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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. Characteristics of **a 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.

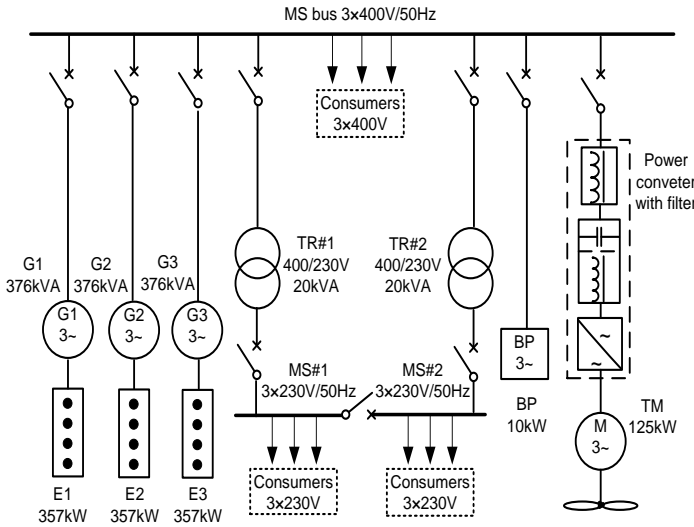


Fig. 1. Simplified diagram of the **investigated** ship electric power system (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engine; TM: bow thruster motor; TR: transformer; MS: main switchboard; BP: Ballast pump)

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.

B. 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 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 dip fault [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.

C. Relevant power quality 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)	$\pm 20\%$, 1.5s	$\pm 10\%$, 5s	8%(50th)
STANAG1008 (Ed8, Ed.9)*	$\pm 16\%$, 2s	$\pm 4\%$, 2s	5%(40th)
* 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.

III. EXPERIMENTAL TESTS

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 $\pm 20\%$ of the rated voltage with the recovery time of 1.5 seconds. The frequency transient variations due to sudden changes in loads are about $\pm 10\%$ 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 $\pm 16\%$ for voltage transient conditions and $\pm 4\%$ 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 problem of inter-harmonics **and requires** to determine THD 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].

D. 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].

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

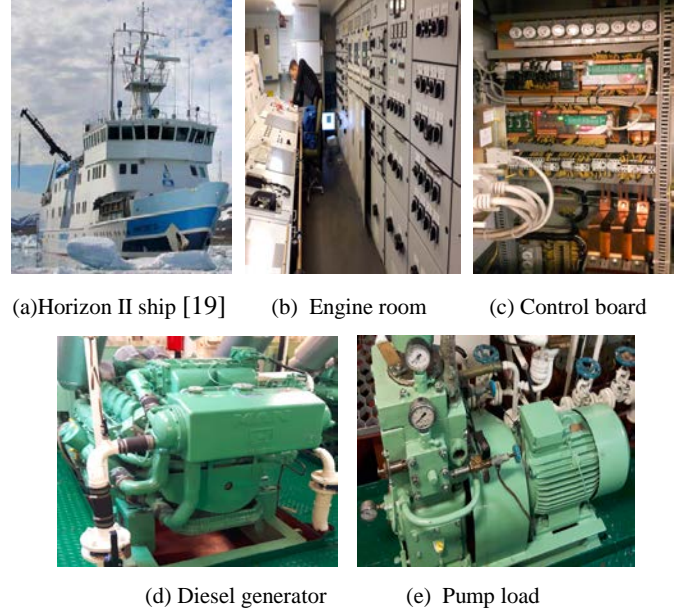


Fig.2 Horizon-II research training ship test environment

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.

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].

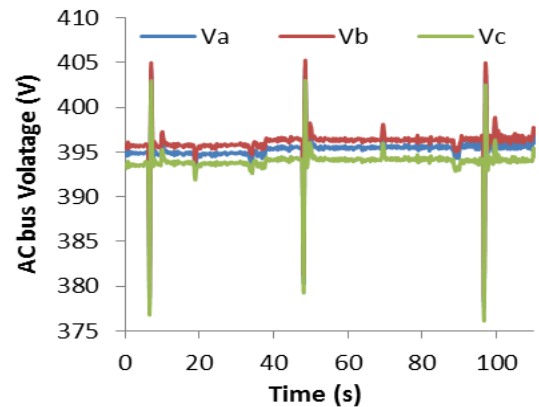
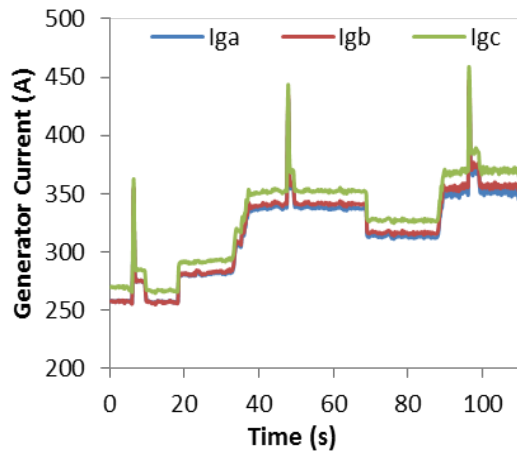
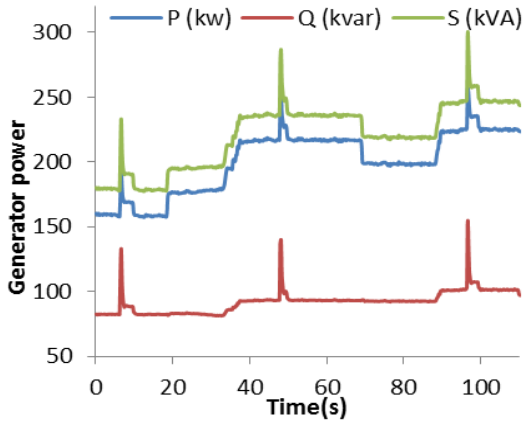


Fig.3 AC bus voltage

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.



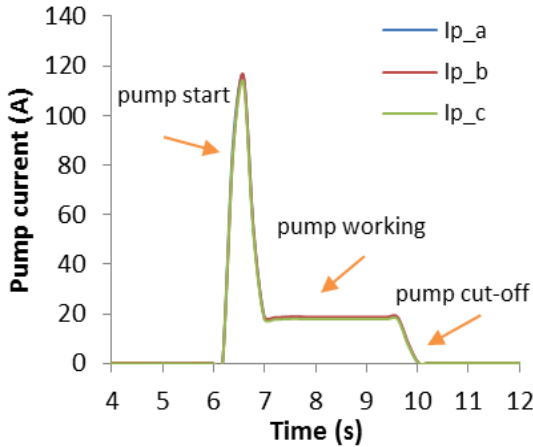
(a) Generator output current



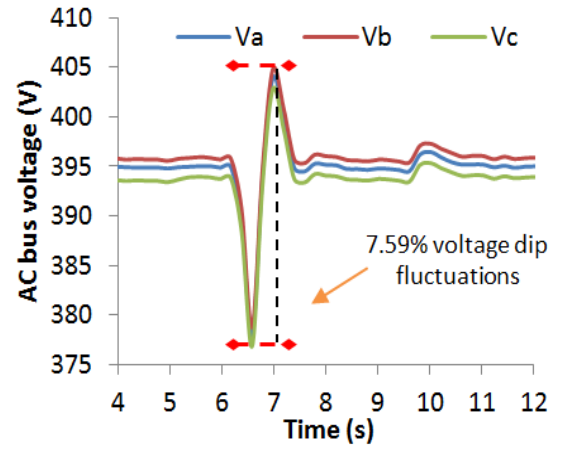
(b) Generator output power

Fig.4 Generator output current and power levels

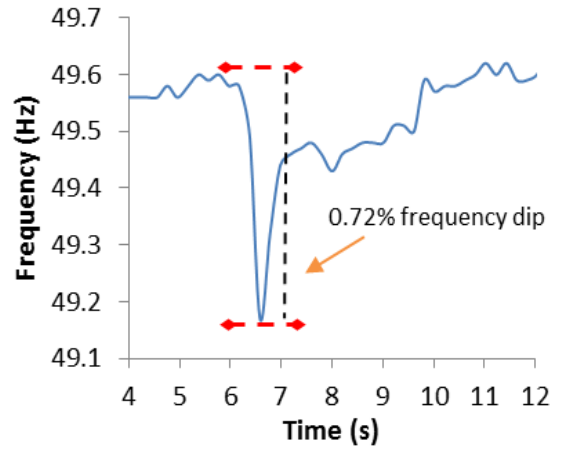
Fig.4 shows the rms value of generator output current with different power levels. It can be observed that the currents were severely increased with 95A or more during each voltage dip, which brought significant risks to the reliability of the shipboard power system. It should be noted that the transient 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.



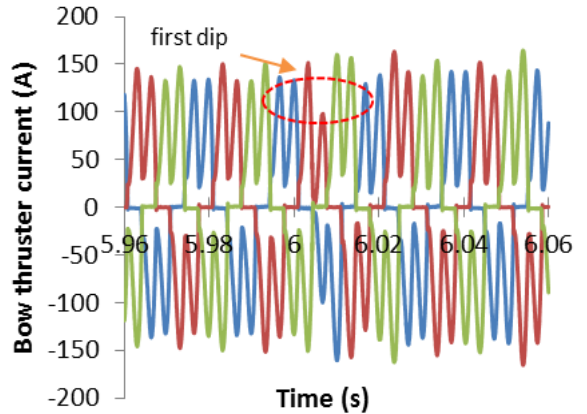
(a) The ballast pump current



(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 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.

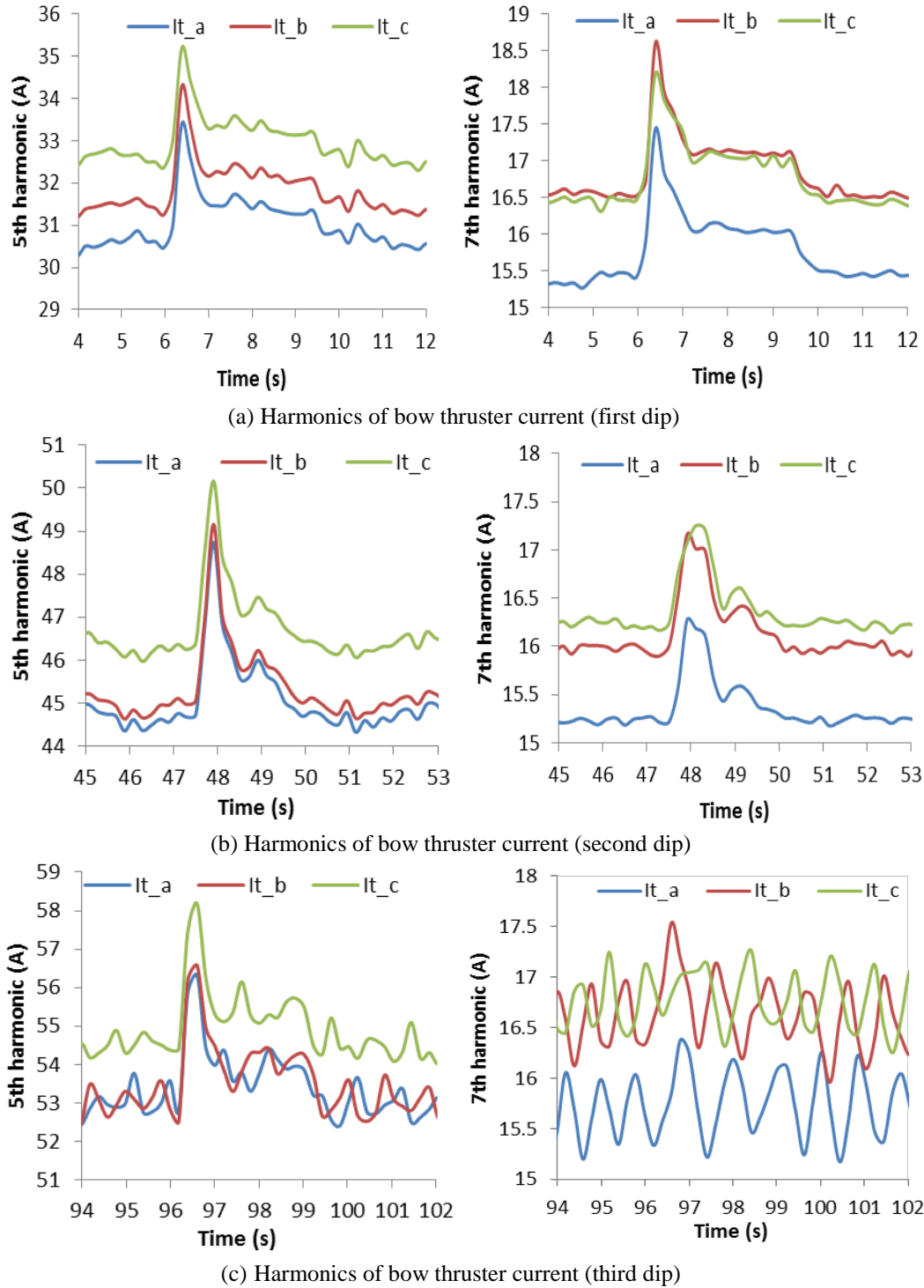


Fig.6 Harmonic impact of the bow thruster current during the voltage dips

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.

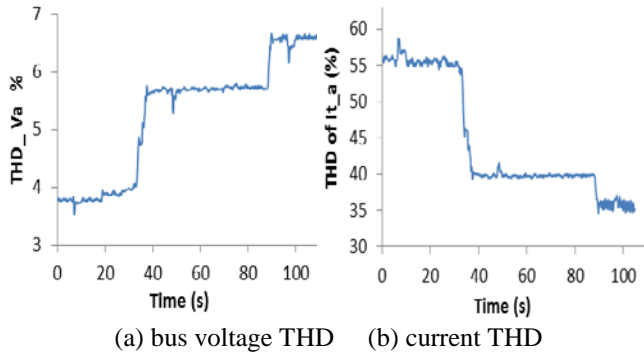


Fig.7 THD of AC bus voltage and bow thruster current

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.

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