_1 represents the generator source impedance at the AC bus and Z_2 is the impedance between the AC bus and the ballast pump motor, including the line impedance and the motor internal impedance.

2.2.1 EVALUATION METHOD

The voltage dip magnitude at the load terminal approximately equals the voltage drop at the AC bus, which can be expressed as the rated voltage of AC bus minus the voltage at the load when the pump is starting up. For a sake of simplicity, the rest loads currents can be ignored, being the voltage dip expressed as [81]:

$$V_{dip}(\%) = (1 - \frac{Z_2}{Z_1 + Z_2}) \times 100\% = \frac{Z_1}{Z_1 + Z_2} \times 100\% \qquad (2\text{-}1)$$

In order to explicitly present the relationships between the voltage dip and the pump starting current, the voltage dip in (2-1) can be rewritten as (2-2):

$$V_{dip}(\%) = \frac{X_g}{X_g + \frac{I_g}{I_m}} \times 100\% = \frac{I_m X_g}{I_m X_g + I_g} \times 100\% \tag{2-2}$$

where X_g is the reactance (in percentage) of the generator during motor starting-up process, which is calculated as the average of the generator transient reactance X_d' and sub-transient reactance X_d'', as shown in (2-3):

$$X_g = \frac{X_d' + X_d''}{2} \tag{2-3}$$

where I_g represents the generator rated current and I_m is the current of ballast pump motor during the starting period, which can be determined as follows:

$$I_m = \frac{Km^2 P_m}{\sqrt{3} V_m \cos\phi_m} \tag{2-4}$$

where K is the ratio of the motor starting current to its rated current. P_m,, V_m and $\cos\phi_m$ represent the rated power, rated voltage, and power factor of the ballast pump motor, respectively. In addition, m is the ratio of motor and system rated voltage during the start-up by applying starting methods such as connecting with transformers [81].

The generator current I_g can be expressed as:

$$I_g = \frac{P_g}{\sqrt{3} V_g \cos\phi_g} \tag{2-5}$$

where P_g, V_g and $\cos\phi_g$ represent the rated power, rated voltage, and power factor of the working diesel generator.

However, during the motor starting period, the voltage dips will affect the actual generator output current; hence the transient generator current surges can be calculated as

$$I_{surge\_g} = \frac{V_g \times V_{dip}(\%)}{\sqrt{3} X_g} \tag{2-6}$$

It should be noted that the impacts of the voltage dip magnitude depend on the loading of power generator during motor starting. In other words, when a large power motor is enabled, the preloaded engine generator effect cannot be neglected due to the already existing high-power demands and the limited power generation.

Assuming that there is a protective voltage limit V_{limit} or a fault ride through (FRT), when the voltage is below this threshold, motors continue working, otherwise, it will be tripped [84]. Hence, the residual voltage can be calculated as

$$V_g[1 - V_{dip}(\%)] = V_g\left(\frac{I_g}{I_m X_g + I_g}\right) \geq V_{\text{limit}} \tag{2-7}$$

The motor capacity must be taken into account during voltage dips. By substituting (2-7) into (2-2) and considering a given power generation, the maximum allowable motor capacity can be calculated as

$$(\frac{P_m}{P_g})_{\max} = \frac{V_m \cos\phi_m}{Km^2 V_g \cos\phi_g} \times \frac{V_g - V_{\text{limit}}}{X_g V_{\text{limit}}} \tag{2-8}$$

For a given limited voltage, the maximum installed motor capacity can be easily estimated from (2-8). It is indicated that the maximum motor capacity decreases when the voltage limitation is increased. However, noted that under some unbalanced voltage faults, the lowest voltage magnitude must be determined to ensure that the actual voltage will not go below the limited value. In such a case, equation (2-8) can be replaced by (2-9)

$$(\frac{P_m}{P_g})_{\max} = \frac{V_m \cos\phi_m}{Km^2 V_g \cos\phi_g} \times \frac{V_{lowest} - V_{\text{limit}}}{X_g V_{\text{limit}}} \tag{2-9}$$

$$V_{lowest} = \min(V_{ga}, V_{gb}, V_{gc}) \tag{2-10}$$

where V_{ga} V_{gb} V_{gc} are the three-phase output voltages of the generator.

2.2.2 MEASUREMENT CALCULATIONS BASED ON RIEMANN-SUMMATION

In order to verify the prediction method for voltage dips, the results obtained basing on the model should be compared with the real measurements onboard. However, the direct comparison of evaluation results with experimental results is quite difficult, because the typical motor starting current are quite different from the assumption for an average starting current of pump motor in the models. In order to solve this problem, IEC Standard 61000-4-30 [84] defined the measurement methods and interpretation of PQ assessment.

The evaluation method based on Riemann Summation was proposed to evaluate the starting voltage and/or current of the high-power pump motor. In addition, the Riemann Summation calculations are employed to approximate the total area of the motor starting current curve during the time between pump motor starting and switching off. The interval is equally divided into N_m subintervals and accordingly, the average value of the motor starting current I_{ms_mea} can be expressed as

$$I_{ms\_mea} = \sqrt{\frac{1}{N_m}\sum_{i=1}^{N_m} I^2_{ms\_rms\_i}} \tag{2-11}$$

where N_m is the number of Riemann subintervals and $I_{ms\_rms\_i}$ is the r.m.s value at the ith subintervals current.

In a similar way, the interval is equally divided into N_g subintervals to calculate the generator current surges I_{gs_mea} as

$$I_{gs\_mea} = \sqrt{\frac{1}{N_g}\sum_{i=1}^{N_g}(I_{gref} - I_{gs\_rms\_i})^2} \quad (2\text{-}12)$$

where N_g is the number of Riemann subintervals, I_{gref} is the reference current and the $I_{gs\_rms\_i}$ is the rms value at the i-th subinterval current.

IEC 61000-4-30 standard characterizes the dips by depth and duration. The depth is equal to the difference between the reference voltage and the residual voltage, the duration is calculated from the time that voltage falls below a predefined threshold until it rises above the threshold plus a hysteresis [84]. The voltage dip is usually expressed as a percentage of reference voltage and calculated as

$$V_{dip\_mea} = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(V_{ref} - V_{dip\_rms\_i})^2} \quad (2\text{-}13)$$

where M is the number of Riemann subintervals, V_{ref} is the reference voltage and the $V_{dip\_rms\_i}$ is the rms value at the ith subinterval voltage.

RESULTS

The voltage dips were monitored for two cases:

#Case A: Quails-balanced AC bus voltage
#Case B: Unbalanced Ac bus voltage

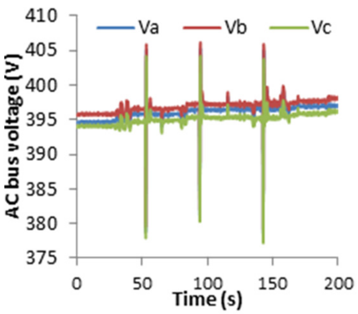
TABLE 2.1. CASE STUDIES IN SHIP MICROGRID

Ship microgrid	Case A	Case B
Diesel generator	enabled	enabled
Ballast pump load	starts three times to generate voltage dips	starts three times to generate voltage dips
Bow thruster load	power increasing until full load	power increasing until full load
Fresh water pump	normal operations	normal operations
Heater load	normal operations	unbalanced operations
Other ship electrical devices	real SMGs contain hundreds of electrical devices working at the same time	

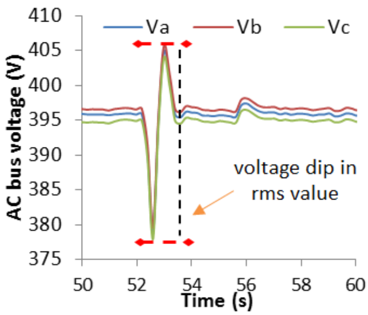
As shown in Table 2.1, the ship experiment processes are designed as the followings steps. Only one generator was enabled and the bow thruster power has step changes to full load. The ballast pump started three times to generate voltage dips. Although the voltage dips were moderate, this condition can represent the typical behaviors in SMGs. The consumption of other loads remained unchanged. In Table 2.1, note that the only difference is the heater load with phase A disconnected and working with phases B and C, which emulate the case of fuse breaking to obtain voltage unbalance in Case study B.

2.3.1 CASE STUDY A

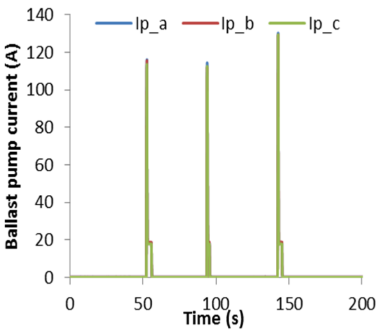
As mentioned in the above study-case of SMG. The detailed SMG behaviors under quasi-balanced voltage conditions depicted in Fig. 2.3.



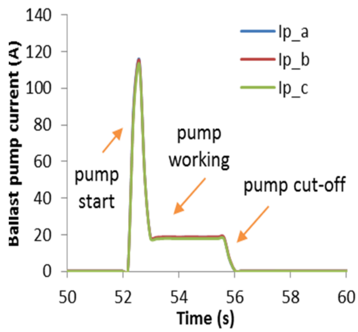
(a) AC bus voltage



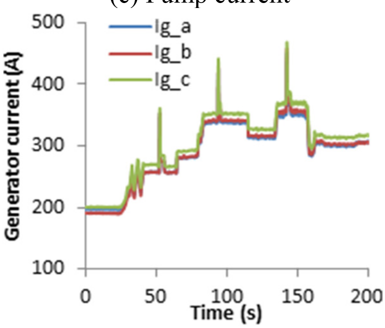
(b) Voltage dip



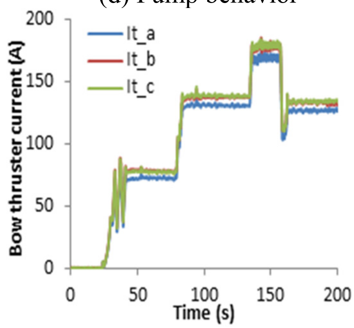
(c) Pump current



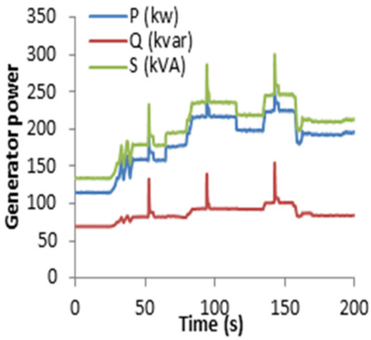
(d) Pump behavior



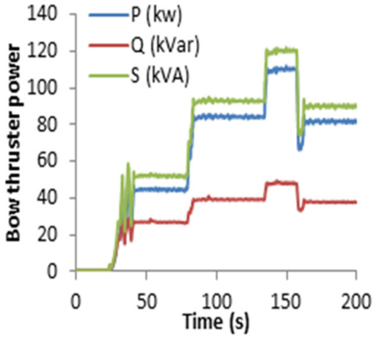
(e) Generator current



(f) Thruster current



(g) Generator powers



(h) Thruster powers

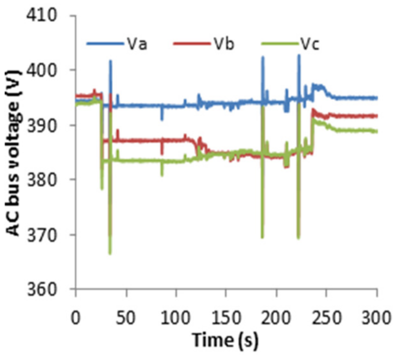
Fig.2.3. Experimental results of SMG in case A

Figs. 2.3 (a) and (b) show the *rms* value of ship AC bus quasi-balanced voltage during ballast pump start-up. The voltage unbalance indices remained quite low and in the range of 0.2%-0.43% with the mean value equal to 0.3%.

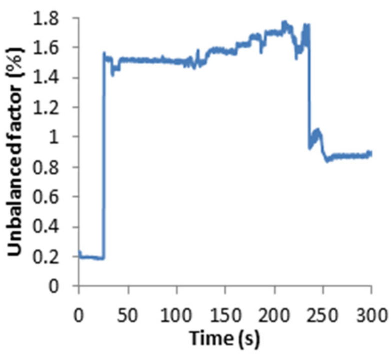
The reason of the voltage dips is the ballast pump starting current effect, shown in Figs. 2.3 (c) and (d), which can reach 120A, if measured on the basis of a ten-cycle window. It reached even 148A within only 0.03s, which is about 6 times the rated current. The latter value was obtained by calculating the current *rms* value over one cycle and refreshing it on each half cycle, following the voltage dips assessment in the standard IEC 61000-4-30 [84].

2.3.2 CASE STUDY B

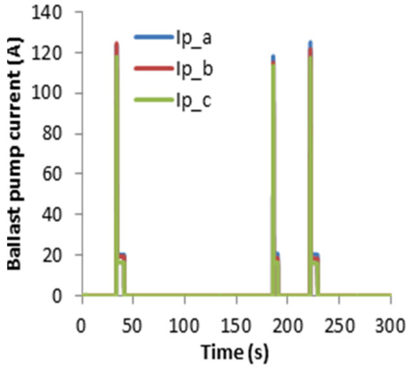
Standard maneuvering behaviors of the SMG were monitored similarly as in case A. However, the voltage unbalance were caused by the heater loads operating with phase "a" disconnected. The detailed operations of the SMG can be seen in Fig. 2.4.



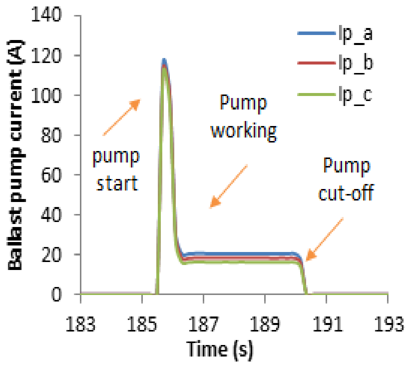
(a) AC bus voltage



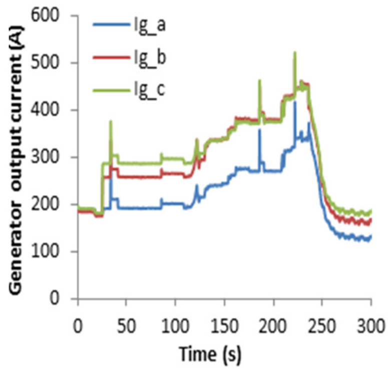
(b) Unbalance factor



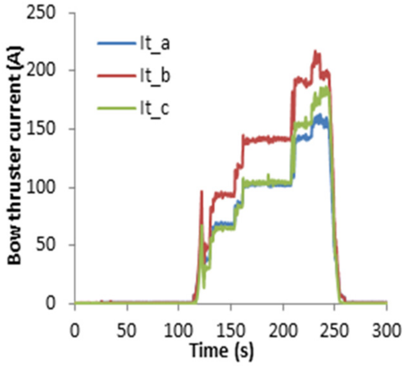
(c) Pump motor current



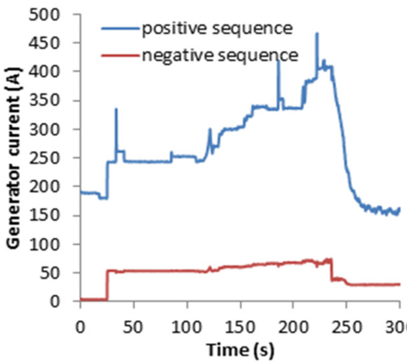
(d) Pump current



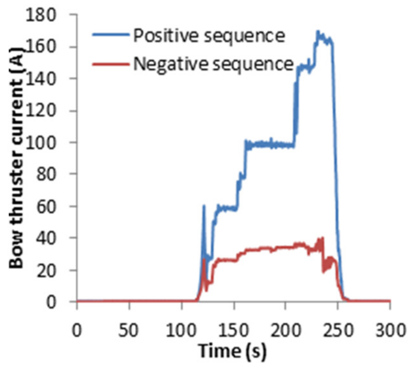
(e) Generator current



(f) Thruster current



(g) Generator positive/negative sequence currents



(h) Thruster positive/negative sequence currents

Fig.2.4. Experimental results of SMG in case B

Figs. 2.4 (a) and (b) show that unbalanced voltage dips occur three times due to the pump motor start-up condition. The bow thruster starts at 120s and increases the voltage unbalance factor from 1.5% to 1.8%.

On the other hand, the pump working currents are slightly unbalanced as shown in Figs. 2.4 (c) and (d). Furthermore, Figs. 2.4 (e)-(h) show that the generator and bow thruster currents are severly unbalanced. The sudden surge produce large generator currents in the respective line currents which can reach 120 A (22% of generator rated current), which may trigger the overcurrent protection system onboard and possibly endanger shipboard operation.

Moreover, the bow thruster currents are also unbalanced and the fundamental negative sequence component is about 40A. The individual maximum rms value is obviously higher than the value in case A, which means unequal thermal stress for generator windings under unbalanced voltage conditions.

2.3.3 RESULTS AND COMPARISON

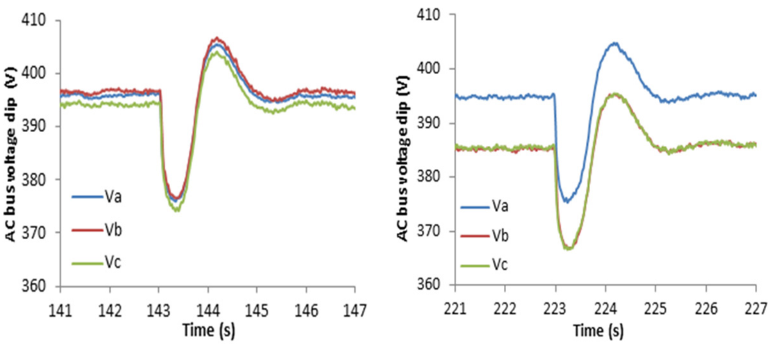


Fig. 2.5. Voltage dips in the two cases.

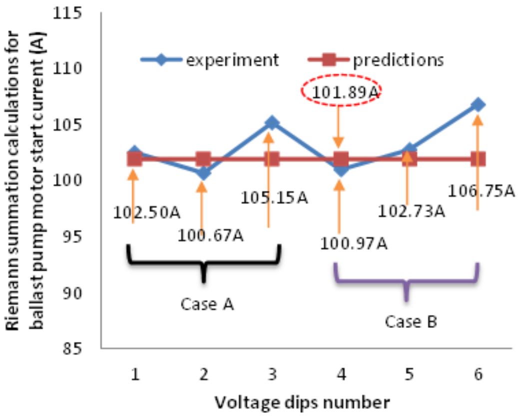
Fig. 2.5 shows the voltage dips in cases A and B. The depth of voltage dip is about 5% of the pre-event voltage in both cases. The differences between values for respective three phase voltages under quasi-balanced conditions remain quite low up to 0.5%, but the differences increase up to 2.5% under unbalanced conditions.

However, the depth of unbalanced voltage dip in case B is larger, reaching 8.35%, and the residual voltage is lower than those values of case A. Therefore, it is indicated that the unbalance affects the AVR operation, which sets only highest line-to-line voltage to rated value especially during the transient dips. This may bring hazards to some sensitive electrical equipment in case of severe voltage dips.

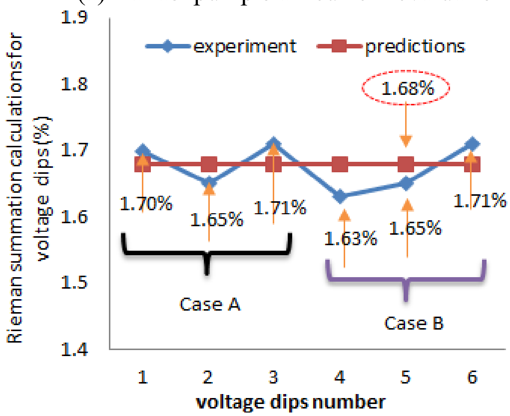
The measurement results of the voltage dips parameters and generator output currents are calculated according to the IEC 61000-4-30 standard (Class A measurement method) as can be found in Table 2.2.

TABLE 2.2 VOLTAGE DIPS AND GENERATOR CURRENT DETERMINED ACCORDING TO THE MEASUREMENTS

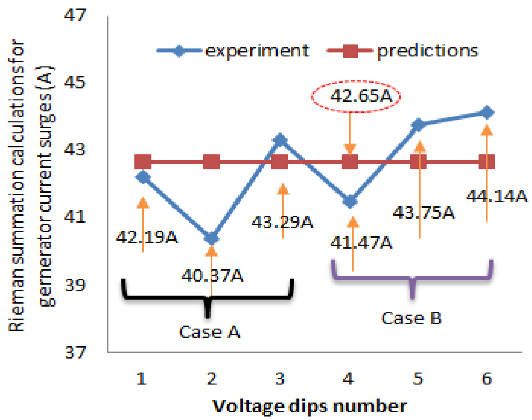
Parameters		***AC bus voltage [V$_{rms}$]***		***Dip depth [%]***		***Generator current peak value[A]***	
		Pre-event	***Residual***	***% of Pre-event voltage***	***% of rated voltage***	***Pre-event Current***	***Max surge current***
Case A	Va	395.72	375.98	4.99	6.00	482.21	685.21
	Vb	396.40	376.66	4.98	5.84	482.37	681.54
	Vc	394.01	374.18	5.03	6.45	480.34	682.79
Case B	Va	394.82	375.33	4.94	6.17	478.62	656.10
	Vb	385.21	366.77	4.79	8.31	646.53	784.25
	Vc	385.47	366.61	4.89	8.35	666.83	845.64



(a) Ballast pump start current evaluation



(b) Voltage dips evaluation



(c) Generator current surges evaluation

Fig.2.6. Evaluation results based on Riemann Summation for comparison

Fig. 2.6 presents the evalution results for the voltage dips, ballast pump motor start current and generator transient current surges under quasi-balanced voltage (case A) and unbalanced voltage (case B) conditions. The predicted values are calculated based on the proposed model (2-2)-(2-6), and the experimental results are calculated by Riemann Summation based on (2-11)-(2-13).

Fig. 2.6 (a) shows that the predicted value based on (2-4), for the ballast pump motor starting current is about 102 A, which almost matches the Riemann summation results from (2-11) for experimental measurements. The maximum error is only 4.8%. Fig. 2.6 (b) shows that the voltage dips calculated by (2-2) are about 1.68%, and the Riemann summation evaluation results based on equation (2-13) are in the range of 1.63-1.71% with the maximum error of 3.0%. It worth noting that the voltage dips mainly depend on the capacity and start current of the pump motor and the dips depths with respect to the pre-event voltages are almost the same for quasi-balanced and unbalanced cases.

As it can be seen in Fig. 2.6 (c), the generator current surges calculated by (2-6) is 42.65A, which also matches the Riemann summation experimental results from (2-12), and the maximum error is 4.9%. In addtion, it should be noted that the generator current surges are relevant to the actual voltage dip depth, and the individual phase current peak value are more likely to trigger the overcurrent protection devices onboard due to the unbalanced waveforms in case B.

On the other hand, considering the unbalanced voltage dip may have extra impact on the SMG. In Fig. 2.7, the lowest voltage should be above the dip threshold value, otherwise, the calculated capacity of the motor will be a negative value which is unacceptable. In the studied cases, for a given voltage dip limit value (e.g. 20% of generator rated volage [84], [87]), the lowest voltage dip is about 360V, and the voltage limit is 320V. Therefore, the total maximum motor capacity can be estimated as 90kW according to (2-9), which provided the proper design information to the allowable motor capacity. However, it should be noted that the maximum allowable motor capacity will fast decrease when decreseing the voltage values.

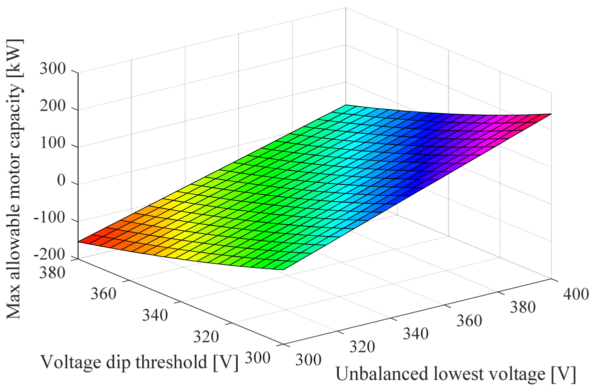


Fig.2.7. Maximum allowable motor capacity estimation

2.4. CONCLUSION

In short, the proposed methods can be used to assess the voltage dips caused by direct starting of motors and its impact. The experimental analyses in SMG were focused on the magnitude/depth of voltage dips and actual impact including transient generator current surges. The results indicated that the voltage dips mainly depend on motor power, and the generator transient current surges are caused by voltage dips for both study cases. On the other hand, the maximum allowable motor capacity can be properly determined and noted that the motor capacity will be decreased even more when the unbalanced low voltages are considered.

CHAPTER 3.

IMPACT OF THE VOLTAGE DIPS IN SHIPBOARD MICROGRID POWER SYSTEM

This section is mainly based on the work of paper 2 [85], which has been published in IEEE IECON 2017. More detailed information can be found in the attached publications.

SUMMARY OF THE CONTRIBUTION

Transient voltage and frequency variations are very common power quality (PQ) issues in shipboard microgrids (SMGs). In this chapter, the impacts of voltage dips induced by pump loads start-ups are carefully analyzed in a SMG. Here, the transient impact of SMGs frequency and harmonic components is presented and the recent relevant maritime PQ standards are introduced. The experimental results from a real ship to show the actual impact of moderate voltage dips on the selected working generator and bow thruster drives.

The contribution of this work is focused on the analysis of the impact of voltage dips in the investigated SMG.

REAL SHIPBOARD MICROGRIDS AND RECENT MARITIME PQ STANDARDS

3.2.1 HORYZONT II SHIP

For the experimental tests for the impact of voltage dips, a research-training ship called Horyzont II in Gdynia was selected as shown in Fig. 3.1. The ship is employed to conduct specialized marine training, research and regular cruises to Polar Regions with supply for Polish polar bases [88].

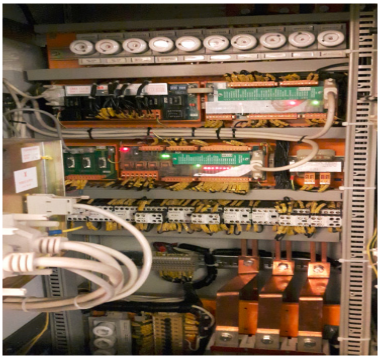
The ship electrical test platform consisted of three generators, a variable speed drive with power converter (bow thruster motor and propeller), a ballast pump motor and auxiliary loads such as fresh water pump in the main engine cooling system, fans and heater loads etc. The pumps driven by induction motors are common electrical energy consumers onboard [89-91]. The system parameters can be found in Table 3.1.

The voltage and current samples were registered by a controller (NI PXIe-8106) equipped with three DAQs (NI PXIe-6124) and anti-aliasing filters (LTC-1564). The

Rogowski's coils (PEM LFR 06/6) and LEMs CV3-1500 were used for signal conditioning.

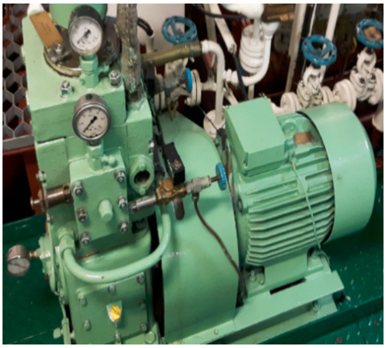
(a) Horyzont II ship in GMU

(b) Engine room



(c) Control board

(d) Diesel generator



(e) Pump load

Fig.3.1. The test environment of the investigated SMG [85], [88]

TABLE 3.1 SHIP PARAMETERS

Ship microgrid	parameters	Value	**Ship microgrid**	parameters	Value
Main AC bus voltage	Vabc [V_{rms}]	400	**Bow thruster load**	P_t [kW]	125
	f [Hz]	50	**Fresh water pump load**	P_f [kW]	11
	Uf [%]	0.35	**Heater load**	P_h [kW]	90
Diesel generator	V_g [V_{rms}]	400	**Ballast pump motor**	$V_{m\text{-}abc}$ [V_{rms}]	400
	P_g [kW]	300.8		P_m [kW]	10
	X_d' [%]	10.6		$\cos\phi_m$	0.85
	X_d'' [%]	7.6		k	6
	$\cos\phi_g$	0.8		m	1
Main engine	P_e [kW]	1280	**Fresh water tank**	tons	60
Speed	Knots	12	**Fuel tank**	Weight [t]	265.6

3.2.2 RENCENT MARITIME PQ STANDARDS

The limitations for voltage and frequency transients and total harmonic distortion (THD) are defined by several maritime standards to ensure the reliability of power electronic devices and the safety of crews on shipboard. Most general standards such as Polish Register Standard IEC60092-101, Lloyd's Register Standard, American Bureau of shipping (ABS) 2008 and the IEEE Coordinating Committee Standard 45-2002 that imposed a lot of peculiar voltage and frequency requirements that must be respected in the shipboard power system. However, the different versions of standards are still not unified and may cause some misunderstanding.

Until recent years, in the rules of amended unified requirements of International Association of Classification Societies (IACS) and its members, which clearly defined the allowable voltage transients due to sudden changes of loads are $\pm 20\%$ of the pre-event voltage with 1.5 seconds of recovery time. The frequency transient variations are about $\pm 10\%$ of the pre-event frequency with 5 seconds of recovery time. In addition, for the military ship system, the STANAG1008 standards are stricter with the demands of $\pm 16\%$ for voltage transient conditions and $\pm 4\%$ variations for SMG frequency.

Regarding the harmonics occurred at SMGs, most societies agreed on that THD of ship switchboard voltage (up to the 50th order harmonic) should remain below 8%.

TABLE 3.2. THE PERMISSION LEVELS OF VOLTAGE AND FREQUENCY FOR SHIP

Standards	**Instruments and Parameter Variations**			
	Range of The Standard	**Voltage**	**Frequency**	**THD**
Polish Register IEC 60092-101	Electrical Installations in ships. Definitions and general requirements	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$5\%(40\,th)$
Lloyd's Register	Selection and Use of Standards for Naval Ship	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$8\%(50\,th)$
American Bureau of shipping 2008	Rules of International Ship Classification Societies, eg PRS/25/P/2006	$+6\%, -10\%$ $\pm 20\%(1.5s)$	$\pm 5\%$ $\pm 10\%(5s)$	$5\%(40\,th)$
IEEE Std.45-2002	IEEE Recommended Practice for Electrical Installations in ships	$\pm 5\%$ $\pm 16\%(2s)$	$\pm 3\%$ $\pm 4\%(2s)$	$5\%(40\,th)$
IACS Members ABS (2016), DNV (2016) PRS(2016) IEEE Std.1662-2016 (2016) IEC Std.61557-12 (2007)		$\pm 20\%,\ 1.5s$	$\pm 10\%,\ 5s$	$8\%(50th)$
STANAG1008 (Ed.8, Ed.9) for the naval ship		$\pm 16\%,\ 2s$	$\pm 4\%,\ 2s$	$5\%(40th)$

3.3. MEASUREMENT METHOD AND RESULTS

The IEC61000-4-30 standard defined using *rms* value to calculate the rapid voltage changes (RVC) event, such as voltage dips that are not beyond the voltage threshold, as shown in Fig. 3.2. Voltage dips as RVC examples are characterized by four main parameters: start time, duration, ΔU_{max} and $\Delta U_{ss.}$ The detailed measurement method based on class A for evaluations can be found in the IEC61000-4-30 standard [84].

However, it should be noted that the *rms* voltage is measured in steady-state conditions, so that if all the immediately preceding 100/120 $U_{rms(1/2)}$ values remain within the RVC threshold from the arithmetic mean of those 100/120 $U_{rms(1/2)}$ values (100/120 means 100 values for 50Hz or 120 values for 60Hz nominal).

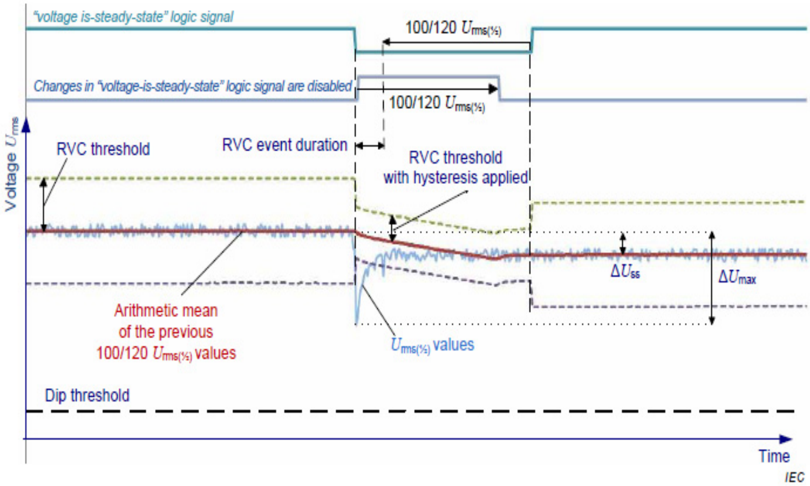
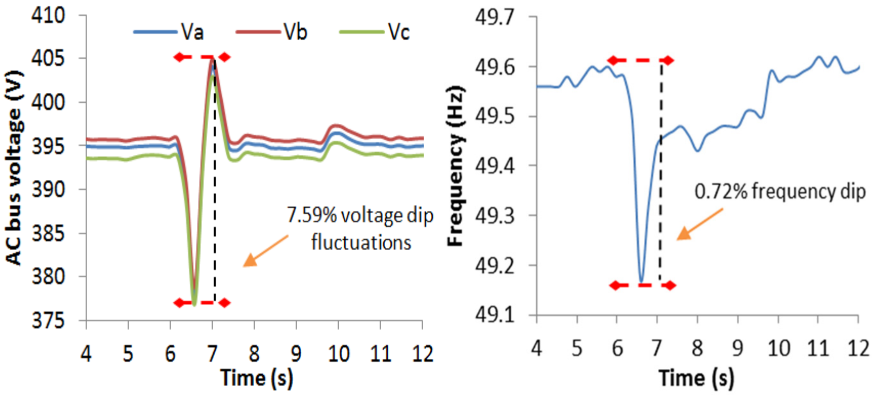


Fig.3.2. Example of voltage dips in *rms* value during RVC event [84]

The voltage dips caused by pump starts measured in the ship are shown as in Fig. 3.3.



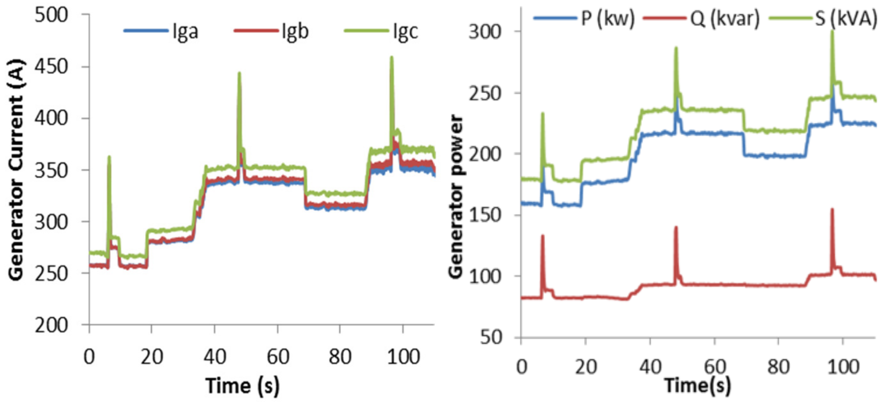
(a)Voltage dips (b) System frequency

Fig.3.3. Measurement of *rms* voltage and frequency dips

3.3.1 IMPACT ON THE GENERATOR

On the other hand, Fig.3.4 shows the *rms* value of generator current with different power levels considering the thruster power increasing until full loaded. As it can be seen that the currents were severely increased with 95A or more during each voltage dip (caused by the 10kW ballast pump starts), which brought significant risks to the reliability of the SMGs.

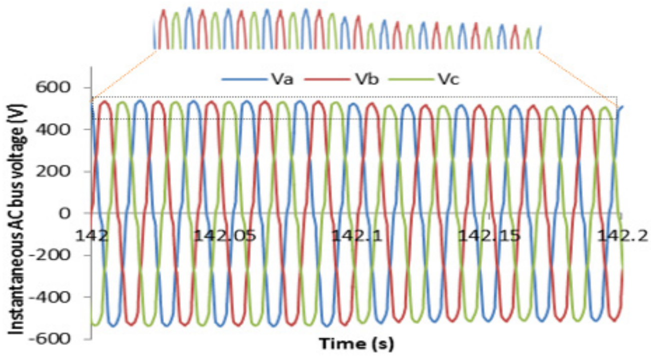
Noted that the transient current surges are not occurred at power step times, which means the transient current surges are not caused by thruster load power increasing. This is because the thruster motors with largest powers are installed with soft-starters devices to decrease the inrush currents. However, this research is focus on analyze the impact of voltage dips caused by the direct starting process of pump loads.



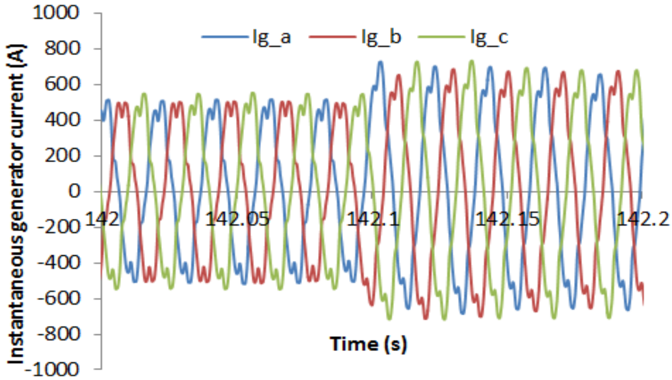
(a) Generator current (b) Generator active reactive and apparent powers

Fig.3.4. Measurement of generator *rms* current and powers

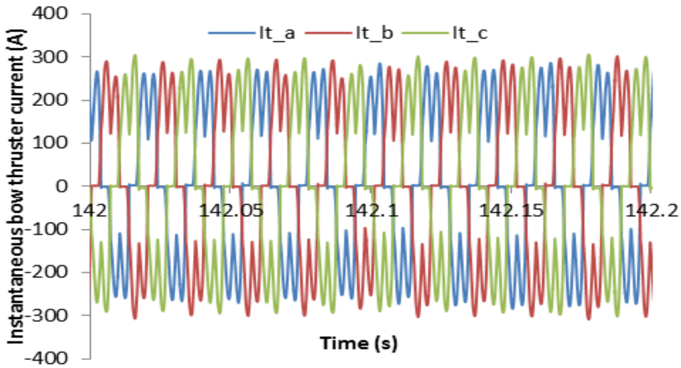
In addition, Fig. 3.5 shows the instantaneous values of the generator voltage/current, which were registered for bow thruster full load during the voltage dip. The voltage dip is about 20V, but the generator output current surges from 500A to 740A in a short time. Furthermore, the THD of voltage changed from 1.1% (bow thruster switched off) to 6.7% (bow thruster full load). Accordingly, the distortions of generator and bow thruster currents were symmetrical and mainly containing 5th, 7th, 11th and 13th harmonics. The THD of generator current changed from 1.5% (bow thruster switched off) to 12.8% (bow thruster full load). Bow thruster current remained balanced but highly distorted (up to 39.6% for full load conditions).



(a) AC bus voltage



(b) Generator current



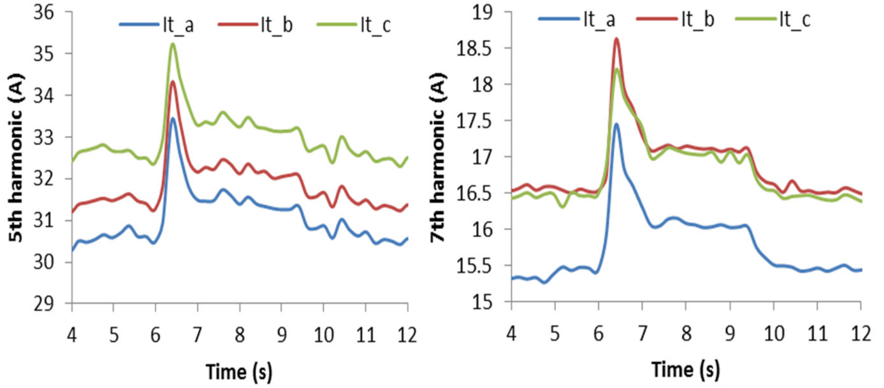
(c) Bow thruster current

Fig.3.5. Instantaneous values examples considering the voltage dip

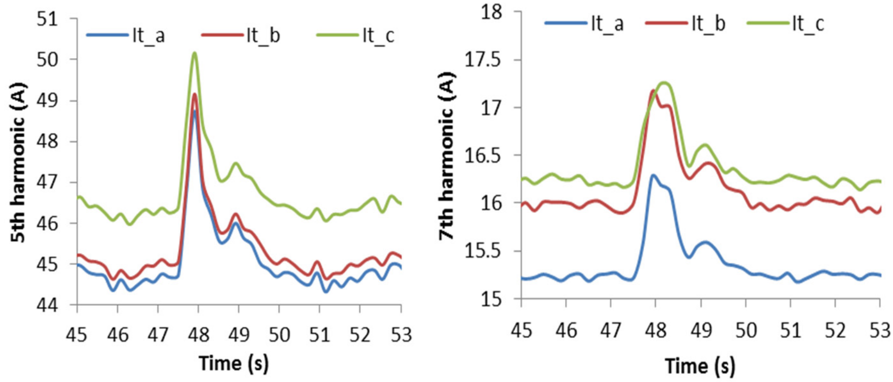
3.3.2 IMPACT ON THE BOW THRUSTER LOAD

In fact, the bow thruster is equipped with a 6 pulse rectifier in the ship and its current mainly contains 5^{th}, 7^{th}, 9^{th}, and 11^{th}…and low-order harmonics components. Therefore, the research is focus on the transient impact on the bow thruster harmonic current components.

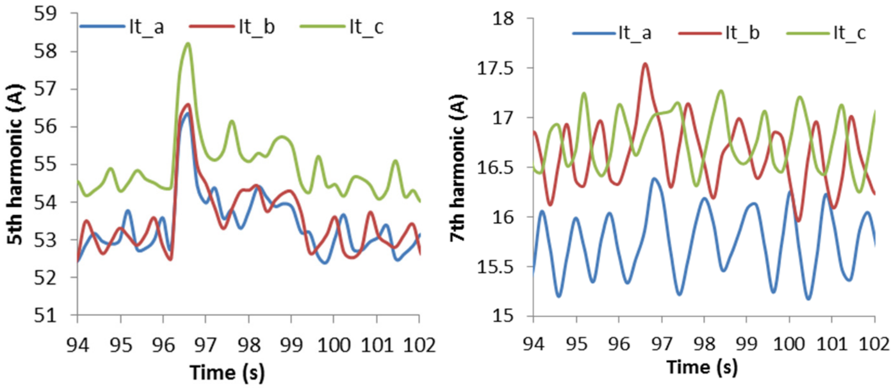
Fig.3.6 shows the transient impact on the 5^{th} and 7^{th} harmonics of the bow thruster current of the three voltage dips at different thruster power levels, as an example. These harmonic components are increasing obviously during the dip intervals. However, for the higher power levels, more harmonics will appear around the individual harmonic components of the bow thruster current. In fact, the current harmonics might affect the stability of the SMGs, especially under high power conditions.



(a) Current harmonics of bow thruster (45kW)



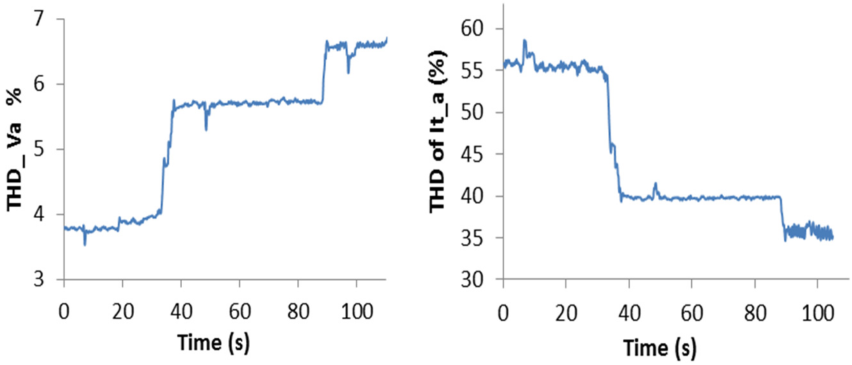
(b) Current harmonics of bow thruster (85kW)



(c) Current harmonics of bow thruster (109kW)

Fig.3.6. Harmonic impact of the bow thruster current during the voltage dips

On the other hand, Fig.3.7 shows the THD of AC bus voltage and bow thruster current with different power levels. It can be observed that the THD of bow thruster current is decreased with the power levels steps up obviously. Furthermore, the voltage dips have short-term variations on the assessment for THD index and the transients of THD even can achieves 1% for AC bus voltage and 3% for bow thruster current in the dip durations, which means that the conventional calculations of THD factor needs further research and considering the transient impact of voltage dips.



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

Fig.3.7. THD of the AC bus voltage and bow thruster current

3.4. CONCLUSION

In a short, this chapter deals with highlighting the actual impact of the voltage dips in a real SMG. Although the dips were not too severe (due to necessity of avoiding risky conditions during sea-going conditions), our findings indicate that the voltage dips have adverse impacts on the electrical installations onboard. These adverse impacts include the SMG frequency deviations, diesel generator current transient surges, increase of bow thruster current harmonic components and short-term disturbances that were found out along the power quality assessment.

CHAPTER 4.

POWER QUALITY ASSESSMENT IN SHIPBOARD MICROGRIDS UNDER UNBALANCED AND HARMONIC AC BUS VOLTAGE

This section is based on the main research work done in paper 3 [92] and paper 4 [86], which have been published in *IEEE Transactions on Industry Applications* and *IEEE APEC conference 2018*, more detailed information can be found in the attached publications.

SUMMARY OF THE CONTRIBUTION

Nowadays, power quality issues are becoming more and more critical in shipboard microgrid systems (SMGs) with the development of power electronic technology. However, the impact of unbalanced voltage combined with harmonics on the behaviors of SMGs are still needs further research and developed.

In this chapter, power quality assessment models are proposed and several controlled experiments are carried out in a real SMG. The PQ assessment is presented by considering a non-linear bow thruster drive motor, and other pumps and heater loads under unbalanced and harmonic voltage cases. Furthermore, the voltage/current distortions of the generator in operation, the thruster and pump loads are carefully analyzed. This paper provides a valuable analysis for coping with PQ issues in the SMG.

BOW THRUSTER MODEL AND PROPOSED PQ ASSESSMENT MEHTOD

4.2.1 BOW THRUSTER MODEL

Typical characteristics of SMG includes isolated power generators with limited capacities, varying voltage/frequency levels, high short-circuit impedance of the power network, and the extensive use of high-power nonlinear and pulsating loads [10], [94]. Based on these characteristics, the SMG is more prone to many PQ issues, such as unbalanced or distorted voltage/current waveforms, transient disturbances, and strong frequency variations [95].

On the other hand, for ships, even moderate unbalanced voltage form AC bus has enormous impact on the uncontrolled rectifiers, typically as a part of the bow thruster drive onboard, as can be seen in Fig. 4.1. In fact, the double-phase and single-phase rectification modes appear when the loads decrease under unbalanced cases, which cause drawing large unbalanced and harmonic currents from the generator [96]. The effect can affect dramatically the AC shipboard weak-grid performances. Therefore, it is necessary to analyze the bow thruster drive and the whole system operation under unbalanced and harmonic conditions.

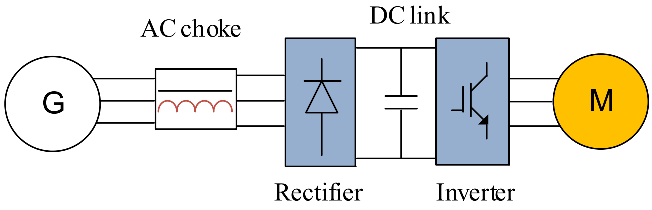


Fig.4.1. Bow thruster motor drive onboard

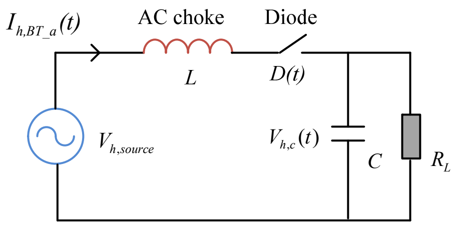


Fig.4.2. One phase equivalent circuit of bow thruster rectifier [92]

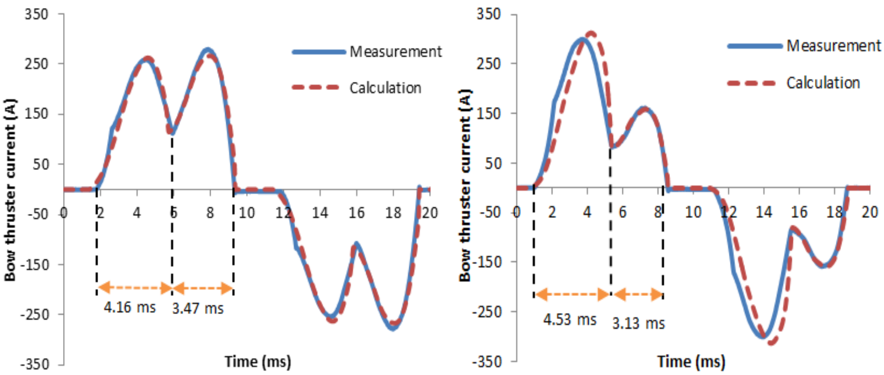
For a simplified analysis, one-phase equivalent rectifier circuit of bow thruster is shown in Fig. 4.2. The capacitor voltage of a rectifier is derived as:

$$V_{h,c}(t) = V_{h,source} \quad if \begin{cases} I_{h,BT\_a}(t_1) = 0, & \dfrac{dI_{BT\_s}(t_1)}{dt} > 0 \\ I_{h,BT\_a}(t_2) = 0, & \dfrac{dI_{BT\_s}(t_2)}{dt} < 0 \end{cases} \tag{4-1}$$

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

$$R_L \cdot L \cdot C \cdot \frac{d^2 I_{h,BT\_a}(t)}{dt^2} + L \cdot \frac{dI_{h,BT\_a}(t)}{dt} + R_L \cdot I_{h,BT\_a}(t) = V(t+t_1) + R \cdot C \cdot \frac{dV(t+t_1)}{dt} \tag{4-2}$$

It can be observed from (4-2) that $I_{h,BT\_a}(t)$ depends on the values of inductor L, 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. It enables approximate assessment of bow thruster current distortions under quasi-balanced and unbalanced voltage conditions. In addition, the comparison between current calculations and measurement of bow thruster under quasi-balanced and unbalanced cases are illustrated in Fig. 4.3.

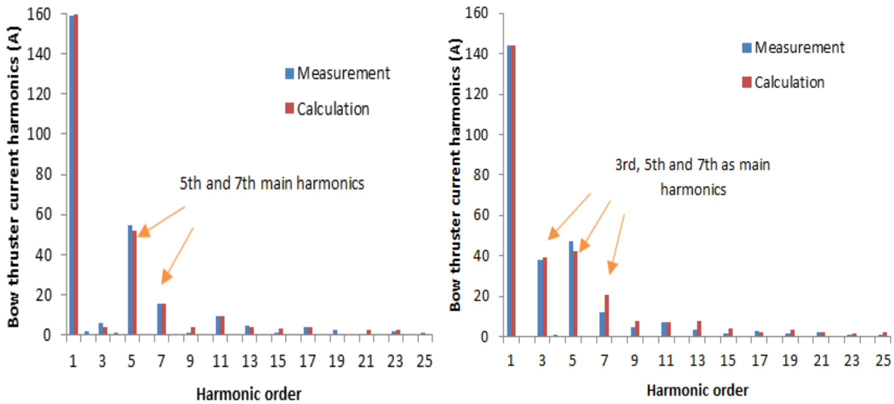


(a) Quasi balanced voltage case (UF =0.39%)

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

Fig.4.3. Line current of bow thruster under quasi-balanced/unbalanced voltage case

As can be seen in Fig. 4.3(a) and (b), the calculation of bow thruster current almost matches the measurement from the ship experiments. However, the differences between respective times and magnitudes show different results for the two cases. For the quasi-balanced case with Unbalance Factor (UF) of 0.39%, the thruster current contains mainly 5^{th} and 7^{th} harmonics. However, with UF of 1.63%, the differences between conduction time of respective diodes increases and higher-order harmonics appear.



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

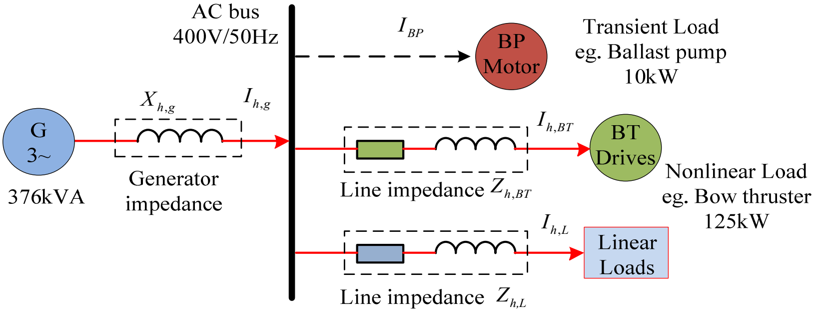
(b) Unbalanced voltage case (UF= 1.63%)

Fig.4.4. Harmonic analysis of thruster current under quasi-balanced/unbalanced voltage case

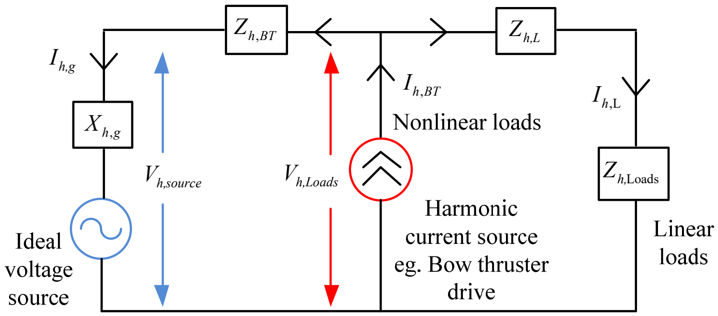
Fig. 4.4 shows the harmonic analysis of thruster current. The calculations were done by using Fourier series up to the 49th-order harmonic, DFT decomposition and following the IACS maritime standards [51], [59], [95]. Note that the 3rd harmonic components will increase obviously when voltage unbalances occur.

4.2.2. PROPOSED PQ ASSESSMENT METHOD

For the harmonic analysis and THD calculations of the AC bus voltage, assuming that only one generator is operating in the ship, the thrusters using power converters are the largest harmonic source onboard. The use of the ballast pump is to test the dynamic performance of the SMG. The harmonic analysis in SMG are simplified as Fig 2.5.



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



(b) Simplified SMG model with harmonic current flow

Fig 4.5. Simplified SMG model considering the main harmonic source onboard [92]

In Fig. 4.5, the voltage harmonic distortion is mainly caused by the bow thruster due to injecting harmonic currents $I_{h,BT}$ to the generator and to 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 negative and positive sequence harmonic voltages, V_h and V_{h+2} can be expressed as [97]

$$\begin{bmatrix} V_h \\ V_{h+2} \end{bmatrix} = \begin{bmatrix} j\frac{h}{2}\cdot(X_q^{"}+X_d^{"}) & j\frac{h}{2}\cdot(X_q^{"}-X_d^{"})\cdot e^{-j2\delta} \\ j\frac{h+2}{2}\cdot(X_q^{"}-X_d^{"})\cdot e^{j2\delta} & j\frac{h+2}{2}\cdot(X_q^{"}+X_d^{"}) \end{bmatrix} \cdot \begin{bmatrix} I_h \\ I_{h+2} \end{bmatrix} \tag{4-3}$$

where $X_q^{"}$ is quadrature-axis sub-transient reactance of generator, $X_d^{"}$ is direct-axis sub-transient reactance of generator, h is the individual 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.

The harmonic currents of the bow thruster drive with six-pulse diode-bridge rectifier is expressed as [98]:

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

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

where I_{h,BT_a}, I_{h,BT_b} and I_{h,BT_c} represent the magnitude of the bow thruster harmonic components, for each line. ω and $\theta_{h,BT}$ are the angular frequency and original phase-shift respectively.

The generator short circuit current I_{sc} can be determined as:

$$I_{sc} = \frac{I_r}{\frac{1}{2}\cdot(X_q^{"}+X_d^{"})}\times 100 \tag{4-5}$$

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. The equivalent AC bus voltage harmonic magnitudes can be obtained as:

$$\begin{cases} I_{h,g} \approx I_{h,BT} \\ \tilde{V}_{h,g} \approx \dfrac{h\times V_g \times I_{h,g}}{I_{sc}} \end{cases} \tag{4-6}$$

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

Then, the AC bus voltage THD_v % can be calculated as

$$THD_v = \frac{\sqrt{\sum_h \tilde{V}_{h,g}^2}}{V_g}\times 100\% \tag{4-7}$$

On the other hand, in order to calculate the power flow under unbalanced voltage cases, IEEE Standard 1459-2010 [99] suggest using the definition of effective apparent power to maintain the active power loss constant, especially considering the voltage unbalances in AC SMG. The effective apparent power S_e is defined as

$$S_e = 3 \times V_e \times I_e \tag{4-8}$$

where for three wire AC systems

$$\begin{cases} V_e = \sqrt{\left(V_{ab}^2 + V_{ac}^2 + V_{bc}^2\right)/9} \\ I_e = \sqrt{\left(I_a^2 + I_b^2 + I_c^2\right)/3} \end{cases} \tag{4-9}$$

The active harmonic power to separate active power components as

$$P = P_1 + \tilde{P}_h = V_1 I_1 \cos\theta_1 + V_0 I_0 + \sum_{h \neq 1} \tilde{V}_h \tilde{I}_h \cos\theta_h \tag{4-10}$$

Considering the distorted and unbalanced voltage/current waveforms onboard, the total active power of the AC system is calculated as the sum of individual powers. The fundamental reactive power is defined as:

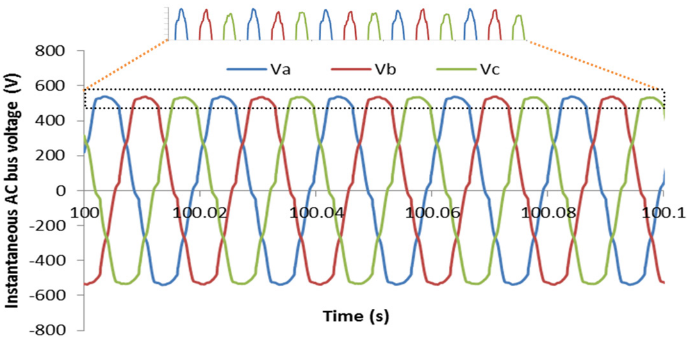
$$Q_1 = \frac{\omega}{nT} \int_{\tau}^{\tau+nT} I_1 \left(\int V_1 \cdot dt \right) \cdot dt = V_1 I_1 \sin\theta_1 \tag{4-11}$$

In addition, the non-active power Q_N is defined for reactive power assessment under non-sinusoidal waveform conditions as follows

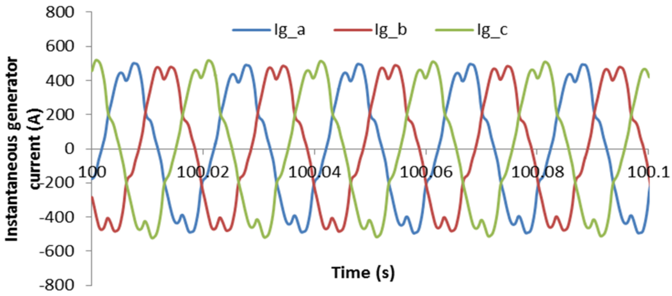
$$Q_N = \sqrt{S_e^{\,2} - (P_1 + \tilde{P}_h)^2} \tag{4-12}$$

RESULTS AND CONCLUSION

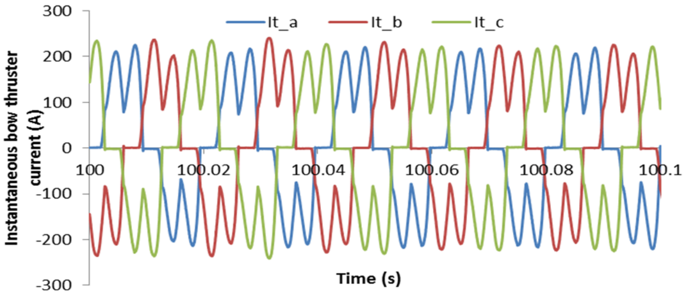
For the comparative harmonic analysis of SMG with full load of bow thruster, two cases were selected. First case was SMG under normal operations and the second case was based on having unbalanced voltage, which was produced by connecting a short-circuited heater load.



(a) AC bus voltages

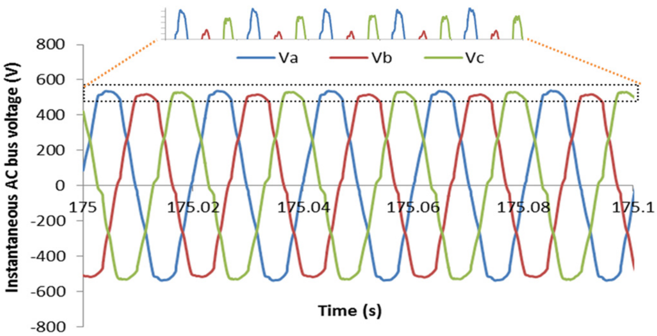


(b) generator currents

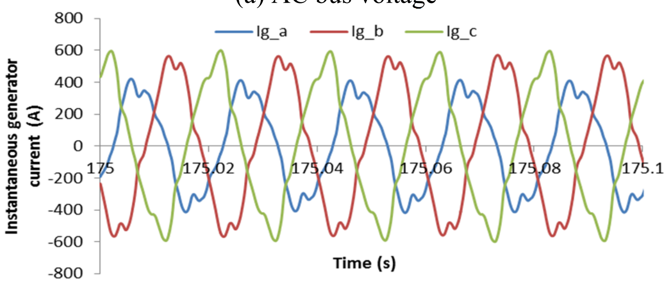


(c) bow thruster currents

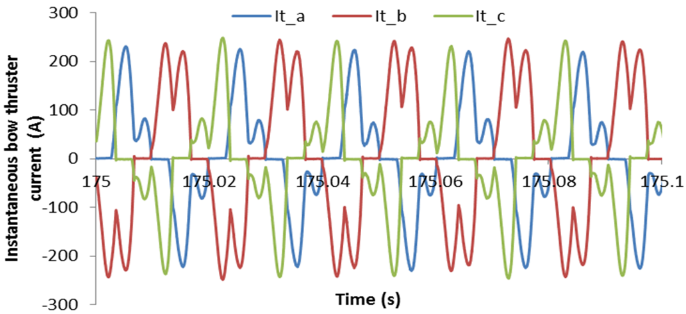
Fig.4.6. Instantaneous values of (a) AC bus voltage, (b) generator current and (c) bow thruster current under quasi-balanced voltage conditions



(a) AC bus voltage

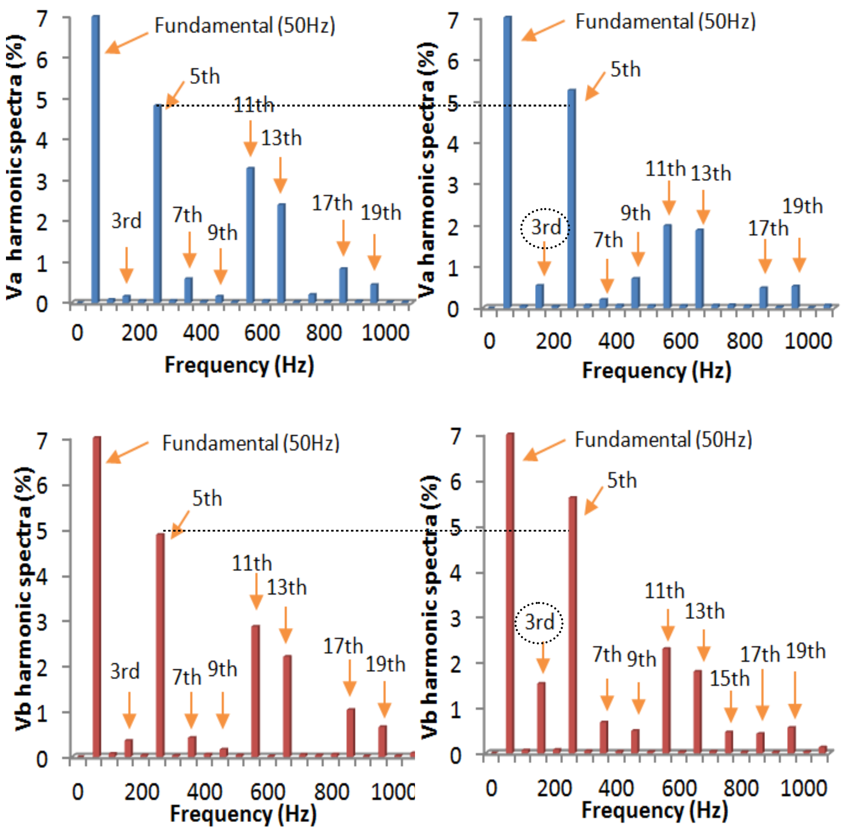


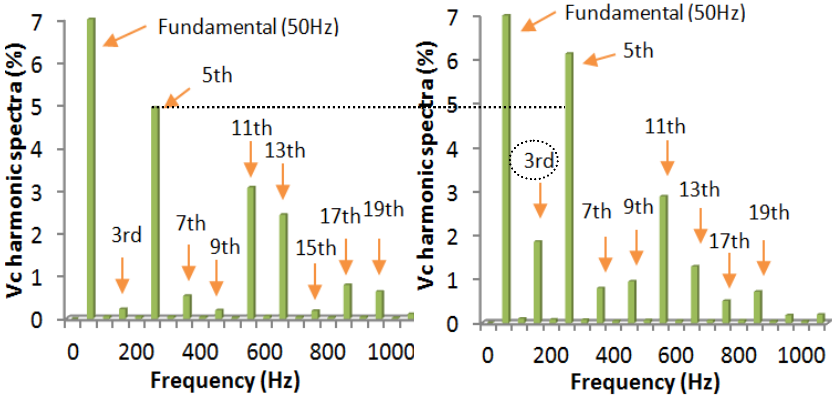
(b) generator current



(b) bow thruster currents

Fig.4.7. Instantaneous values of (a) AC bus voltage, (b) generator current and (c) bow thruster current under unbalanced voltage conditions





(a) Quasi-balanced conditions (b) Unbalanced conditions

Fig.4.8. Harmonic spectra of AC bus voltages up to 25th harmonic under full load of bow thruster

The detailed power quality assessment under two cases can be found in Table.4.1 and the description of Table 4.1 can be found in the attached paper 3 and paper 4 in this thesis.

TABLE 4.1 PQ ASSESSMENT FOR SMG UNDER QUASI-BALANCED AND UNBALANCED VOLTAGE CONDITIONS

Network parameters		**Shipboard microgrid**	
		Quasi-balanced AC bus voltage	**Unbalanced AC bus voltage**
Main AC bus voltage unbalance factor		0.35%	1.75%
Main AC bus voltages	Va [V]	395.2	394.9
	Vb [V]	396.3	385.2
	Vc [V]	393.9	385.9
Main AC bus voltage distortion factors [calculations from Eq.(4-6), (4-7) 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

Network parameters		**Shipboard microgrid**	
		Quasi-balanced AC bus voltage	**Unbalanced AC bus voltage**
Generator parameters	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	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	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

The calculation of maximum voltage THD of the SMG and the proposed models under quasi-balanced and unbalanced voltage conditions can be found in Table 4.2.

TABLE 4.2 COMPARSIONS FOR MEASURED AND CALCULATED VOLTAGE THD CONSIDERING GENERATOR AND BOW THRUSTER LOAD OF109KW

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 (4-2),(4-6), and (4-7)

In short, this chaperter provides an assessment method to obtain PQ parameters in the SMG. It can be concluded that the permissible voltage unbalances should be tied with the voltage distortions for PQ assessment in real time. On the other hand, 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. Finally, the proposed calculations may led to overestimation of voltage THD, but the experimental results verified the proposed models for quick PQ assessment in SMGs.

CHAPTER 5. CONCLUDING REMARKS

SUMMARY

This part is the conclusion of the present PhD project and the contribution of this thesis can be summarized as follows:

- This project carefully analyzed the actual impact of voltage dips produced by the pump motor start-ups in a SMG under quasi-balanced and unbalanced voltages. In a real SMG, the experimental analyses were focused on the magnitude and depth of the voltage dips and their impact including transient generator current surges and AC bus voltage harmonics.

  Our findings indicate that the voltage dips induced by the sudden-load of ballast pump have adverse impacts on the electrical installations onboard. These adverse impacts include the diesel generator transient current surge, system frequency deviations, bow thruster current individual harmonics increase and the short-term disturbances for accurate power quality assessment.

- Proposed evaluation methods for voltage dips, pump motor starting current and generator transient current surges under quasi-balanced and unbalanced AC bus voltage for SMGs.

  The evaluation and analysis results indicated that the voltage dips mainly depend on the motor capacity, and the generator transient current surges are calculated considering the voltage dips for different study cases. The proposed methods are validated by Riemann summation calculations based on the measurements in a real SMG and the maximum error was less than 4.9%.

- Proposed assessment for the maximum capacity of motors that can be installed onboard under unbalanced voltage conditions.

  The research indicated that the maximum allowable motor capacity still will be decreased more when the unbalanced voltages are considered. In such cases, the individual phase voltage and/or current may violate the threshold limits as suggested with maritime standards and consequently, transient dip originates at the lowest voltage, which means smaller powers of motors are allowed in comparison to normal operations of the SMGs.

- Proposed simplified PQ assessment model for SMGs, the model confirmed the main harmonic source onboard is the nonlinear bow thruster motor (125kW) in the investigated ship.

  The proposed models can be easily applied to assess PQ parameters in the ship power system. Noted that the differences between critical parameters under quasi-balanced and unbalanced conditions are quite 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.

  On the other hand, the 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. Finally, it can be stated that the proposed calculations based may led to overestimation of voltage THD but the experimental results verified the proposed models for quick PQ assessment in real shipboard power systems.

FUTURE WORK

- Power quality improvement for the traditional AC SMGs still needs further research. Control strategies base on active and/or passive power filters can be developed for SMGs. Power-sharing or load-sharing controllers based on distributed control strategies can be also applied to SMGs to realize unbalance compensation and harmonic suppression when considered more generators or thruster loads working in parallel. This need further research and developing based on the proposed PQ assessment.

- Stability of SMGs is another trendy topic [100-102]. In fact, the harmonics of thruster with higher power levels may affect the stability of the SMGs, especially considering the transient voltage dips. The AC SMGs presented the characteristics of typical weak grid, so that the stability analysis should be explored to achieve higher stable operation ranges, even under SMGs fault conditions.

- The power management strategies based on energy storage systems can be investigated to achieve higher energy efficiency onboard. More power quality aspects can be also considered for AC and DC SMGs, and hierarchical control of multiple MG clusters can be used to enhance PQ in larger ships.

- SMGs can be extended as a part of the land-based grid when connected to the shore power at berth, so how to realize the control and management between the shore power and ship power and energy is an important issue to be researched in the near future.

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APPENDIX PAPERS

PAPER 1

An Evaluation Method for Voltage Dips in a Shipboard Microgrid under Quasi-balanced and Unbalanced Voltage Conditions

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An Evaluation Method for Voltage Dips in a Shipboard Microgrid under Quasi-balanced and Unbalanced Voltage Conditions

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Abstract— **High power motor loads are widely used in shipboard microgrids (SMGs) consuming about 70% of generated electrical power. Voltage dips, which are usually caused by the starting current of high power motors, are one of the main causes of onboard sensitive electrical equipment dropout. This phenomenon must be considered in design of SMGs to comply with maritime standards. In this paper, an evaluation method is proposed to estimate the expected severity of voltage dips and also generator current transient surges due to the onboard motor start-ups under real sea-going conditions. This is based on the Riemann-summation-principle evaluation method. The quasi-balanced and unbalanced AC bus voltage cases were carefully selected to present the actual impact of the voltage dips in real SMG. The evaluations are validated by measurements gathered from the ballast pump motor start -up in the SMG. The proposed method can provide ship engineers with necessary information about the actual magnitude/depth of voltage dips. Accordingly, the allowable capacities of high power motors can be estimated, which is beneficial to determine proper motor starter designs and improve the power quality in real SMGs.**

Index Terms—**shipboard microgrid; voltage dips; unbalance; power quality**

I. Introduction

With the growing development of power electronics technology onboard, shipboard microgrids (SMGs) display specific features such as higher torque-dense electric propulsion system, large-power pump motor loads and smart power management and monitoring devices, which are required for the improvement of power supply continuity and reliability [1-3]. In this background, power quality issues onboard is a significant concern caused by the wide application of variable frequency drives such as bow thruster motors, pumps loads, fans and propellers.

Generally, due to the limited power generation, extensive use of non-linear power electronic devices and fast-response demand in SMGs, serious voltage and frequency variations including voltage dips, harmonics, power oscillations and incorrect power sharing among parallel generators are easily produced [4], [5]. To assess the scope of the voltage or frequency variations and possible harmonic impacts, especially during large motors transient starts, existing isolated power systems are a good choice as testing grounds [6]. Modern SMGs can be seen as smart microgrids with capabilities for self-diagnosis and self-reconfiguration [7]. It can be stated that the characteristics of the SMGs, including the voltage or frequency variations, match with those of the islanded-based microgrids [8]. Hence, under normal operating conditions, the ship can be considered as a typical isolated microgrid [9].

However, it is difficult for the SMGs to provide the required ride through capability in the case of faults [10]. On the other hand, marine engineers and researchers have faced the rising number of ship accidents related to the power quality issues, like the AC bus voltage dips, transient excessive harmonics, etc[11]. Voltage dips are mainly originated from the short-term faults and starting of large motors onboard [12]. The voltage unbalances and harmonics are easily generated by three phase devices malfunctions and faults, might not be promptly cleared and lead to the tripping or malfunction of sensitive electric devices onboard [13]. Therefore, the voltage dips and their impacts on the real SMG under quasi-balanced and unbalanced voltage combined with harmonic distortions need to be further studied.

The voltage dips are normally divided into balanced and unbalanced cases and characterized by depth and duration. The maritime standards required that the depth of voltage dips should remain below 20% of the rated voltage [14], [15]. However, the unbalanced voltage dips are difficult to investigate in real ships due to the clear lack of requirements regarding voltage unbalances in the rules of recently amended unified

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requirements of International Association of Classification Societies (IACS) and its members [16-19]. In fact, only IEEE Standard 45.1-2017 defines that the line-to-line voltage unbalance onboard should not exceed 3%, otherwise, it must be mitigated or protection system should be triggered [14]. Furthermore, the voltage dips can be caused by the transient current harmonic flow through the cables (mainly produced by non-linear loads such as thrusters), which not only causes the energy losses, but also affects the communication and management of electrical devices especially under unbalanced voltage dips [20].

Several works in the literature confirmed that voltage dips mitigations at the main switchboard AC bus are required in severe conditions [21], [22]. A straight-forward solution is using motor starters, which reduce the motor terminal voltage for a short time and then supply the full voltage value, but necessary information about the actual magnitude and depth of voltage dips are required [23]. The mitigation of voltage dips can also be achieved by series compensation but extra power electronic converters should be installed on the limited shipboard system and the dip information is required [24]. There are a few methods for voltage dips calculations and characterization [25], which require various quantitative data for calculations. A root mean square (rms) calculation method based on sliding window to detect the voltage dip has been proposed in [26], but the method needs a remarkable amount of memory. In addition, a fast calculation method for voltage dips caused by pump motor was proposed in [27], but this approach has not considered the actual impact of the voltage unbalances and harmonics in SMGs. Furthermore, in general standards, the voltage dips are calculated for each cycle or half cycle [15].

In this paper, an evaluation method for voltage dips assessment under unbalanced and harmonic cases has been proposed for the SMG. The method only requires the motor capacity and main parameters of the SMG, which can be easily obtained. Furthermore, the dynamic impacts of voltage dips have been carefully analyzed in a real SMG and the maximum allowable motor capacities to be installed can also be determined. The performance of the proposed method is validated using Riemann Summation calculations based on the gathered experiments in the SMG under various quasi-balanced and unbalanced voltage conditions.

II. Proposed Evaluation Model for Voltage Dips in Shipboard Microgrid System

A. Shipboard microgrid system description

For the simplified analysis, the simplified diagram of the investigated SMG is shown in Fig. 1. The typical radial architecture is implemented on the research ship. It consists of three identical synchronous generators with the rated power of 376 kVA connected to the main switchboard AC bus directly, using three 3x120 mm^2 cables with XLPE insulation and copper wires for each generator. Each generator is driven by a four-stroke diesel engine with the rated power of 357 kW. The generating sets are equipped with Automatic Voltage Regulator (AVR) (Stamford type MX341), power supplied by a separate permanent magnet generator, and mounted on the rotor shaft of generator. The typical response time of the AVR is 10 ms.

The load with the greatest power onboard is the bow thruster motor (125kW), supplied by a variable frequency power converter. The ballast pump load is used to hold the sea water in order to balance the ship body and ensure its stability. Being high-power loads both, bow thruster drive and ballast pump motor, are supplied directly from the main switchboard.

Different AC voltage levels for consumers such as lights or small hotel appliances onboard can be achieved through different transformer conversion ratios. Normally, the rated AC bus voltage of SMG is 400V and the system frequency is 50Hz.

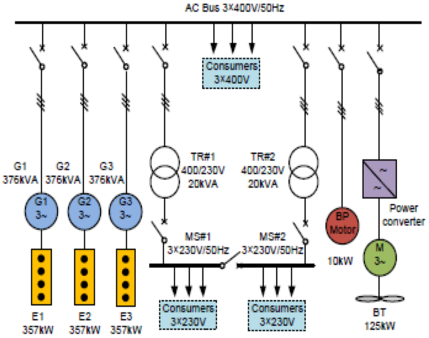


Fig.1. Simplified diagram of the investigated SMG (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engines; BT: bow thruster; TR: transformer; MS: main switchboard; BP: Ballast Pump motor)

B. Proposed prediction model for the voltage dips

For the sake of analysis and modeling, the voltage dips caused by the sudden start of pump motor in SMG is analyzed considering only one generator and ballast pump motor. The main harmonic source is the bow thruster drive. It should be noted that the situation in which only one generator works can be considered as the worst case from the harmonic distortions point of view onboard a real ship [21], [28]. The simplified diagram for ballast pump motor starting in the SMG can be seen as Fig.2.

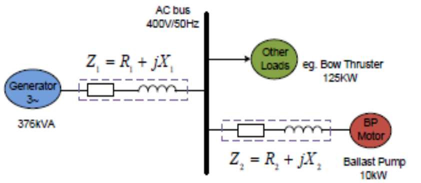


Fig.2. Simplified diagram for analysis of pump motor starting in the SMG

According to Fig.2, in order to calculate the voltage dip magnitude at the AC bus during the starting of a large motor such as ballast pump, the impedances between the generator and the ballast pump, Z_1 and Z_2 must be identified. Z_1 represents the generator source impedance at the AC bus and Z_2 is the impedance between the AC bus and the ballast pump motor including the line impedance and the motor internal impedance.

The voltage dip magnitude (in percentage) at the load terminal equals the voltage decrease at the AC bus, which equals the rated voltage of AC bus minus the voltage while the pump starting, if other loads currents are ignored. The voltage dip can be expressed as

$$V_{dip}(\%) = (1-\frac{Z_2}{Z_1+Z_2})\times 100\% = \frac{Z_1}{Z_1+Z_2}\times 100\% \quad (1)$$

The cables between the AC bus and generator and/or ballast pump motors are quite short, so that the output impedances of the generator and motor are predominant, in which the reactance are significantly larger than the resistances ($X_1 >> R_1$, $X_2 >> R_2$). On the other hand, some maritime standards requires that the drop in voltage from each generator to its switchboard should not exceed 1% [14], [19]. Furthermore, the generators are usually located in proximity of main switchboard due to the limited space onboard. In this way, the impedance of the connection lines and resistance of the generator and motor can be neglected. In order to explicitly present the relationships between the voltage dip and the pump starting current, the voltage dip in (1) can be rewritten as (2):

$$V_{dip}(\%) = \frac{X_g}{X_g+\frac{I_g}{I_m}}\times 100\% = \frac{I_m X_g}{I_m X_g + I_g}\times 100\% \quad (2)$$

$$X_g = \frac{X_d' + X_d''}{2} \quad (3)$$

where X_g is the reactance (in percentage) of the generator during motor start, which is calculated as the average of the generator transient reactance X_d' and sub-transient reactance X_d'' as shown in (3). I_g represents the rated current of generator and I_m is the current of ballast pump motor during the starting period which can be determined as follows

$$I_m = \frac{Km^2 P_m}{\sqrt{3}V_m \cos\phi_m} \quad (4)$$

where K is the ratio of the motor starting current to its rated current. P_m, V_m and $\cos\phi_m$ represent the rated power, rated voltage, and power factor of the ballast pump motor, respectively. m is the ratio of motor and system rated voltage during the start-up by applying starting methods such as connecting with transformers [27].

On the other hand, generator current I_g can be expressed as

$$I_g = \frac{P_g}{\sqrt{3}V_g \cos\phi_g} \quad (5)$$

where P_g, V_g and $\cos\phi_g$ represent the rated power, rated voltage, and power factor of the working diesel generator.

However, during the motor starting period, the voltage dips will affect the actual generator output current, the transient generator current surges can be calculated as follows

$$I_{surge\_g} = \frac{V_g \times V_{dip}(\%)}{\sqrt{3}X_g} \quad (6)$$

It should be noted that the impacts of the voltage dip magnitude depend on the loading of power generator during motor starting. In other words, when a large power motor is enabled, the preloaded engine generator effect cannot be neglected due to the already existing high-power demands and the limited power generation. For example, a 50% preloaded engine generator may lead to additional 2% voltage dips [29].

Assume that there is a protective voltage limit V_{limit} or fault ride through (FRT) voltage threshold above which the motors continue working, otherwise, will be tripped [15]. The residual voltage is expressed as

$$V_g[1-V_{dip}(\%)] = V_g(\frac{I_g}{I_m X_g + I_g}) \geq V_{limit} \quad (7)$$

It should be noted that the motor capacity must be taken into account during voltage dips. By substituting (7) into (2) and considering a given power generation, the maximum allowable motor capacity can be calculated as

$$(\frac{P_m}{P_g})_{max} = \frac{V_m \cos\phi_m}{Km^2 V_g \cos\phi_g}\times\frac{V_g - V_{limit}}{X_g V_{limit}} \quad (8)$$

For a given limited voltage, the maximum installed motor capacity can be easily estimated from (8). It is indicated that the maximum motor capacity decreases when the voltage limitation is increased. However, it should be noted that under some unbalanced faults, the lowest voltage magnitude must be considered to ensure that the actual voltage will not go below the limited value. In such a case, equation (8) can be replaced by (9)

$$(\frac{P_m}{P_g})_{max} = \frac{V_m \cos\phi_m}{Km^2 V_g \cos\phi_g}\times\frac{V_{lowest} - V_{limit}}{X_g V_{limit}} \quad (9)$$

$$V_{lowest} = \min(V_{ga}, V_{gb}, V_{gc}) \quad (10)$$

where V_{ga} V_{gb} V_{gc} are the three phase output voltages of the generator. The lowest voltage can be calculated by several methods [30], [31]. However, detailed explanations in this regard are beyond the scope of the present paper.

C. Evaluation method based on Riemann-summation principle

In order to verify the prediction method for voltage dips, the results obtained basing on the model should be compared to the real measurements onboard. However, direct comparison of the evaluation results with experimental results is difficult, because the typical motor starting current are quite different from the assumption for an average starting current of pump motor in the models. In order to solve this problem, IEC Standard 61000-4-30 [15] defined the measurement methods and interpretation of PQ parameters assessment, the evaluation method based on Riemann Summation principle was developed to evaluate the starting voltage and current of the pump motor.

In addition, the evaluation method based on Riemann Summation principle is employed to approximate the total area of the motor starting current curve during the time between pump motor starting and switching off. The interval is equally divided into N_m subintervals and accordingly, the average value of the motor starting current I_{ms_mea} can be expressed as

$$I_{ms\_mea} = \sqrt{\frac{1}{N_m}\sum_{i=1}^{N_m} I_{ms\_rms\_i}^2} \quad (11)$$

where N_m is the number of Riemann subintervals and $I_{ms\_rms\_i}$ is the rms value at the ith subintervals current.

In a similar way, the interval is equally divided into N_g subintervals to calculate the generator current surges I_{gs_mea} as

$$I_{gs\_mea} = \sqrt{\frac{1}{N_g}\sum_{i=1}^{N_g}(I_{gref} - I_{gs\_rms\_i})^2} \qquad (12)$$

where N_g is the number of Riemann subintervals, I_{gref} is the reference current and the $I_{gs\_rms\_i}$ is the rms value at the ith subinterval current.

IEC 61000-4-30 standard characterizes the dips by depth and duration. The depth is equal to the difference between the reference voltage and the residual voltage, the duration is calculated from the time that voltage falls below a predefined threshold until it rises above the threshold plus a hysteresis [15]. The voltage dip is usually expressed as a percentage of reference voltage and calculated as

$$V_{dip\_mea} = \sqrt{\frac{1}{M}\sum_{i=1}^{M}(V_{ref} - V_{dip\_rms\_i})^2} \qquad (13)$$

where M is the number of Riemann subintervals, V_{ref} is the reference voltage and the $V_{dip\_rms\_i}$ is the rms value at the ith subinterval voltage.

III. Experimental Results and Comparisons

For the experimental tests, a research-training ship Horyzont-II was selected. The ship is employed to conduct specialized marine training, research and regular cruises to polar regions with supply for Polish polar bases. More information about the ship can be found in [32].

The ship electrical test platform consisted of a generator, a variable speed drive with power converter (bow thruster motor and propeller), a ballast pump motor and auxiliary loads such as fresh water pump in the main engine cooling system, fans and heater loads etc. The pumps driven by induction motors are common electrical energy consumers onboard. The ship and its main parts are shown in Fig.3 and the system parameters can be found in Table I.

(a) Horyzont-II ship (b) Engine room (c) Control board (d) Diesel generator (e) Pump load

Fig.3 Horyzont-II ship test environment [20], [32].

TABLE I. Ship Microgrid System Parameters

Ship microgrid	parameters	Value
Main AC bus voltage	Vabc [V_{rms}]	400
	f [Hz]	50
	Uf [%]	0.35 (CaseA) 1.5-1.8 (Case B)
Diesel generator	V_g [V_{rms}]	400
	P_g [kW]	300.8
	X_d' [%]	10.6
	X_d'' [%]	7.6
	$\cos\phi_g$	0.8
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
Main engine	P_e [kW]	1280
Fuel tank	Weight [t]	265.6
Speed	Knots	12

TABLE II. Case Studies in Ship Microgrid

Ship microgrid	Case A	Case B
Diesel generator	enabled	enabled
Ballast pump load	starts three times to generate voltage dips	starts three times to generate voltage dips
Bow thruster load	power increasing until full load	power increasing until full load
Fresh water pump	normal operations	normal operations
Heater load	normal operations	unbalanced operations
Other ship electrical devices	real SMGs contain hundreds of electrical devices working at the same time	

The investigated voltage dips were monitored for two cases: quails-balanced voltage (Case A) and unbalanced voltage (Case B). The ship experiment processes are designed in Table II. For each case in Table II, only one generator was enabled and the bow thruster power has step changes to full load. The ballast pump started three times to generate voltage dips. Although the voltage dips were moderate, this condition can represent typical behaviors in SMGs. The consumption of other loads remained unchanged. It should be noted that the only difference is the heater load with phase A disconnected and working with phases B and C , which emulated the case of fuse breaking to obtain voltage unbalance in Case B.

A. Case A. SMG under quasi-balanced voltage condition

As mentioned in the above study case in SMG. The detailed SMG behaviors under quasi-balanced voltage conditions can be found in Fig. 4.

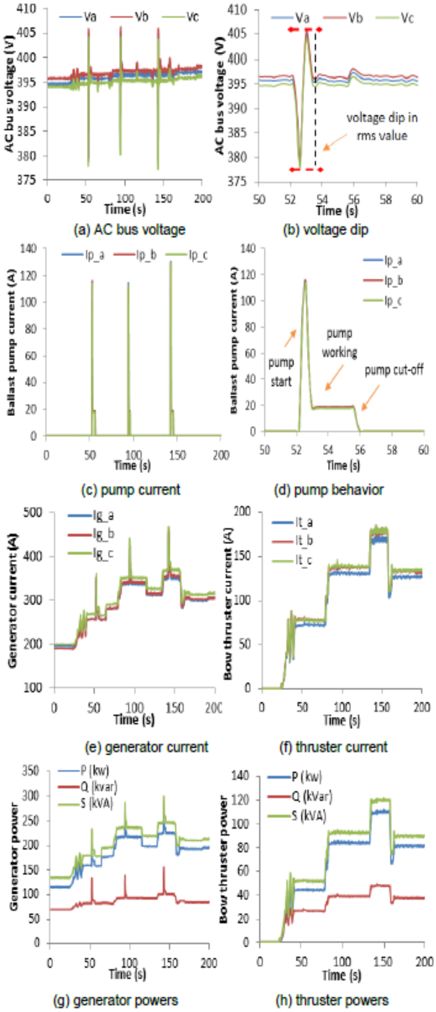


Fig.4. Experimental results of SMG in Case A

Figs. 4 (a) and (b) show the rms value of ship AC bus quasi-balanced voltage during ballast pump start up. The voltage unbalances indices (ratio of negative and positive sequence components as defined in [15]) remained quite low and in the range of 0.2%-0.43% with the mean value equal to 0.3%.

The obvious reason of the voltage dips is the ballast pump starting current shown in Figs. 4 (c) and (d), which can reach 120A, if measured on the basis of ten cycle window. It reached even 148A within only 0.03s, which is about 6 times of the rated current. The latter value was obtained by calculating the current rms value over one cycle and refreshed each half cycle, following the voltage dips assessment in IEC 61000-4-30.

Other voltage dips during the starting of the ballast pump are quite similar, which depends on the ratio of impedance between the pump motor and generator, and independent of the actual power level of bow thruster load.

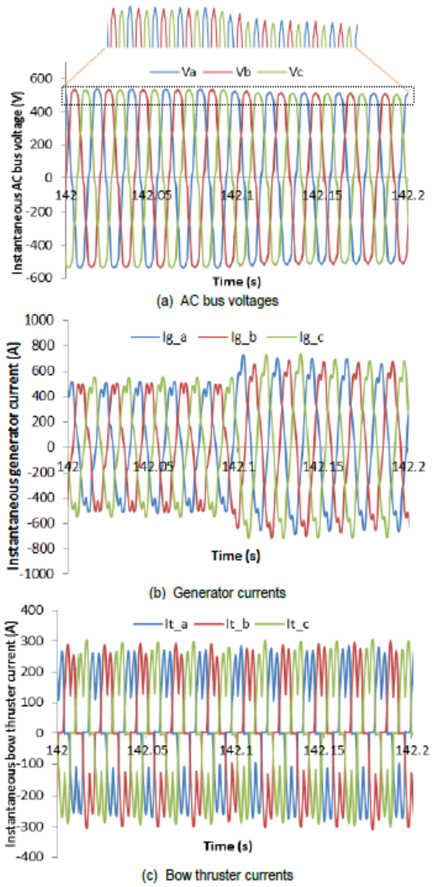
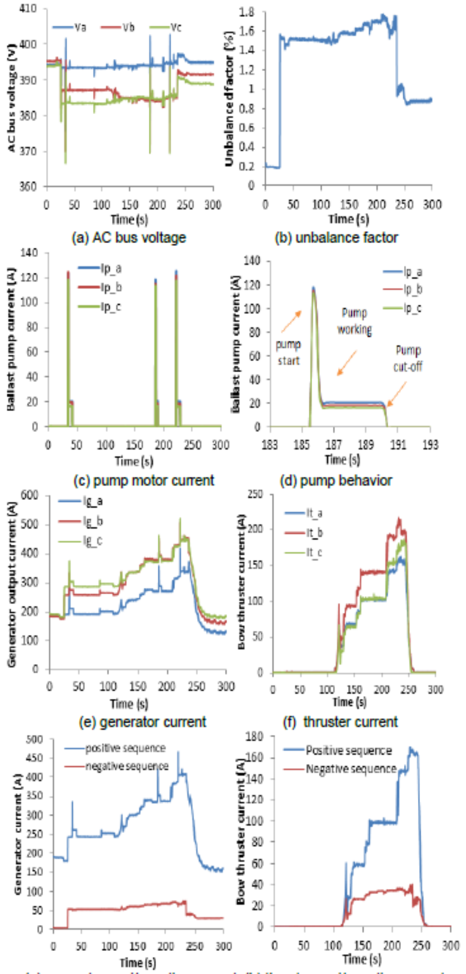


Fig.5. Case A-Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) during voltage dips

Fig.5 shows the instantaneous values of the generator output voltage/current and bow thruster current, which were registered for bow thruster full load during the voltage dip. The voltage dip is about 20V, but the generator output current surges from 500A to 740A in a short time. Furthermore, the THD of voltage changed from 1.1% (bow thruster switched off) to 6.7% (bow thruster full load). Accordingly the distortions of generator and bow thruster currents were symmetrical and mainly containing 5th, 7th, 11th and 13th harmonics. The THD of generator current changed from 1.5% (bow thruster switched off) to 12.8% (bow thruster full load). Bow thruster current remained balanced but highly distorted (up to 39.6% for full load conditions).

B. Case B SMG under unbalanced voltage condition

Standard maneuvering behaviors of the SMG were monitored like Case A. However, the voltage unbalances were caused by the heater loads working with phase A disconnected. The detailed behaviors of SMG can be seen in Fig. 6.

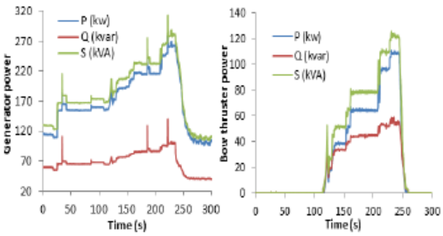


(a) AC bus voltage (b) unbalance factor

(c) pump motor current (d) pump behavior

(e) generator current (f) thruster current

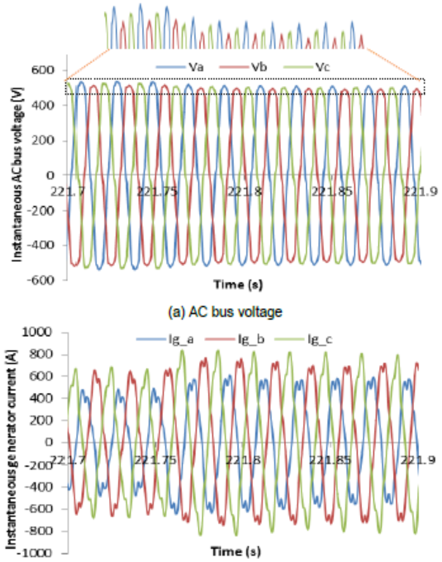
(g) generator posi/negative current (h) thruster posi/negative current



(i) generator powers (j) thruster powers

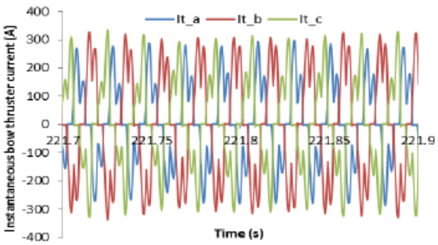
Fig.6. Experimental results of SMG in Case B

It can be seen in Figs.6 (a) and (b) that the unbalanced voltage dips occur three times due to the pump motor start. The bow thruster starts at 120s and increases the voltage unbalance factor from 1.5% to 1.8%. On the other hand, the pump working currents are slightly unbalanced as shown in Figs.6 (c) and (d). Furthermore, it is observed in Figs. 6(e)-(h) that the generator and bow thruster currents are severly unbalanced. The sudden surge effects of generator currents in respective line currents can reach 120 A (22% of generator rated current), which may trigger the overcurrent protection system onboard and possibly endanger ship operations. Moreover, the bow thruster currents are also unbalanced and the fundamental negative sequence component is about 40A. The individual maximum rms value is obviously higher than the value in Case A, which means unequal thermal stress for generator windings under unbalanced voltage conditions. The actual apparent, active and nonactive powers of the generator and bow thruster can be found in Figs. 6 (i) and (j).



(a) AC bus voltage

(b) Generator current



(c) Bow thruster current

Fig.7. Case B- Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) during unbalanced voltage dips

In addition, Fig.7 shows the instantaneous values of the generator voltage/current and bow thruster currents for the full load condition under unbalanced voltage cases. The voltage dips are around 20V for three phase voltages, however, the generator maximum current surges from 620A to about 850A due to the transient voltage dip and unbalanced faults, which are more severe than those of Case A. Note that the THD of bow thruster current increases for two phases and harmonic current can even reach 77 A for particular phase (normally only 57A in Case A).

These results lead to the conclusion that the impact of voltage dips depend on ballast pump start current and is independent from bow thruster loading. However, in Case B, the unbalanced voltage dips and the generator current surges are more likely to go beyond the voltage/current limit values, which undoubtedly deserves more concern.

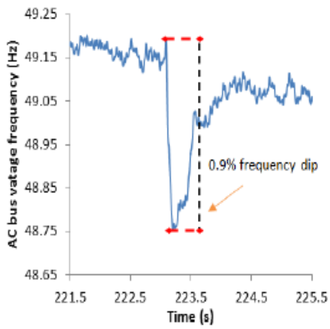
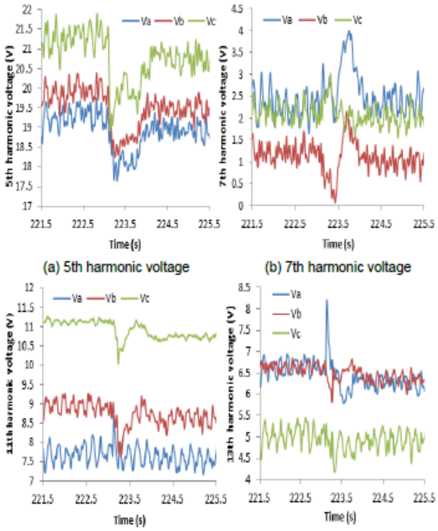


Fig.8. Frequency changes during the unbalanced voltage dip under bow thruster full load conditions

Fig.8 presents the AC bus voltage transient frequency changes during the transient voltage dip. In fact, the transient frequency variations are quite small with only 0.9% of the rated system frequency. SMG is capable to operate satisfactorily under the transient frequency variations of ±10% as required by maritime standards [17-19]. However, it should be noted that in the studied cases, the frequency transient dips are relevant to the ballast pump current changes and have actual impact on the transient harmonics for AC bus voltage and bow thruster current, which are very important for PQ assessment in SMGs [28].

Figs. 9 (a)-(d) show the unbalanced dip transient impact on 5th, 7th, 11th, and 13th harmonics of AC bus voltage under bow thruster full load conditions. In order to asses harmonic transient performance, harmonic values were determined by zoom-DFT and refreshed every 1 ms, the Kaiser window (parameter β =7.65) was used to suppress spectrum leakage [5]. The window was dynamically synchronised (every 1 ms) to the momentary duration of 3 fundamental cycles.



(a) 5th harmonic voltage (b) 7th harmonic voltage

(c) 11th harmonic voltage (d) 13th harmonic voltage

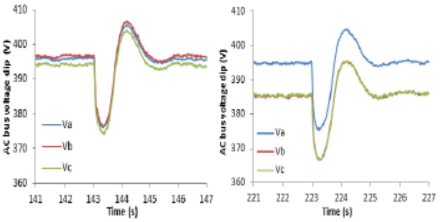
Fig.9. Harmonics of AC bus voltage during the unbalanced voltage dip under bow thruster full load conditions

It can be seen that the harmonic components change during the voltage dip intervals. As the main low-order harmonic, the 5th harmonic voltage can be even beyond 6% of the fundamental component. In fact, the voltage harmonics are mainly originated from the bow thruster current. For a higher power levels under unbalanced voltage cases, more harmonic and inter-harmonic currents will appear around the individual bow thruster currents. The dynamic harmonic analysis of bow thruster current can be found in [20], and the harmonic spectra of AC bus voltages up to 25th harmonic under bow thruster full load for steady state analysis can be found in [28].

It can be concluded that during voltage dips in real SMGs, temporary increase of voltage harmonics can be determined and should be taken into account during SMGs modelling in order to avoid possible interference with sensitive equipment.

C. Comparative analysis of voltage dips under quasi-balanced and unbalanced voltage conditions

Many motor starting designs devised for practical ship electric power applications can be used to ensure the performance of the proposed method [33]. For the comparative analysis of the voltage dips in SMG, the voltage dips under quasi-balanced and unbalanced voltage cases under bow thruster full load were selected to verify the proposed evaluation method.



(a) Case A (b) Case B

Fig.10. Voltage dips in two cases under full load of bow thruster

Fig.10. shows the registered voltage dips in Case A and Case B. The depth of voltage dip is about 5% of the pre-event voltage in both cases. The differences between values for respective three phase voltages under quasi-balanced condition remain quite low up to 0.5%, but the differences increase to 2.5% under unbalanced conditions.

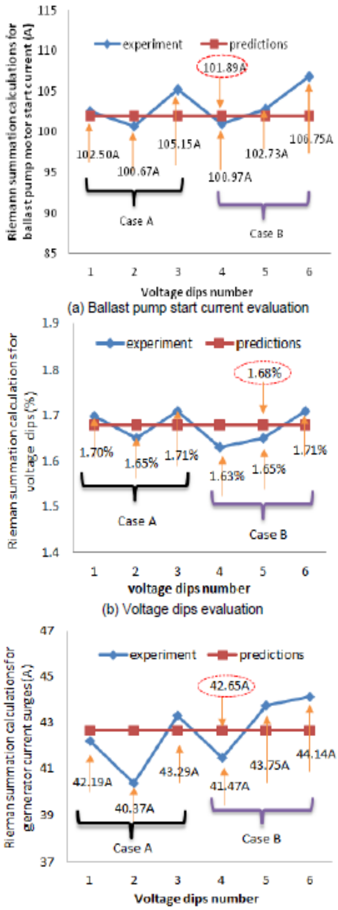
However, the depth of unbalanced voltage dip in Case B is higher reaching 8.35% and the residual voltage is lower than the values in Case A. Therefore, it is indicated that the unbalance affects the AVR operation, which sets only highest line-to-line voltage to rated value especially during the transient dips. This may bring hazards to some sensitive electrical equipment in case of severe voltage dips.

The measurement results of the voltage dips parameters and generator output currents are calculated according to IEC 61000-4-30 standard (Class A measurement method) as can be found in Table III.

TABLE III. VOLTAGE DIPS AND GENERATOR CURRENT DETERMINED ACCORDING TO THE MEASUREMENTS

Parameters		*AC bus voltage* [V_{rms}]		*Dip depth* [%]		*Generator current peak value*[A]	
		Pre-event	*Residual*	*% of Pre-event voltage*	*% of rated voltage*	*Pre-event Current*	*Max surge current*
Case A	Va	395.72	375.98	4.99	6.00	482.21	685.21
	Vb	396.40	376.66	4.98	5.84	482.37	681.54
	Vc	394.01	374.18	5.03	6.45	480.34	682.79
Case B	Va	394.82	375.33	4.94	6.17	478.62	656.10
	Vb	385.21	366.77	4.79	8.31	646.53	784.25
	Vc	385.47	366.61	4.89	8.35	666.83	845.64

Although the ballast pump motor starting current in the analytical model (built based on the generator transient and sub-transient average impedance) was assumed to be constant during the whole starting period, the practical motor starting current and the voltage dips may not remain constant. For validating the proposed evaluation model during the dynamic voltage dips, the predicted values obtained from the model using equations (2)-(6) were compared with the Riemann summation calculations used as approximate average values for the experimental measurements of ballast pump start current, transient voltage dips and generator current surges in real SMG as shown in Fig.11.



(a) Ballast pump start current evaluation

(b) Voltage dips evaluation

(c) Generator current surges evaluation

Fig.11. Evaluation results based on Riemann-Summation for comparison between two cases

Fig.11 presents the evalution results for the voltage dips, ballast pump motor start current and generator tranisent current surges under quasi-balanced voltage (Case A) and unbalanced voltage (Case B) conditions. The predicted values are calculated based on the proposed model (2)-(6), and the experimental results are calculated by Riemann summation based on (11)-(13). According to the existing design criterion for the SMG, the parameter K in (4) is selected as 6, and m is 1 for the direct-on-line starting method [27]. The other parameters used for model can be found in Table I.

Fig. 11 (a) shows that the predicted value based on (4), for the ballast pump motor starting current is 101.89A, which almost matches the Riemann summation results from (11) for experimental measurements. The maximum error is only 4.8%.

Fig. 11 (b) shows that the voltage dips calculated by (2) are about 1.68%, and the Riemann summation evaluation results based (13) are in the range of 1.63%-1.71% with the maximum error of 3.0%. It is observed that the voltage dips mainly depend on the capacity and start current of the pump motor and the dips depths with respect to the pre-event voltages are almost the same for quasi-balanced and unbalanced cases.

As it can be seen in Fig.11 (c), the generator current surges calculated by (6) is 42.65A, which also matches the Riemann summation experimental results from (12), and the maximum error is 4.9%. In addtion, it should be noted that the generator current surges are relevant to the actual voltage dip depth, and the individual phase current peak value are more likely to trigger the overcurrent protection devices onboard due to the unbalanced waveforms in Case B.

In addition, if more generators work in parallel, the proposed model based on the average value of transient reactance X_d' and sub-transient reactance X_d'' of the generators can be still applied. However, it should be noted that for the more generators operations onboard, the measured voltage dips during the pump motor starting would be less severe than for one generator work. This is due to the fact that the average value of transient and sub-transient reactance of more generators is smaller than the only one generator case. Furthermore, the proposed voltage dip assessment for one generator case is beneficial to estimate the maximum allowable capacity of motor.

D. Maximum allowable motor capacity estimation considering the unbalanced voltage dips

The maximum allowable capacity of the pump motor considering the unbalanced voltage dips can be estimated from Fig. 12.

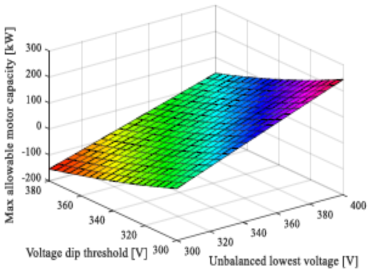


Fig.12. Maximum allowable motor capacity estimation

As it can be seen in Fig. 12, the unbalanced voltage should be above the dip threshold value, otherwise, the calculated capacity of the motor will be a negative value which is unacceptable. On the other hand, for a given voltage dip limit value (e.g. 20% of generator rated volage [14], [15]), the lowest voltage under unbalanced condition must be beyond this value, which provided the proper design information to the allowable motor capacity. For example, in the studied cases, the lowest voltage dip is about 360V (Table III), and the voltage limit is 320V. Therefore, the total maximum motor capacity can be estimated as 90kW according to (9). However, it should be noted that the maximum allowable motor capacity will decrease quickly with the actual lowest voltage values.

IV. Conclusions

This paper highlights the actual impact and proposed evaluation model of voltage dips induced by the pump motor start-ups in a SMG under quasi-balanced and unbalanced voltages. The proposed method is validated by Riemann Summation calculations based on the experiments in real SMG and the maximum error is less than 4.9%.

The experimental analyses in SMG were focused on the magnitude and depth of the voltage dips and actual impact including transient generator current surges and AC bus voltage harmonics. The results indicated that the voltage dips mainly depend on motor power, and the generator transient current surges are caused by voltage dips for both study cases. In addition, the dynamic responses of voltage harmonics were presented under unbalanced voltage dips conditions. The research indicates that temporary increase of harmonics content can be even beyond 6% of the fundamental component, which can interfere with sensitive electronic equipment.

On the other hand, the maximum allowable motor capacity will be decreased more when the unbalanced voltages are considered. In such cases, the individual phase voltage and/or current may violate the threshold limits and consequently, transient dips are observed at the lowest voltage, which means smaller powers of motors are allowed in comparison with normal conditions.

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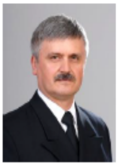

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PAPER 2

Impact of the Voltage Dips in Shipboard Microgrid Power Systems

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Impact of the Voltage Dips in Shipboard Microgrid Power Systems

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***Abstract*—Voltage and frequency transient variations are the most common power quality issues in a ship microgrid system. In this paper, the impacts of the voltage dips induced by the sudden-load of ballast pump are analyzed in detail for the ship power systems. Several relevant ship power quality standards and potential solutions are introduced and discussed properly. The experimental tests from a real ship are presented to show the impact of moderate voltage dips on the selected working generator and bow thruster.**

Keywords—power quality; shipboard microgrid; voltage dips; bow thruster

I. Introduction

Development of ships electrification has been started from the end of 19th century. A ship that features integrated power system was popular for the characteristics such as less fuel consumption, higher torque-dense electric propulsion and increased continuity and survivability [1]. In this background, power quality issues that come with the power electronic applications onboard was a significant concern since the wide applications of variable frequency drives for loads such as pumps, fans, bow thruster motors and propellers [2].

Generally, due to the limited power generation, extensive use of these non-linear power electronic devices and fast dynamic response demands in ship microgrid systems, serious voltage and frequency variations, distorted waveforms, power oscillations and incorrect distribution among parallel generators and transient disturbance are widely produced [3], [4]. Also, this situation can lead to the unwanted power loss in generators, unpredictable resonances, and even malfunction or failures in the vital propulsion systems. Coping with these issues is becoming more and more pressing for the shipping industry.

In case of three phase AC ship microgrid systems, the voltage dips caused by short-circuit faults lead to serious power fluctuations at specific frequency among parallel generators. Next, sudden and severe voltage and frequency dips are caused by switching high power loads such as motors and pumps. Voltage dips are usually characterized by the rms magnitude and duration. Voltage dips should remain below a certain threshold. Dip magnitude is the remaining rms voltage considering the phase with the minimum voltage. Normally, the typical voltage dips thresholds are 20% of the rated voltage [5].

Furthermore, since the ship microgrid is an autonomous network with high impedances, power flow through the cables (with the amount of current transient harmonics mainly produced by non-linear loads such as bow thrusters) not only leads to the energy waste, but also affects the communication and management of electrical equipment onboard especially under the voltage dip conditions.

In this paper, the impacts of the voltage dips induced by the sudden-load of ballast pump are analyzed in detail for the ship board microgrid systems. Several relevant ship power quality standards and potential solutions are introduced and discussed properly. Real experimental tests are presented to show the impact of voltage dips on selected working generator and bow thruster.

II. Shipboard Microgrid System under Voltage Dips

A. Impact of voltage dips in ships

As one of the most important power quality issue in ships, voltage dips are characterized by a transient decrease of rms value and usually occurred at the main switchboard bus.

Generally, ship voltage dips are not only induced by the short circuit faults but also affected by large disturbance from dynamic behaviors of high power mechanical/electrical loads onboard. Such kinds of loads usually start with a huge amount of peak power in a very short interval time (e. g. bow thruster motor or ballast pump). Even if these types of equipment can be reset or cut-off depending on the inherent design and the protection system under incorrect operation, the contactors may easily be false triggered because of the voltage dips.

On the other hand, for the variable frequency bow thruster motor, the sudden decrease of speed or torque cannot be tolerated due to the deep voltage dips. In this case, the induction motors cannot be managed to reaccelerate after the decrease of speed and torque. Further, problems are also delivered to the drive controllers of the bow thruster power

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converter. Power converters that experience the voltage dips will temporarily operate as generations to inject active/reactive power to support voltage recovery. However, it shows up with a slow decay in voltage magnitude during the voltage dips [2].

In addition, due to these facts that the length of the cables is relatively short and the networks short-circuit impedance onboard is quite high, the bow thruster transient current harmonic components are very sensitive to voltage dips. The temporary harmonic swell may damage the stability of the power system, especially under the ship weak grid conditions. Furthermore, for the high power operations of the bow thruster, the impact of current individual harmonics should be taken into account because the THD of current decreases drastically as a result of large fundamental component. Note that the analysis of the high-order harmonics is even more difficult during the voltage dips in the shipboard microgrid system and concurrent frequency variations [4], [6].

Moreover, during the voltage dips, more transient current harmonics emanating from the bow thruster power converter go through the motor [5]. Voltage supplied to the motor sets up magnetic fields in the core, which creates iron losses in the magnetic frame. The hysteresis losses are proportional to frequency, and the eddy current losses vary as the square of the frequency. Therefore, the higher frequency harmonic components will produce additional losses in the core of AC motor as well as increasing the operating temperature of the core and the windings surrounding the core.

As mentioned above, voltage dips have a critical negative effect on the electrical equipment onboard. Analysis of voltage dips is quite complex in the ship power system and needs further investigations because of the voltage unbalance transient frequency fluctuations and also phase angle between sequences in real time.

B. Relevent power qualtiy standards for ships

All electrical equipment is supplied from the main switchboard or emergency sources onboard. The power system should be so designed and manufactured that it is capable of operating satisfactorily under transient variations of voltage and frequency values.

TABLE I. CLASSIFICATION OF SOCIETY RULES AND STANDARDS

Standards	***Parameters Variations***		
	Voltage transient	***Frequency transient***	***THD***
ABS (2016) DNV (2016) IEEE Std.1662-2016 (2016) IEC Std.61557-12 (2007) PRS(2016)	±20%, 1.5*s*	±10%, 5*s*	8%(50*th*)
STANAG1008 (Ed8, Ed.9)*	±16%, 2*s*	±4%, 2*s*	5%(40*th*)
* for the naval ship			

Table.I shows the transient voltage and frequency variations limit and also contains the requirements of Total Harmonic Distortion (THD) proposed in recent years by several famous international associations and professional classification societies for ship power systems.

Until recently, from most ship industry societies such as American Bureau of shipping (ABS) [7], Lloyd's Register and Polish Register of Shipping (PRS) [8], and relevant standards of DNV GL[9], IEEE Std. 1662-2016[10] and IEC Std. 61557-12[11], there were similar requirements related to voltage and frequency transient variations. The allowable voltage transient variations due to sudden changes in loads are about ±20% of the rated voltage with the recovery time of 1.5 seconds. The frequency transient variations due to sudden changes in loads are about ±10% of the rated frequency with 5 seconds of recovery time. However, for the military ship system, the STANAG1008 standards are stricter with the demands of ±16% for voltage transient conditions and ±4% variations for system frequency [12].

Regarding the harmonics and inter-harmonics occurred on the ship power systems, Most societies including PRS (2016), have verified that THD of ship grid voltage (up to the 50th order) remains below 8%. However, assumption of the same permissible limits for all harmonics independent on their order seems at least disputable.

PRS classification society deals with the problem of inter-harmonics and requires to determine THD parameter including harmonics and inter-harmonics with the frequency band up to 10 kHz [8]. The PRS rules result from the fact that on some ships, components above harmonic of 50th order exist, sometimes with dominant share of inter-harmonics, which requires the other approaches for THD calculations [6].

C. Potential solutions for ship voltage dips

Voltage dips can be divided into balanced and unbalanced conditions. The unbalanced ship voltage dips might produce negative sequence components which are usually perceived as harmful components to the power quality assessment.

Reactive power support control is the most common control solutions for mitigating voltage dips in microgrids, and also allowed to ride through short-term dips [13]. The strategies are commonly known as Q/V and P/f droop control [14]. In fact, reactive power injection can be easily achieved either using existing power electronics based power sources or additional dynamic reactive power devices, such as static synchronous compensators (STATCOMs). The STATCOM can combine both active and reactive power capabilities into the power converter to achieve frequency and voltage regulation and thus becoming popular in modern ship power systems [15].

On the other hand, the uninterruptable power supplies (UPS) can restrain voltage/frequency transient disturbance for low power devices in the distribution network and realize the fast recovery of voltage dips [16].

In addition, the dynamic voltage regulator (DVR) is aimed at controlling alternators voltage at main bus voltage and jointly optimizing the reactive power generated by each alternator and support the recovery of ship voltage dips [17]. The unified power quality controller (UPQC) also can be used to compensate voltage dips, frequency interruptions, and harmonic components and support reactive power [18].

III. Experimental Tests

A. Characteristics of an example (investigated) shipboard microgrid system

The simplified diagram of the investigated vessel's electrical microgrid system is shown in Fig. 1. The ship power system consists of three identical synchronous generators with the rated power of 376 kVA connected with the main switchboard AC bus directly. Each generator is driven by a four-stroke diesel engine with the rated power of 357 kW. The loads with the greatest power onboard are the bow thruster motor (125kW), which is supplied by a variable frequency power converter. The ballast pump is used to hold the sea water in order to balance the ship and ensure its stability.

Different AC voltage levels for different consumers onboard can be achieved through the transformer conversions. Normally, the rated voltage of the ship power system is 400V and the rated system frequency is 50 Hz.

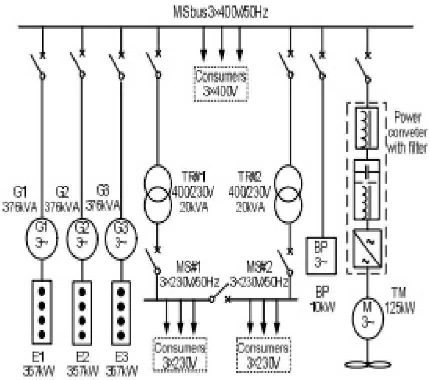
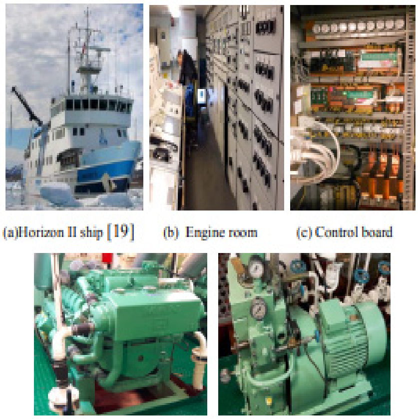


Fig. 1. Simplified diagram of the investigated ship electric power system (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engine; TM: bow thruster motor; TR: transformer; MS: main switchboard; BP: Ballast pump)

The characteristics of ship microgrid includes the isolated power generations with limited capacities, different voltage and frequency levels, high short-circuit impedance of the supply power network and the extensive use of high power nonlinear/pulsed loads etc. Based on these characteristics, the system is more prone to poor power quality, such as unbalanced or distorted voltage/current waveforms, high magnitude of waveforms under transient disturbance and global frequency variations, which brings potential safety hazard to the shipboard power systems.

In order to test the impact of voltage dips in real shipboard microgrid systems, the investigation on the Horizon-II research training ship was carried out for various configurations of the power plant and high power loads as shown in Fig. 2.



(a)Horizon II ship [19] (b) Engine room (c) Control board

(d) Diesel generator (e) Pump load

Fig.2 Horizon-II research training ship test environment

The ship tests system with only one generator and the bow thruster motor was selected. During the research, step changes of the bow thruster motor power were introduced and ballast pump loads are started three times to generate voltage dips under different generator power levels.

B. Experimental results

The voltage and current samples were registered by a controller (NI PXIe-8106) equipped with three DAQs (NI PXIe-6124) and anti-aliasing filters (LTC-1564). The Rogowski's coils (PEM LFR 06/6) and LEMs CV3-1500 were used for signal conditioning [20].

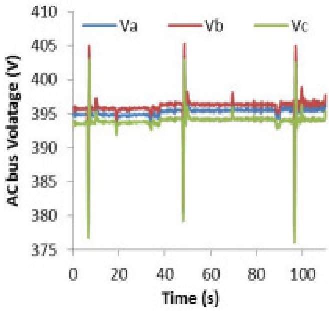
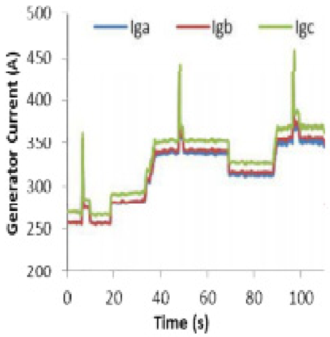
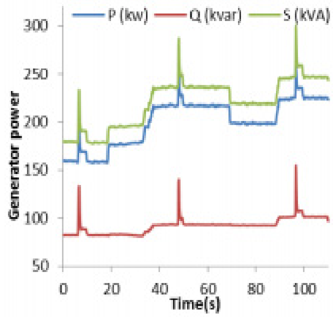


Fig.3 AC bus voltage

Fig. 3 shows the rms value of AC bus voltage onboard. The voltage dips occurred three times because of the sudden starts of the ballast pump load. The lowest rms value of transient dips can drops to around 376V.



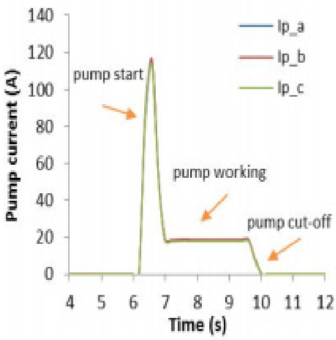
(a) Gernarator output current



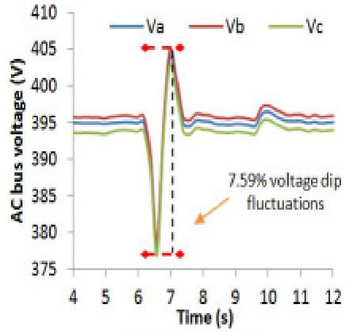
(b) Generator output power

Fig.4 Generator output current and power levels

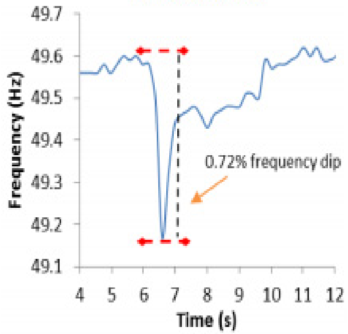
Fig.4 shows the rms value of generator output current with different power levels. It can be observed that the currents were severely increased with 95A or more during each voltage dip, which brought significant risks to the reliability of the shipboard power system. It should be noted that the transient current surges are not occurred at power step times, which means that the transient current surges are not caused by the steps of generator power increasing.



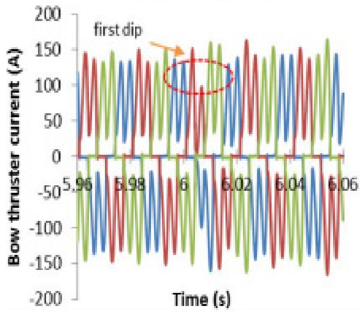
(a) The ballast pump current



(b) AC bus voltage



(c) System frequency



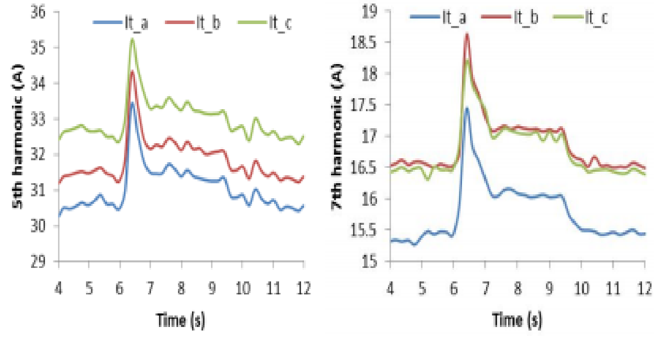
(d) Bow thruster output current

Fig.5 The analysis for the first voltage dip

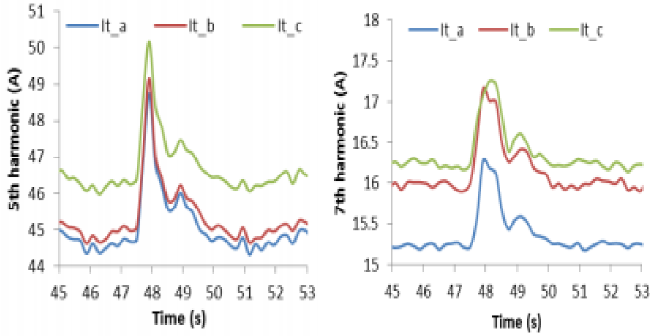
In order to further elaborate the impact of voltage dips, the first dip was chosen as an example. The impacts of other dips are quite similar to first one.

Fig. 5 shows the analysis of the first voltage dip as an example. As it can be seen in Fig.5 (a), the start current of the ballast pump can reach as high as 120A within only 0.5s, which is about 6 times as the rated current levels. In Fig.5 (b), the voltage dips fluctuations are about 7.59% of the pre-event value and the duration is about 1.3s.

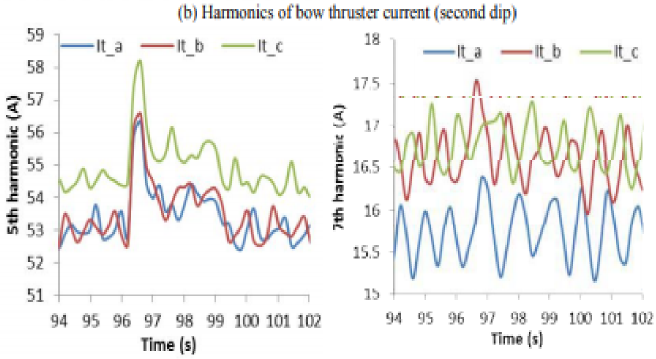
Furthermore, it should be noted that the maximum residual voltage dip occurs at the moment of pump starting with rated power, which means that the inherent reason of dips is the ballast pump behavior. As shown in Fig.5(c), the impact of transient frequency variation is quite small with only 0.72% of the rated frequency. However, the frequency trend is relevant to the pump current changes and the pump starts with the slight frequency decline. On the other hand, bow thruster instantaneous current with large low-order harmonics and transient waveforms swells because of the voltage dip can be observed in Fig. 5(d). In such a case, more transient current harmonics poured to the main switchboard AC bus will cause more voltage harmonics which will be delivered to other electric devices.



(a) Harmonics of bow thruster current (first dip)



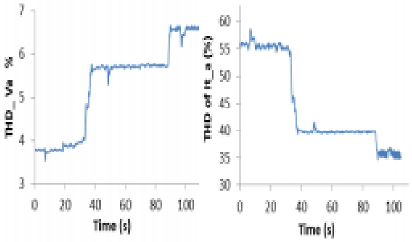
(b) Harmonics of bow thruster current (second dip)



(c) Harmonics of bow thruster current (third dip)

Fig.6 Harmonic impact of the bow thruster current during the voltage dips

Fig.6 shows the transient impact on the 5th and 7th harmonics of the bow thruster output current during the three voltage dips. It can be seen that these harmonic components are increasing obviously in the dip intervals. However, for the higher power levels, more inter-harmonics will appear around the individual harmonic components of the bow thruster current. In fact, the current harmonics and inter-harmonics might affect the stability of the ship power systems especially under high power conditions.



(a) bus voltage THD (b) current THD

Fig.7 THD of AC bus voltage and bow thruster current

Fig.7 shows the THD of AC bus voltage and bow thruster output current. It can be seen that the THD of bow thruster current is reduced with the power levels steps up obviously. Furthermore, the voltage dips have short-term variations on the assessment for THD index and the transients of THD even can achieves 1% for AC bus voltage and 3% for bow thruster current in the dip durations, which means that the conventional calculations of THD factor needs extended research and consider the dip conditions.

IV. CONCLUSIONS

This paper deals with highlighting the actual impact of the voltage dips in the real shipboard microgrid systems. Although the dips were not severe (due to necessity of avoiding risky conditions during sea going), our findings indicate that the voltage dips induced by the sudden-load of ballast pump have adverse impacts on the electrical installations onboard. These adverse impacts include the diesel generator transient current surge, system frequency deviations, bow thruster current individual harmonics increase and the short-term disturbances for accurate power quality index assessment. More severe voltage dips will lead to risky situations for real ship power system cannot be considered in this paper.

ACKNOWLEDGMENT

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PAPER 3

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

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

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***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

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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].

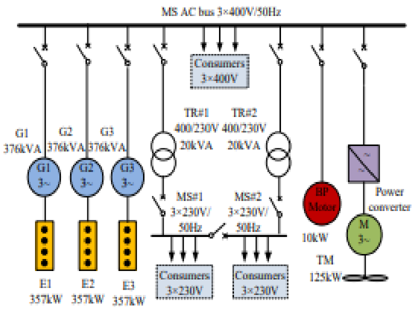

Fig.1. Simplified diagram of the investigated SMG (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engine; BT: bow thruster; TR: transformer; MS: main switchboard; BP: ballast pump motor)

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.

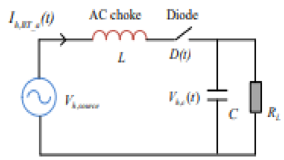

Fig.2. The one-phase equivalent rectifier circuit of bow thruster VFD

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

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

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

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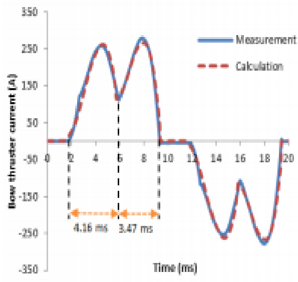
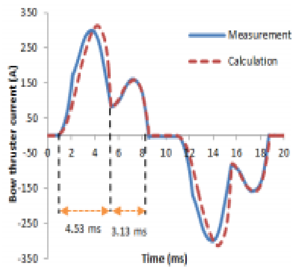
$$R_L \cdot L \cdot C \cdot \frac{d^2 I_{k,BT\_a}(t)}{dt^2} + L \cdot \frac{dI_{k,BT\_a}(t)}{dt} + R_L \cdot I_{k,BT\_a}(t) = V(t+t_1) + R \cdot C \cdot \frac{dV(t+t_1)}{dt} \qquad (2)$$

It can be observed from (2) that $I_{k,BT\_a}(t)$ 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%)



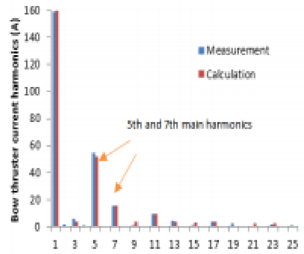
(b) Unbalanced voltage case (UF= 1.63%)

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

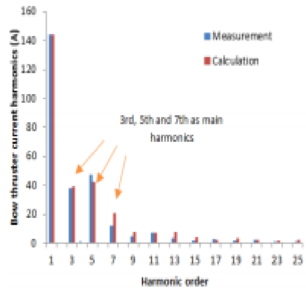
In addition, the comparison between current calculations and measurement of bow thruster load (109kW) under two cases, quasi-balanced and unbalanced, in the investigated ship can be found in Fig. 3. As can be seen in Fig. 3(a) and (b), the calculation of bow thruster current almost matches the measurement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

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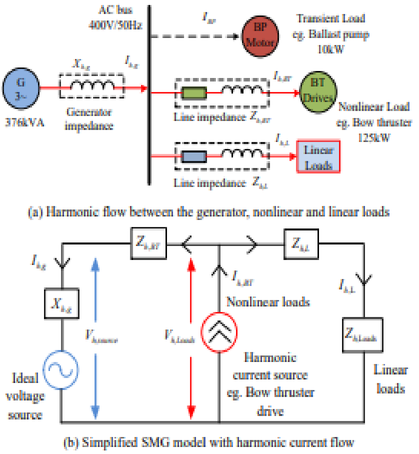
C. Proposed PQ assessment and harmonic analysis for SMG

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

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

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

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

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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].

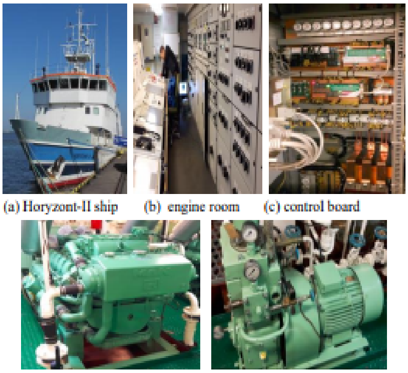
The fundamental reactive power is defined as [22-24]:

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

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

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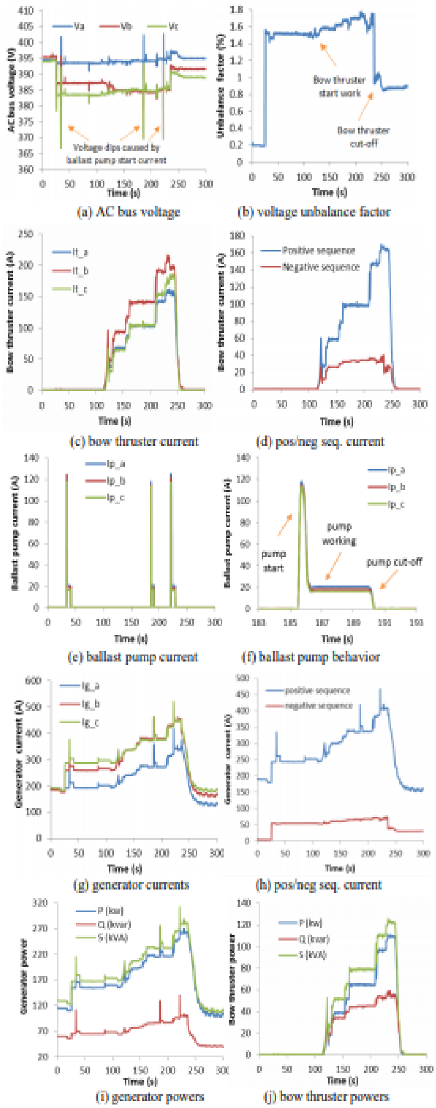
electronic devices, but the main harmonic source in this case is bow thruster drive load.



(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.

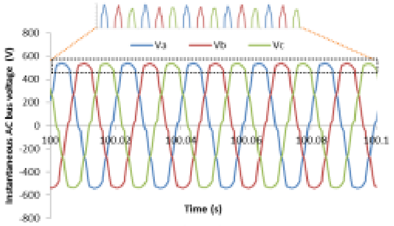
Moreover, the maximum r.m.s current is higher than the respective value in the normal conditions, which means unequal thermal stress for generator windings under unbalanced voltage conditions. On the other hand, the unbalanced voltage affects the operation of ship automatic voltage regulator, which sets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

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

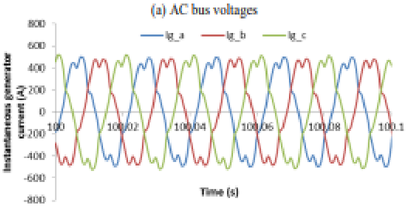
For the comparative harmonic analysis of SMG under normal and unbalanced AC bus voltage conditions, two cases were selected. First case was SMG under normal operations and the second case was faulty heater load operation, which created voltage unbalance, UF additionaly increased by bow thruster power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

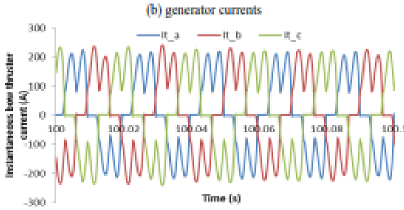
a) Bow thruster full loaded under quasi-balanced voltage conditions



(a) AC bus voltages



(b) generator currents

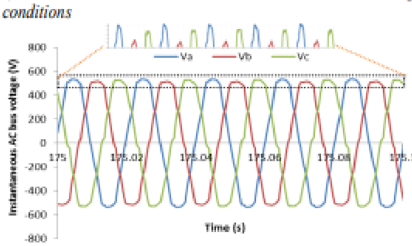


(c) bow thruster currents

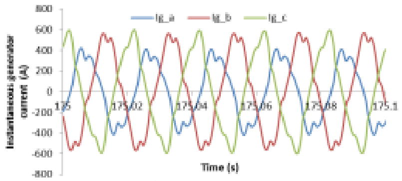
Fig.8. Instantaneous values of (a) AC bus voltage, (b) generator current and (c) bow thruster current under quasi-balanced voltage conditions

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 5th, 7th, 11th and 13th 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.

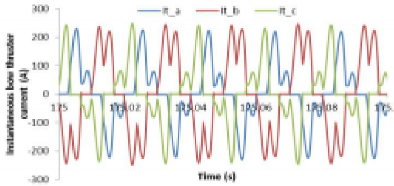
b) Full Load Bow thruster under unbalanced voltage conditions



(a) AC bus voltage



(b) generator current

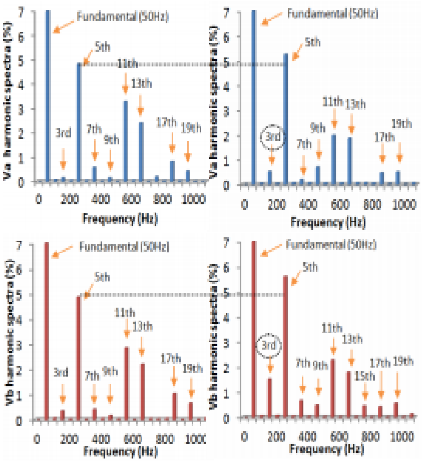


(c) bow thruster currents

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



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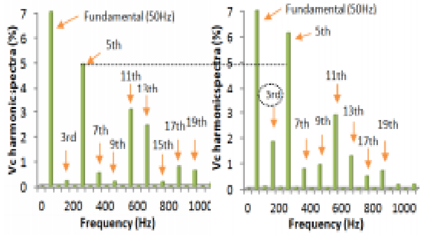


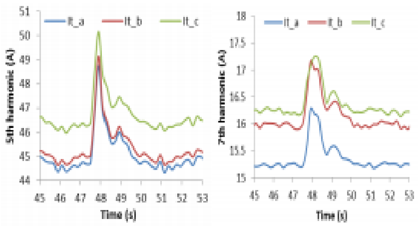
(a) quasi-balanced conditions (b) unbalanced conditions

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

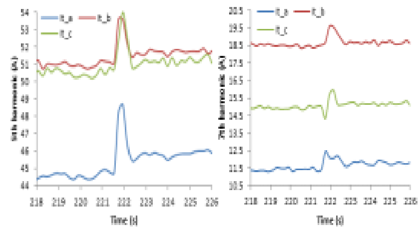
As it can be seen in Figs. 10(a) and (b), the spectra of AC bus voltage harmonics change when unbalances are considered, e.g. 5th harmonic content increases, even beyond 6% of the fundamental component in comparison to approximately 5 % under balanced condition.

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%)

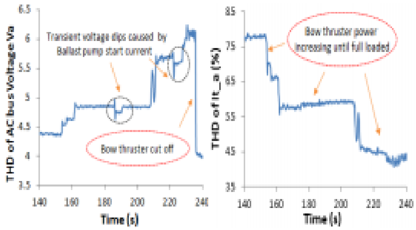


(b) Transient 5th and 7th harmonics of bow thruster current (AC bus unbalanced voltage UF=1.75%)

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].

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

Network parameters		Shipboard microgrid	
		Quasi-balanced AC bus voltage	**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. COMPARISONS 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 gemerator 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

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PAPER 4

Power Quality Assessment in Real Shipboard Microgrid Systems under Unbalanced and Harmonic AC Bus Voltage

Wenzhao Liu, Tomasz Tarasiuk, Mariusz Gorniak, Josep M. Guerrero, Mehdi Savaghebi, Juan C. Vasquez, and Chun-Lien Su

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Power Quality Assessment in Real Shipboard Microgrid Systems under Unbalanced and Harmonic AC Bus Voltage

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***Abstract*—Power quality (PQ) becomes more and more pressing issue on shipboard microgrid systems (SMG). Especially, the impact of voltage unbalance combined with harmonic distortions on the SMG behaviors has not been well investigated before. For this paper, a series of controlled experimental investigations were proposed and carried out in a real ship under sea-going conditions to address this problem. The ship experimental results were 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 voltage transient dips during ballast pump starting up is presented. Further, 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 real ship power system.**

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: pumps, fans, bow thruster motors and propellers [1].

Unlike the terrestrial microgrid systems, the characteristics of the SMGs usually included generators with limited capacity, amount of nonlinear and pulsed loads with high power which are always hard to control but have more flexibility requirements [2]. The typical ship operates in different working modes to suite specific voyage conditions, with significantly varying PQ characteristics. Based on these characteristics, the SMGs are more prone to poor power quality, such as unbalances and harmonic voltage/current waveforms, high magnitude of transient disturbances and global frequency variations, which brings potential safety hazards to shipboard power services. All of these also lead to the requirements for the PQ assessment and improvement onboard become more and more visible and efficient.

However, the analysis for the behaviors of the whole SMGs were still quite complex and especially under unbalanced and distorted conditions, most papers and standards were not fully investigated. In fact, there is a clear lack of requirements regarding voltage/current unbalances in the maritime rules of International Association of Classification Societies (IACS) and its members, except the IEEE Standard 45-2002, which requires that line to line voltage unbalance should not exceed 3% onboard [3]. Further, the consequences of voltage unbalance on generators and other electrical devices can be various, such as the damage of the auxiliary diesel engines by unbalanced distortions which may cause malfunctions to the bearings of the engine and forced the generator breakdown [4]. This may in turn 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 the real ship power systems [6-9].

In fact, every SMGs, even relatively small one, contains dozens or hundreds electrical devices working at the same time and supplied by voltage with fluctuating frequency and magnitude, located on pitching and rolling vessel [10], [11]. Therefore, the behaviors of SMGs can be hardly determined by calculations only, since the system very characteristic changes continuously over time and unpredictable number of interactions occurs. The problem of the PQ assessment validity is recognized by IACS, which requires that the level of harmonic distortion experienced onboard would be determined by calculations, but its "results and validity of the guidance provided are to be verified by the survey or during sea trials" [12].

Therefore, the main aim of this paper is try to fill the aforementioned gap and investigate the particular SMGs behavior in the presence of voltage unbalance and waveform distortions occurring concurrently. Also taking into account IACS's recommendation which requires sea trials, authors carefully planned and set series of controlled experiments

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during the ship voyage for determining the SMGs behaviors under voltage unbalanced and harmonic distortions occurring simultaneously.

In this paper, experimental study cases were carefully selected: full load of bow thruster supplied via power converter and small level of voltage unbalance on main switchboard bus bars (0.35%) as well as similar load with higher level of the voltage unbalances, up to 1.75%. The present research is devised as the first step toward investigation of real SMGs behaviors under unbalanced and distorted voltage conditions, which undoubtedly deserves more concern.

II. SHIPBOARD MICROGRID SYSTEM UNDER RESEARCH

A. Shipboard microgrid system description

As a typical isolated microgrid power system, the characteristics of ship microgrid includes the isolated power generations with limited capacities, different voltage and frequency levels, high short-circuit impedance of the supply power network and the extensive use of high power nonlinear/pulsed loads etc. Based on these characteristics, the system is more prone to poor power quality, such as unbalanced or distorted voltage/current waveforms, high magnitude of waveforms under transient disturbance and global frequency variations, which brings potential safety hazard to the shipboard power systems.

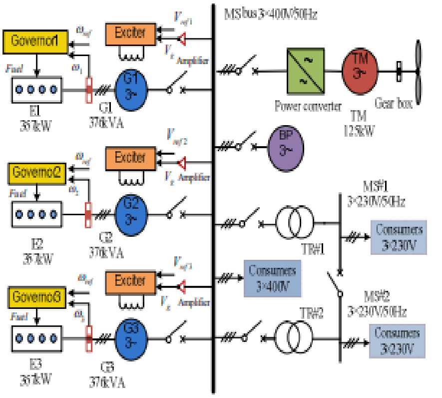


Fig.1 Simplified diagram of the SMG based ship HORYZONT II (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engines; TM: bow thruster motor; TR: transformer; MS: main switchboard; BP: ballast pump)

In this research, the simplified diagram of the SMG based real ship HORYZONT II is shown in Fig. 1. The real SMG consists of three synchronous generators with the rated power of 376 kVA connected directly to the main switchboard AC bus bar. Each generator is driven by four-stroke diesel engine with the rated power of 357 kW. The load with the greatest power onboard is the bow thruster motor (125kW), which is supplied by a variable frequency power converter. The rated RMS voltage/frequency of main switchboard bus is 400V/50 Hz. The RMS voltage of auxiliary switchboard connected with the main AC bus bar via transformers is 230V/50Hz for other power consumers.

B. Potential solutions for power qualtiy improvement

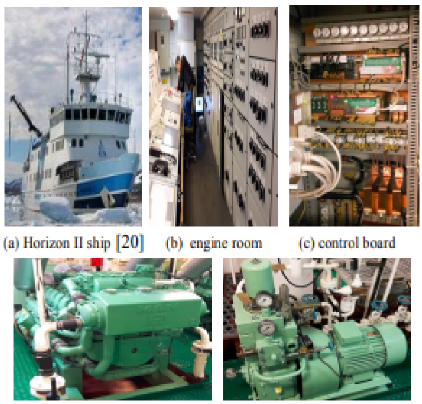
Reactive power support control is the most common control solutions for mitigating voltage unbalances and harmonics in SMGs, and also allowed to ride through short-term dips or sags [13]. The strategies are commonly known as Q/V and P/f droop control [14]. Reactive power injection could be achieved either using existing power electronics based power sources or additional dynamic reactive power devices, such as static synchronous compensators (STATCOMs). STATCOM can combine both active and reactive power capabilities into the power converter to achieve frequency and voltage regulation and thus becoming popular in modern ship power systems [15].

On the other hand, the uninterruptable power supplies (UPS) can restrain voltage/frequency transient disturbance for low power devices in the distribution network and realize the fast recovery of voltage/current unbalances and harmonic compensations [16].

In addition, the dynamic voltage regulator (DVR) is aimed at controlling alternators voltage at main bus voltage and jointly optimizing the reactive power generated by each alternator and support the recovery of ship voltage dips [17]. The unified power quality controller (UPQC) also can be used to compensate voltage dips, frequency interruptions, and harmonic components and support reactive power [18].

III. EXPERIMENTAL STUDIES

The investigation on the real ship HORYZONT II was carried out for various configurations of the power plant and high power loads as shown in Fig.2. During the research, the behaviors of generator, bow thruster and ballast pump were monitored carefully. The ballast pumps driven by induction motors are common electrical devices to balance the ship body and ensure its stability onboard [19].



(a) Horizon II ship [20] (b) engine room (c) control board

(d) diesel generator (e) pump load

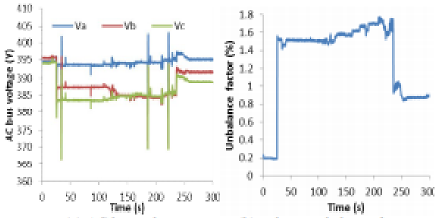
Fig.2 Horizon-II research training ship test environment

The investigation on the Horizon-II research training ship was carried out for various configurations of the power plant and high power loads as shown in Fig. 2. The ship tests system with only one generator and the bow thruster motor was selected. During the research, step changes of the bow thruster motor power were introduced and ballast pump loads are started three times to generate voltage dips under different generator power levels.

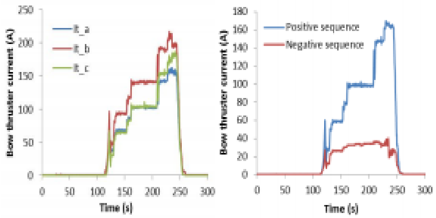
The details of algorithms and mathematical formulas for respective parameters calculations are from IEC 61000-4-30 [21] and IEC 61000-4-7 [22] standards definitions and calculations based on simple Discrete Fourier Transform (DFT) with rectangular 10 cycles window were used for determining the harmonics values and subsequently THDs and harmonic currents and powers, the window duration was determined by counting the voltage zero crossing after low pass filtration. The voltage and current samples were registered by a controller (NI PXIe-8106) equipped with three DAQs (NI PXIe-6124) and anti-aliasing filters (LTC-1564). The Rogowski's coils (PEM LFR 06/6) and LEMs CV3-1500 was used for signal conditioning [23].

A. The SMGs under unbalanced and distorted AC bus voltage

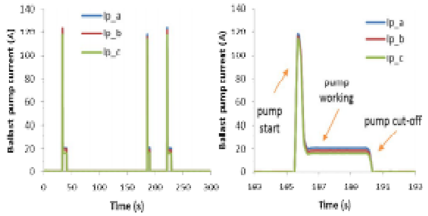
Detailed behaviors of the real SMGs were monitored as follows: Generator working+ ballast pump starts (three times) + bow thruster power increasing until full loaded + ship heating system with phase A disconnected and working with phase B and C, (simulation of fuse blowing to generate the unbalanced voltage faults, the unbalances are set as moderate in real time due to the security considerations) + other ship power electrical devices (In fact, the real SMGs contains hundreds of electrical devices working at the same time, but the main harmonic sources are considered as bow thruster loads in this research.)



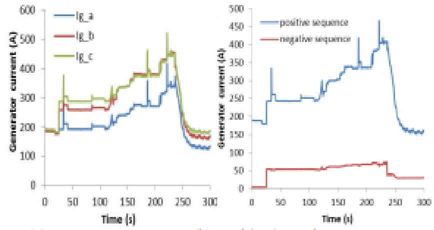
(a) AC bus voltage (b) voltage unbalance factor



(c) bow thruster current (d) positive/negative seq. current



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



(g) generator currents (h) positive/negative seq. current

Fig.3 Experimental results of SMG under unbalanced voltage conditions

Figs. 3 (a) and (b) show the rms values of ship AC bus voltage and its unbalance factor, respectively. The unbalance factor was increasing to 1.75% with the bow thruster power increase. Next, the ballast pump started to balance ship body under sea-going but generate the AC bus voltage dips because it starts drawing a large amount of power in a very short time. As can be observed in Figs. 3(e) and (f), the ballast pump starting current can exceed 120A which contains slight unbalances, sometimes it can even reach 148 A (about 7 times of the rated working current level of ballast pump within only 0.3s. On the other hand, the generator current surges, Fig. 3(g), only occurs at the fundermental positive sequence component and does not affect the fundamental negative sequence component as shown in Fig. 3(h) because the ballast pump current contains very small negative components with quite limited capacity to disturb the negative current of the working generator.

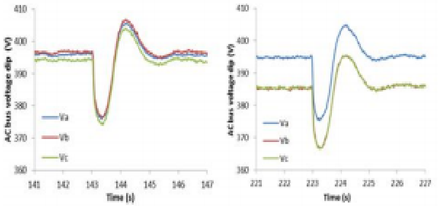
In Figs.3 (c), (d), (g) and (h), it can be seen that the generator and bow thruster currents are severely unbalanced with the sudden transient surges for generator currents. The differences between respective line currents can reach up to 120 A (22% of generator rated current), which may trigger the overcurrent protection devices and possibly endanger ship voyage operations. In fact, the maximum rms 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 ship automatic voltage regulator work, which sets only highest line to line voltage to more or less rated voltage.

B. Comparative analysis of SMG under normal and unbalanced grid conditions

For the comparative analysis of SMG under normal and unbalanced grid voltage conditions, two cases were selected. First is voltage dips as transient state and second is bow thruster full load as an example of steady state.

a) Analysis of the transient voltage dips

Voltage dips are characterized by a transient decrease of rms value and usually occurred at the main switchboard bus. Voltage dips can be also divided into balanced and unbalanced conditions.



(a) normal voltage conditions (b) unbalanced voltage conditions

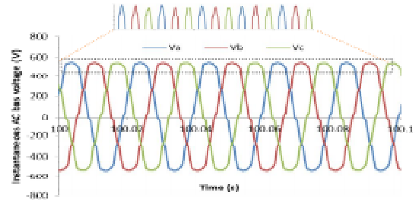
Fig. 4. Transient dips of AC bus voltage in two conditions

Fig. 4 shows the registered transient dips under Quasi-balanced and unbalanced AC bus voltage conditions. The voltage dip depths are about 5% of the pre-event voltage under both normal and unbalanced grid conditions. The differences between values for respective three phase voltages under normal condition remain very low up to 0.5%. The differences slightly increase for unbalanced condition to 2.5%. But the dip depth is higher due to voltage unbalances in relation to rated voltage, reaching 8.35% and the residual voltage is much lower. The detailed results of dip parameters according to standard method for Class A measurements [21] and calculations can be found in Table. I.

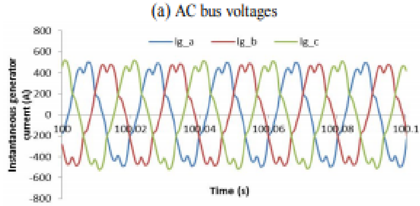
TABLE I. DIPS PARAMETERS DETERMINED ACCORDING TO CLASS A MEASUREMENTS (IEC 61000-4-30 [21])

Parameters		***AC bus voltage* [V]**		***Depth* [%]**	
		Pre-event	***Residual***	***% of Pre-event voltage***	***% of rated voltage***
Normal grid voltage	Va	395.72	375.98	4.99	6.00
	Vb	396.40	376.66	4.98	5.84
	Vc	394.01	374.18	5.03	6.45
Unbalanced grid voltage	Va	394.82	375.33	4.94	6.17
	Vb	385.21	366.77	4.79	8.31
	Vc	385.47	366.61	4.89	8.35

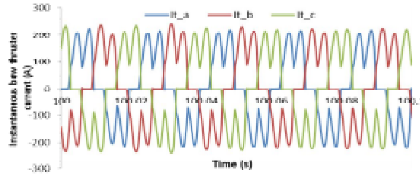
b) Analysis of the system under full load of bow thruster conditions



(a) AC bus voltages



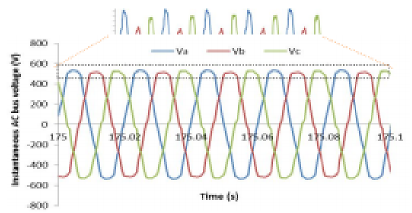
(b) generator currents



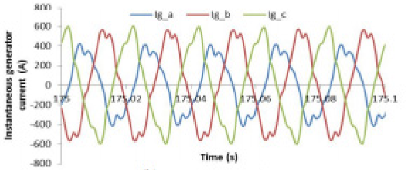
(c) bow thruster currents

Fig. 5 Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) under normal quasi-balanced grid conditions

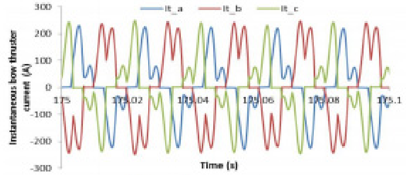
Fig. 5 shows the instantaneous values of the voltage as well as generator and bow thruster currents under normal grid conditions as an example. These were registered for bow thruster full load. The voltage THD changed from 1.1% (bow thruster switched off) up to 6.7% (bow thruster full load) and remained roughly the same for all line to line voltages. Accordingly the distortions of generator and bow thruster currents were symmetrical, mainly containing 5th, 7th, 11th and 13th 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 (up to 39.6% for full load) but balanced, including the harmonics currents (differences below 2% of harmonic currents mean value (57 A) for full loaded).



(a) AC bus voltage



(b) generator current



(c) bow thruster currents

Fig. 6. Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) under unbalanced grid conditions

In addition, Fig. 6 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 particular case (57 A for balanced condition). Also THDs of the line to line voltage differs even with the slight unbalances (UF=1.75%) and distortions in AC bus voltage, which means PQ problems can be more critical onboard especialy under unbalanced conditions.

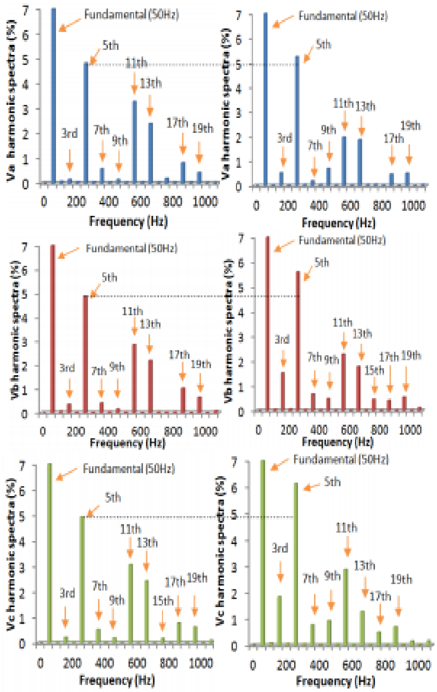
c) Power quality assessment for the ship microgrid under quasi-balanced and unbalanced conditions

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

TABLE II. COMPARASION S OF SMG MAIN PARAMETERS FOR BALANCED AND UNBALANCED CONDITIONS

Network parameters		Shipboard microgrid: Quasi-balanced AC bus voltage conditions	Shipboard microgrid: Unbalanced AC bus voltage conditions
Main AC bus bars voltage unbalance factor		0.35%	1.75%
Main AC bus bars voltages	Va [V]	395.2	394.9
	Vb [V]	396.2	385.2
	Vc [V]	393.8	385.9
Main AC bus bars voltage distortion factors	THD_va [%]	6.43	6.04
	THD_vb [%]	6.23	6.63
	THD_vc [%]	6.43	7.33
Generator parametrs	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	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	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

It can be seen from the Table II that unbalance lead to increse in the harmonic power flow in the system for the same active power of nonlinear load. Combining with increase in nonactive power and currents unbalance, it means additional losses in the generators, transformers and cables. Obviously, the unequal currents of generator and pump motors also mean unvenen thermal stress of the machines windings, which can lead to increased speed of overall thermal ageing. It should be noted that the harmonic power flows mainly from the bow thruster to the generator and also go through the fresh water pump and other devices, which also means that the bow thruster is the main harmonic source in this system.



(a) normal conditions (b) unbalanced conditions

Fig. 7 Harmonic spectra of AC bus voltages up to 25th harmonic under full load of bow thruster

One of the effects of voltage unbalance is relatively significant difference between voltage THDs, as can be seen in the Table III. However, it does not mean that all of harmonic values changes proportionally. As can be seen in Fig. 7, the spectra of voltages changes, e.g. fifth harmonic content increases, it can be even beyond 6% of the fundamental component, and significant value of third harmonics appears under unbalanced condition, which also means the power quality assessment under unbalanced AC bus voltage conditions is more challenging for the SMGs.

IV. Conclusions

This paper provides valuable experimental investigations on the power quality assessment onboard. It highlights the particular effects of voltage unbalance and distortions in the real SMG. The permissible voltage unbalances should be tied with the level of voltage waveform distortion, which means that flexible threshold of the unbalance factor has to be adopted in the furture maritime standards. Furthermore, the transient voltage dips caused by sudden-load of ballast pump can lead to generater current surges, which may also treated as harzard to the ship power system.

In our conclusions, the differences between critical grid parameters under balanced and unbalanced conditions are quite huge in the real ship power system. It particularly concerns increase of voltage THD for some line to line voltages, which can adversely impact on operation of sensitive one phase receivers, which must be taken into account by the system integrator, when calculating the level of harmonic distortion experienced, the effect augments problems resulting from current distortions, like increase in harmonic active power flow in the system. It clearly necessitates the amendment current maritime standards and including unbalance factor into them.

Acknowledgment

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SUMMARY

This project provides PQ assessment methods for SMGs under both unbalanced and harmonic AC bus voltage conditions. The impact of voltage unbalance combined with harmonics on the SMG behaviors are analyzed, some models and controllable experimental research are proposed and carried out in a real ship under sea-going conditions. The experiments are presented considering real non-linear bow thruster load and high power ballast pump loads at steady and transient conditions. In addition, the transient impact of voltage dips has been carefully analyzed based on maritime standards methods. The research work done proposed modelling methods based on the critical ship system parameters, which can be easily applied for PQ assessment onboard. Moreover, voltage dips caused by pump loads can lead to generator unbalanced fundamental current and harmonic current surges, which also have been analyzed.

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