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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.

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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 [24]. In addition, there are several 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 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 mm² 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.

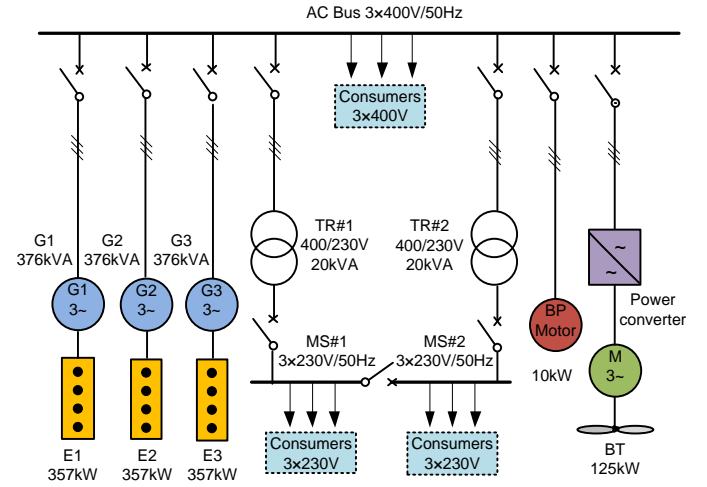


Fig.1. Simplified diagram of the investigated SMG (G1, G2, G3: diesel generators; E1, E2, E3: four-stroke diesel engines; BT: bow thruster; TR: transformer; MS: main switchboard; BP: Ballast Pump motor)

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 can be seen as Fig.2.

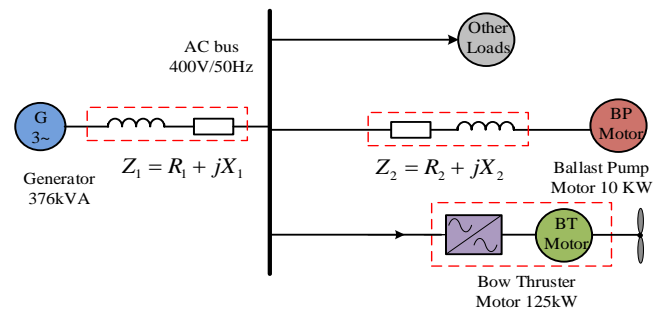


Fig.2. Simplified diagram for analysis of pump motor starting in the SMG

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.

In fact, the generators are usually located in proximity of main switchboard due to the limited space onboard. However, the

thruster motor may be installed far away from the generator plant, leading to a longer cable as shown in Fig.2. Hence, during the thruster motor starting-up process, there is a voltage drop on the line impedance. However, it should be noted that the direct-on-line starting-up for thruster (above 100kW) is not recommended and the thruster is usually started via autotransformer or soft-started via power electronic devices, so that the inrush current phenomenon is fairly reduced during the starting-up [29] (also can be seen in Fig.4 (b)). Therefore, the line impedance of thruster have limited impact for the voltage dips assessment.

On the other hand, some maritime standards require that the voltage drop from each generator to its switchboard should not exceed 1% [14], [19]. For the whole distribution circuits, the combined maximum voltage drop from the ship's service switchboard to any point in the system should not exceed 5% [14]. In addition, most of the medium power motors are located in the proximity of the main switchboard, such as compressors, a number of pumps, fuel purifiers, etc. Their cables are short and the voltage drop over cables for these motors usually does not exceed 2%. Therefore, neglecting the impact of cable can be true for the direct starting motors. The voltage dip magnitude 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 ($X_1 \gg R_1$, $X_2 \gg R_2$).

In order to explicitly present the relationships between the voltage dip and the starting current of the direct-on-line pump motor, the voltage dip in (1) can be rewritten as (2) [27]:

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

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

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

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

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. 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

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

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

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

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)

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

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

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].

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 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 assessment, the evaluation method based on Riemann Summation principle was developed to evaluate the voltage dips and current of the pump motor.

In addition, the evaluation method 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 i th 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

$$I_{gs_mea} = \sqrt{\frac{1}{N_g} \sum_{i=1}^{N_g} (I_{gref} - I_{gs_rms_i})^2} \quad (12)$$

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

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

$$V_{dip_mea} = \sqrt{\frac{1}{M} \sum_{i=1}^M (V_{ref} - V_{dip_rms_i})^2} \quad (13)$$

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 i -th 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 [32].

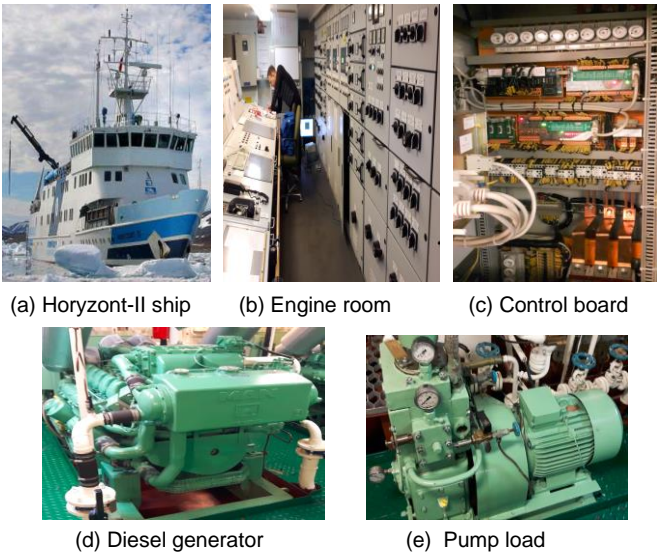


Fig.3 Horyzont-II ship test environment [20], [32].

The ship 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 consumers onboard. The ship and its main parts are shown in Fig.3 and the system parameters can be found in Table I.

TABLE I. SHIP MICROGRID SYSTEM PARAMETERS

Ship microgrid	parameters	Value
Main AC bus voltage	V _{abc} [V _{rms}]	400
	f [Hz]	50
	U _f [%]	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
	cosφ _g	0.8
Ballast pump motor	V _{m-abc} [V _{rms}]	400
	P _m [kW]	10
	cosφ _m	0.85
	k	6
	m	1
Bow thruster load	V _{t-abc} [V _{rms}]	400
	P _t [kW]	125
Fresh water pump load	V _{f-abc} [V _{rms}]	400
	P _f [kW]	11
Heater load	V _{h-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). 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

The detailed SMG behaviors under quasi-balanced voltage conditions can be found in Fig. 4.

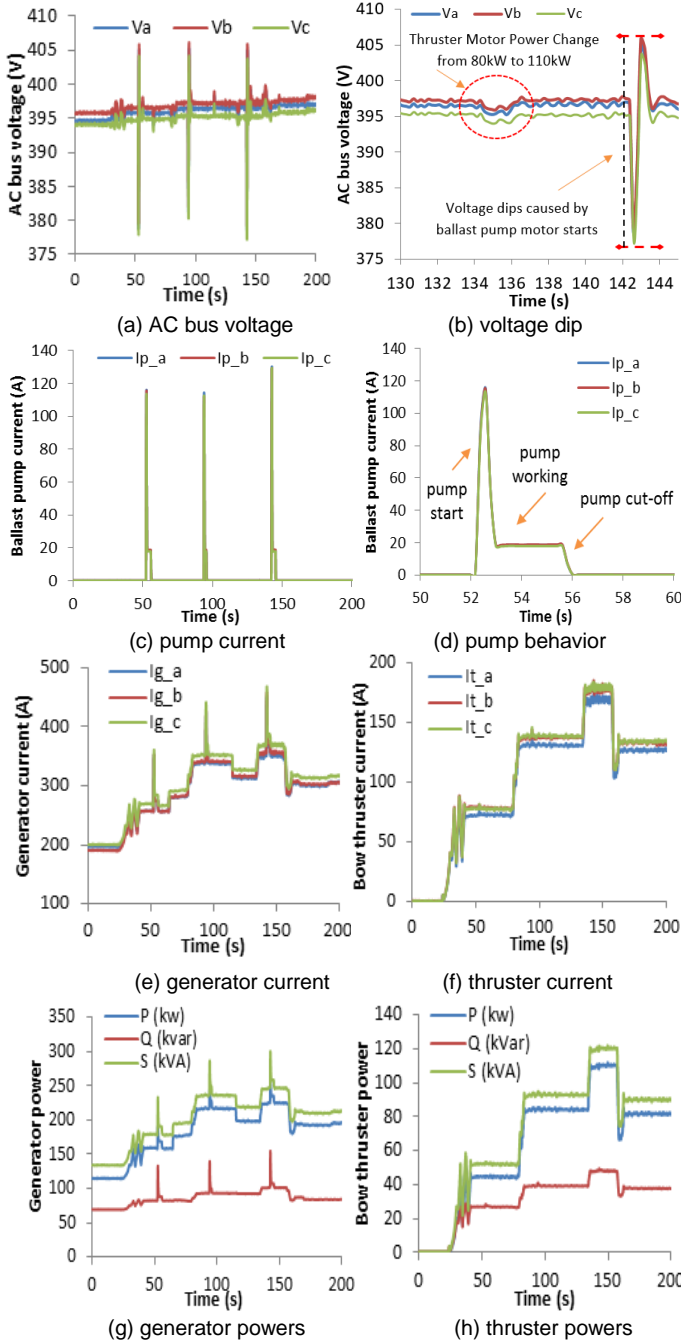


Fig.4. Experimental results of SMG in Case A

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%. However, it should be noted that due to the power electronics

operation, the current ramp changes are limited; see Fig. 4(f), in contrast to the large and abrupt current spikes from the pump, shown Fig. 4(c). In order to illustrate this effect, from Fig. 4(b), the thruster power changed from 80kW to 110kW at $t=134s$, but it has almost negligible impact on the AC bus voltage compared with the ballast pump motor start-up at $t=142s$ (about 5% dip).

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.

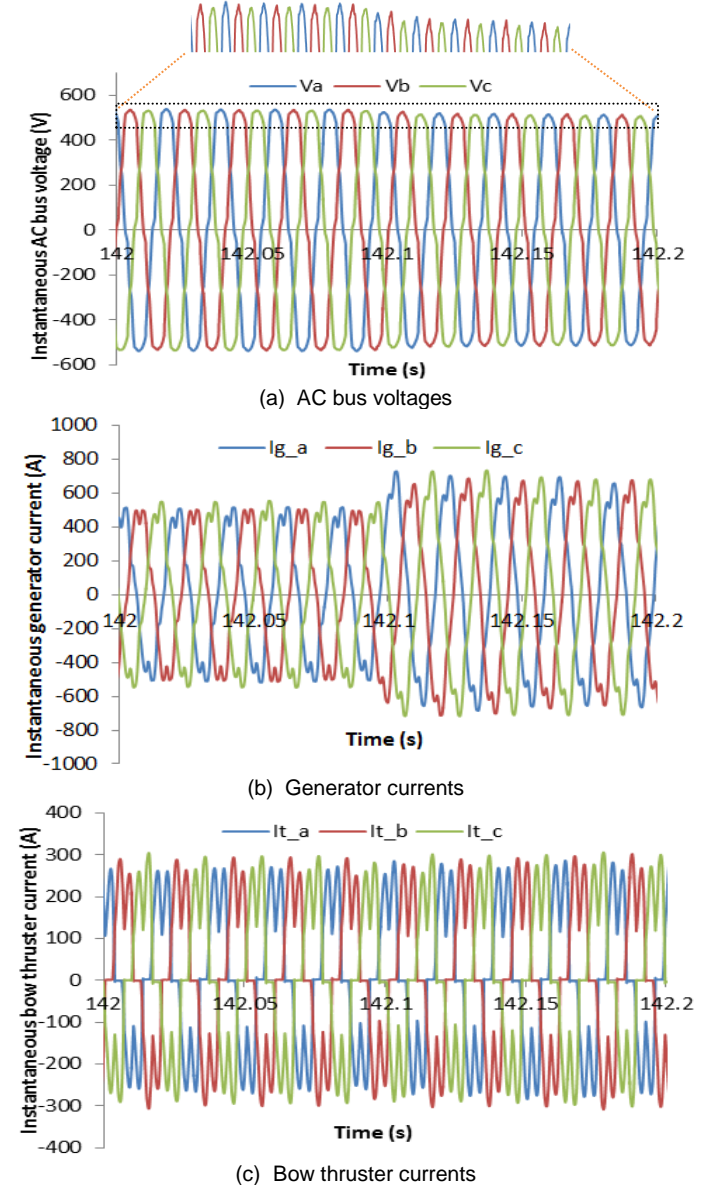


Fig.5. Case A-Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) during voltage dips

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.

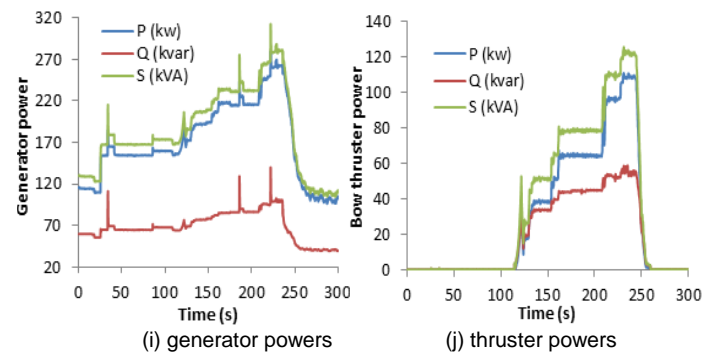
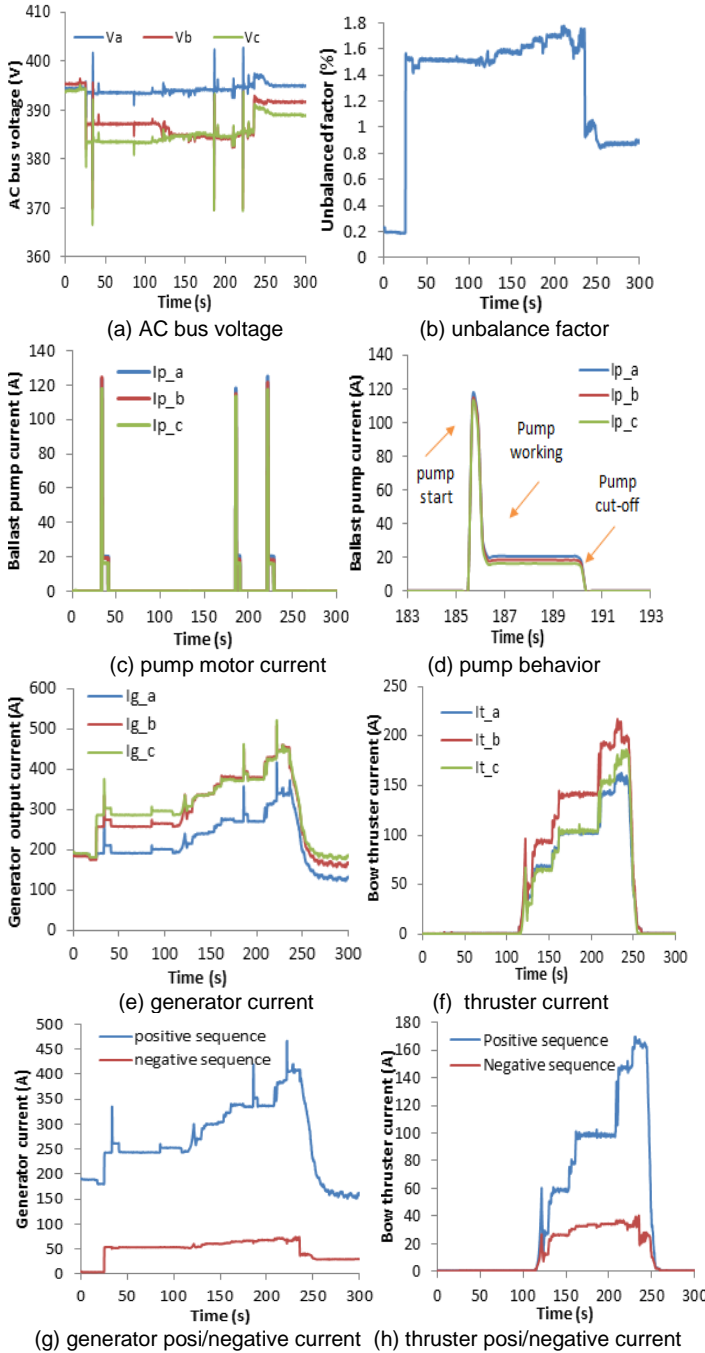
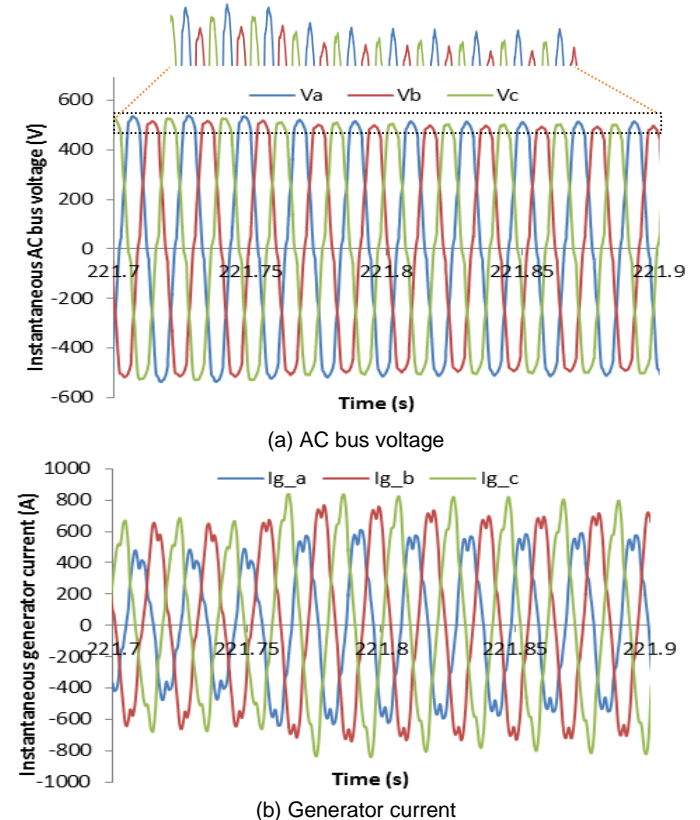


Fig.6. Experimental results of SMG in Case B

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 severely unbalanced. The sudden surge effects of generator currents in respective line currents can reach 120 A, 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).



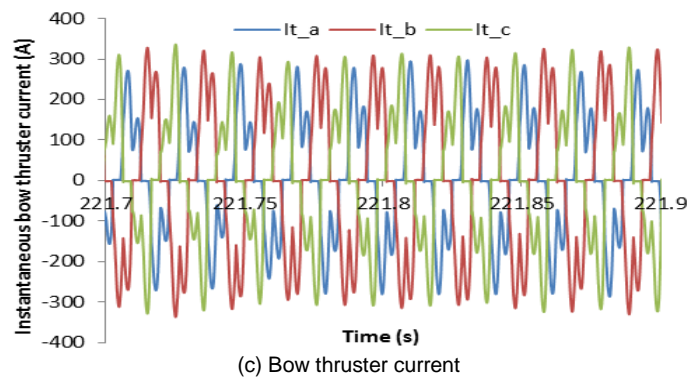


Fig.7. Case B- Instantaneous values of AC bus voltage (a) and currents: generator (b) and bow thruster (c) during unbalanced voltage dips

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 the 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.

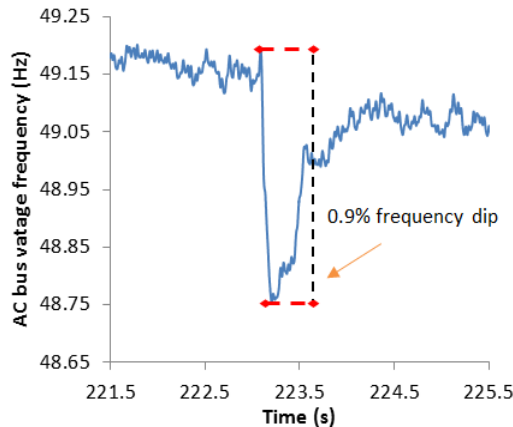


Fig.8. Frequency changes during the unbalanced voltage dip under bow thruster full load conditions

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 $\pm 10\%$ 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].

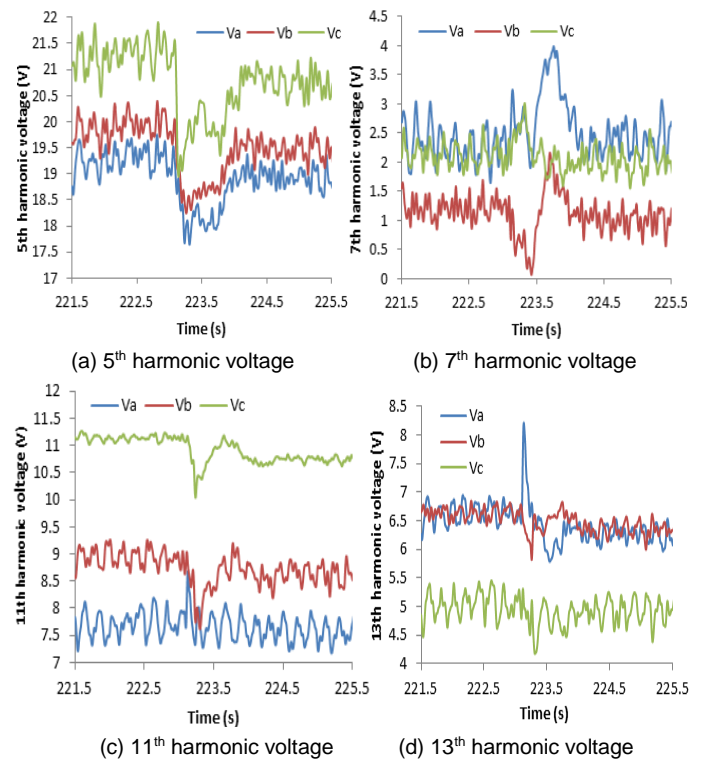


Fig.9. Harmonics of AC bus voltage during the unbalanced voltage dip under bow thruster full load conditions

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 assess harmonic transient performance, harmonic values were determined by zoom-DFT and refreshed every 1 ms, the Kaiser window (parameter $\beta=7.65$) was used to suppress spectrum leakage [5]. The window was dynamically synchronised (every 1 ms) to the momentary duration of 3 fundamental cycles.

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, temporary increase of voltage harmonics can be determined and should be taken into account 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.

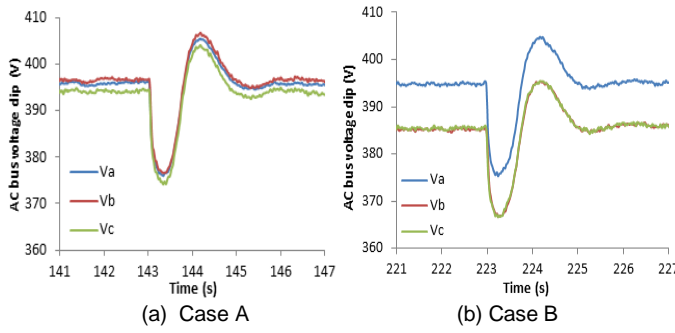


Fig.10. Voltage dips in two cases under full load of bow thruster

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.

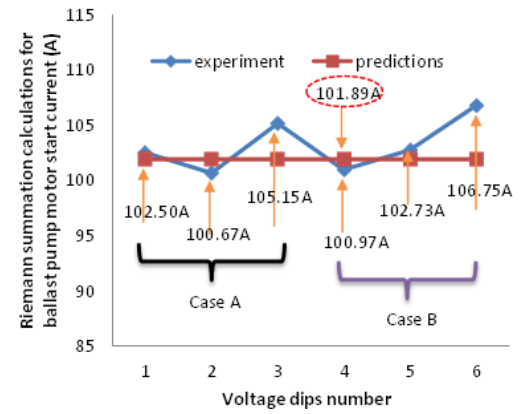
However, the depth of unbalanced voltage dip in Case B is higher reaching 8.35% and the residual voltage is lower than the values in Case A. Therefore, it is indicated that the unbalance affects the AVR operation, which sets only highest line-to-line voltage to rated value especially during the transient 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.

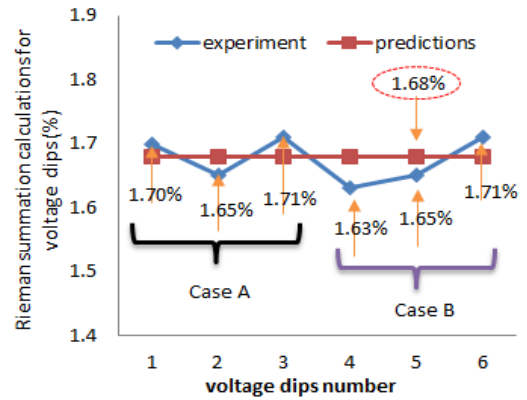
TABLE III. VOLTAGE DIPS AND GENERATOR CURRENT DETERMINED ACCORDING TO THE MEASUREMENTS

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

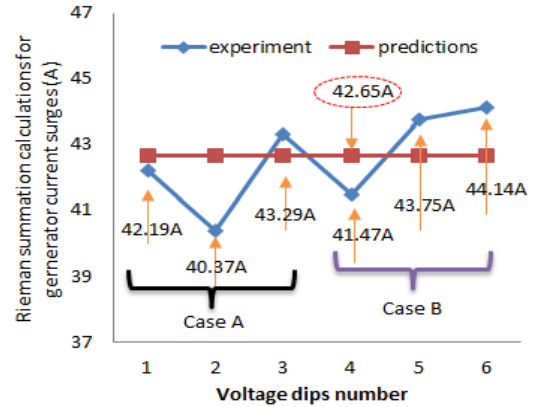
Although the ballast pump motor starting current in the analytical model (built based on the generator transient and sub-transient average impedance) was assumed to be constant during the whole starting period, the practical motor starting current and the voltage dips may not remain constant. For validating 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 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 evaluation 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)-(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 addition, 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 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 motor capacity.

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.

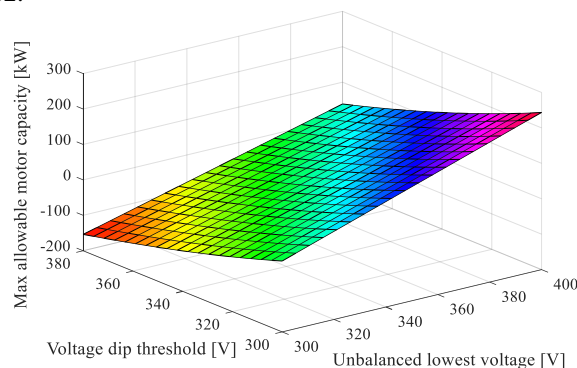


Fig.12. Maximum allowable motor capacity estimation

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 voltage [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 directly 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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