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DC Voltage Level–Based Power Supply Prioritization in Multi–Inverter System: Marine Use–Case

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***Abstract*—This paper introduces multi–inverter system power supply prioritization method based on the system's DC voltage level. The purpose of the functionality is to first utilize the more desirable power source in the inverters' intermediate DC circuit to the fullest, before loading the less desirable one. This is done without any external controllers but rather utilizing existing inverter functionalities in novel manner. First, the basic principle of the functionality is explained and then the operation is demonstrated in marine environment by presenting monitoring data from a ship utilizing said function in 1.7 MW shaft generator system with 2.0 MW thruster connected to the intermediate DC circuit. The functionality enables to use the full benefits of the shaft generator as more fuel efficient power source, prior the rest of the thruster's required power is taken from ship's auxiliary generators. This lowers the overall fuel consumption of the ship and helps to keep the ship's AC grid stable as only the power the shaft generator is not able to provide for the thruster is taken from the AC grid.**

***Index Terms*—shaft generator, thruster, power supply prioritization, multi–inverter system, DC voltage**

NOMENCLATURE

Abbreviations

AC	Alternating Current
CAN bus	Controller Area Network bus
DC	Direct Current
IM	Induction Machine
LNG	Liquefied Natural Gas
ME	Main Engine
MV	Motor Vessel
PM	Permanent Magnet
SG	Shaft Generator

Symbols

D_{Gen}	Generator inverter's DC drooping coefficient
P_{Gen}	Power output of the generator inverter
P_{GenMax}	Maximum longterm power output of the generator inverter
P_{Load}	Power consumption of the load
P_{LoadMax}	Maximum power consumption of the load
PTO	Power Take Out, shaft generator operation mode for generating electrical power
$U_{\text{SystemDCRef}}$	Level where inverters are controlling the system DC voltage to
U_{GenDCRef}	Generator inverter's DC voltage reference
U_{GridUV}	Grid side inverter's undervoltage regulator limit
We	Watts of electrical power

I. INTRODUCTION

Fuel consumption optimization in ships is one of the primary ship owner requirements today. However, at the same time this must be achieved without sacrificing the maneuverability of the ship itself while keeping the AC grid's quality at high level, i.e. to keep the grid voltage & frequency stable and prevent blackouts due to sudden load changes. Therefore, the ship's electrical system must be designed so, that a) the propulsion motors are robust and powerful enough to move the ship safely, as well as b) power producers are selected according to planned load variations and/or be protected against disturbances and suddenly variating large propulsor loads.

Shaft generators have been used in ships for decades to produce power to the ship's electric network as efficiently as possible. This is since the main engine must run anyway for the ship to move and it is certainly powerful enough to provide the electricity generation capacity required by the consumers in the ship even without auxiliary generators. The simplest shaft generator systems are synchronous generators directly connected between the main engine shaft and ship electric grid, as shown in Fig. 1. This design forces the main engine to be constantly running at certain speed or otherwise the electric grid would be affected and possibly even cause blackout. The ship sailing speed is adjusted by propeller pitch angle, which combined with constant main engine running speed, causes the fuel efficiency to be very low outside ship's nominal speed.

Over time technology has been evolving, new novel concepts have been developed, and nowadays it is possible to equip the shaft generators with wide speed range generators together with inverter systems (Fig. 2). This gives the main engine much wider speed window compared to synchronous

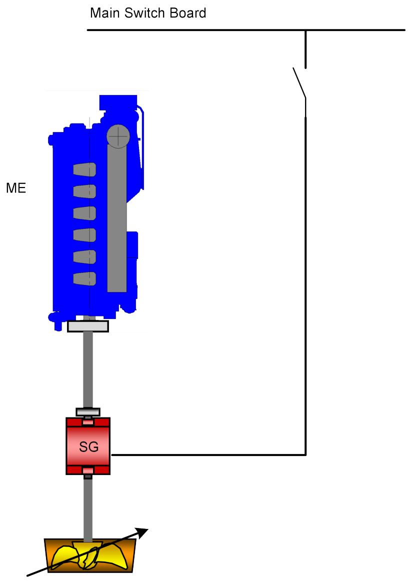

Fig. 1. Directly to AC grid connected shaft generator.

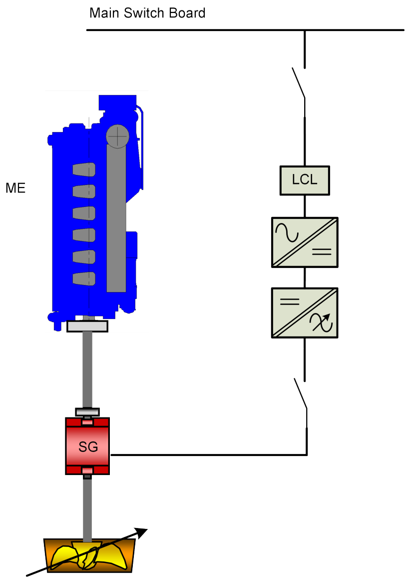

Fig. 2. Shaft generator with inverter system.

generators; thus, the crew can run the main engine at different speeds as required to optimize the fuel consumption e.g. in different sailing speeds. This enables to save massive amount of fuel and the ship grid is kept stable by the inverter system handling the voltage & frequency control on the electric grid.

With inverter system equipped shaft generator, the generator is generating AC power from the main propeller shaft–line rotated by the main engine (ME in Fig. 2 & ME 1 and 2 in Fig. 3) of the ship [1] – [3]. AC power is then converted to DC by generator side inverter and then back to AC by grid side inverter which will then feed AC power to the ship grid. This kind of inverter system is covered by [3] in relation with IM–based generator, here PM–based shaft generator is used. The inverter system enables the main engine to run constantly at optimal speeds in terms of fuel consumption without compromising the AC network power quality.

Large motor loads, like bow and/or stern thrusters, bring their own challenges in form of their connection methods to the ship grid and quick load changes induced on them. For example, one traditional way to connect thrusters directly to the ship grid is to use auto–transformer systems. While a simple and straightforward solution, it causes quite big concerns on the stability of the grid. The thrusters' rated powers can be in megawatts and the amount of magnetization current they and the auto–transformers consume during the connection is extensive. This directly causes disturbances on the grid voltage & frequency proportional to the magnetization current and the size and type of the running generators. LNG generators for example are not capable of reacting as fast to sudden load changes as traditional diesel generators. Soft–starters and frequency converters can be used to minimize said disturbances but they have other drawbacks, like harmonic distortions induced on the ship grid.

The ship AC grid has traditionally been the only electric dristribution grid on the ship, and connecting all power consumers and producers there has been the only way to go. However, today with the inverter systems for the shaft generators and other DC power distribution topologies, like in [4], have been introduced. The stability of the ship AC grid can be protected by locating the large loads, like thrusters, e.g. in the intermediate DC circuit between the shaft generator system's inverters (Fig. 3), instead of the ship AC grid, and this paper covers the power supply prioritization in such use–case.

Figure 3 shows principle single line diagram of MV Tasmanian Achiever II and her sister MV Victorian Reliance II shaft generator systems and main switchboards. There the thrusters are connected to the intermediate DC circuits between the inverters of the shaft generator systems. This way the power for the thrusters can be fed directly from the shaft generators, without the AC network being disturbed at all. Here the challenge is that, due to practical reasons, the thruster motors are actually larger than the shaft generators themselves, but the system must be as fuel efficient as possible. The system must be built so that DC supply prioritization maximizes the power production from the shaft generators first, before the rest of the needed power is taken from the auxiliary generators located in the ship AC grid.

A. *Research Questions*

This paper focuses on the following research questions:

- What if the most fuel efficient power generating method in the DC circuit is not cost effective, or is otherwise unpractical, to be as large as the maximum load on the DC circuit?
- How to reliably, and without active external controller, use the full benefits of the fuel efficient power source, while taking only the power which is absolutely needed from the less efficient source?

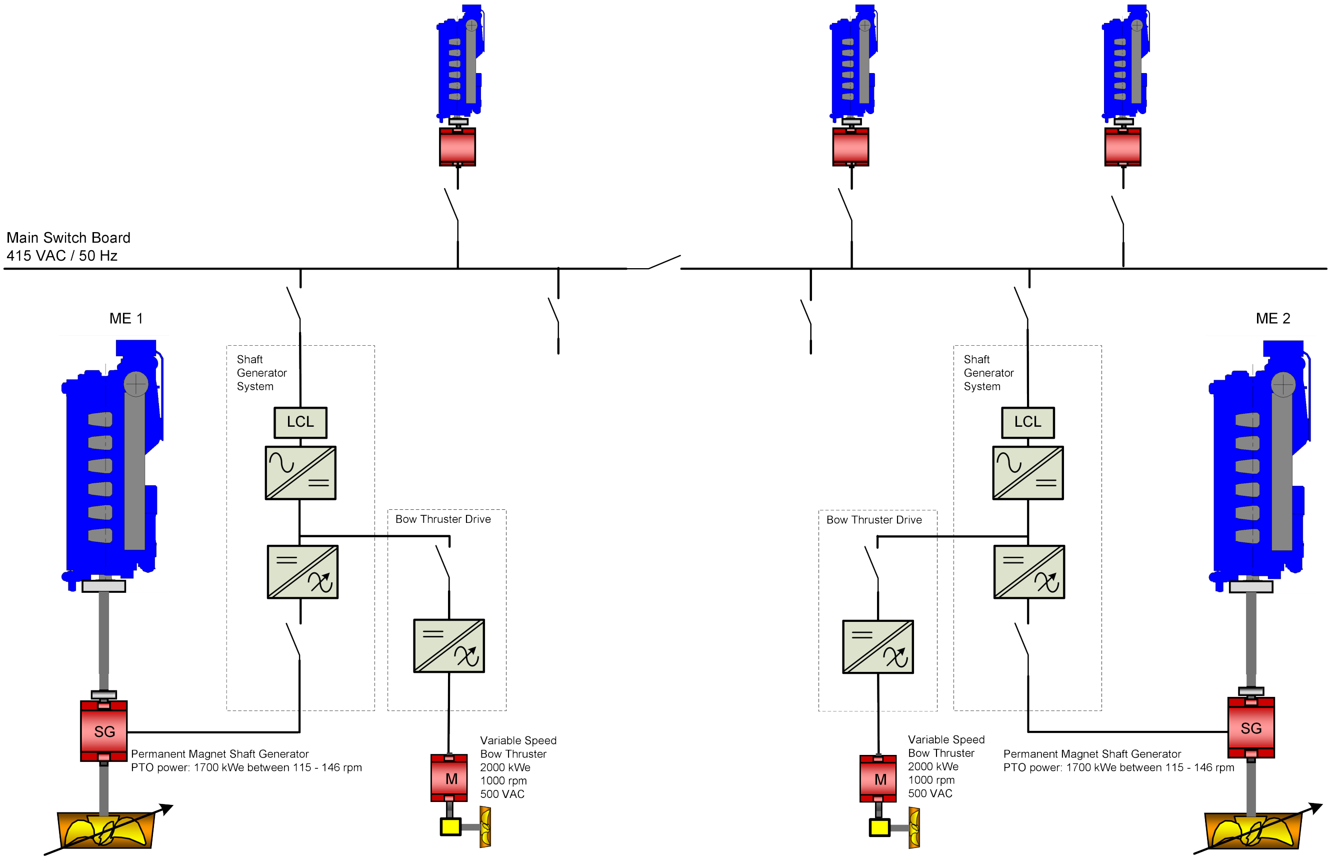

Fig. 3. Principal single line diagram of the power distribution system in MV Tasmanian Achiever II and MV Victorian Reliance II.

Finding answers to these research questions gives the ship designers more freedom in designing the ship electric system. The solution would give simple and elegant option to include large consumers in the DC circuit, while still keeping the main power supply reasonably dimensioned and run the system easily as fuel efficiently as possible.

II. OPERATIONAL PRINCIPLE

This paper introduces DC voltage level–based power supply prioritization method in multi–inverter system, where a load with maximum power of P_{LoadMax} is connected to the intermediate DC circuit between the generator and grid side inverters, while generator side inverter's maximum power is P_{GenMax} where $P_{\text{LoadMax}} > P_{\text{GenNom}}$. Grid side inverter is assumed to be bi–directional i.e. current can flow to and from the AC network it is connected to.

The prioritization is based on existing built–in inverter functionalities, that are used in novel manner. This way the functionality does not require any external controllers that would add delays to the system and increase the possibility of

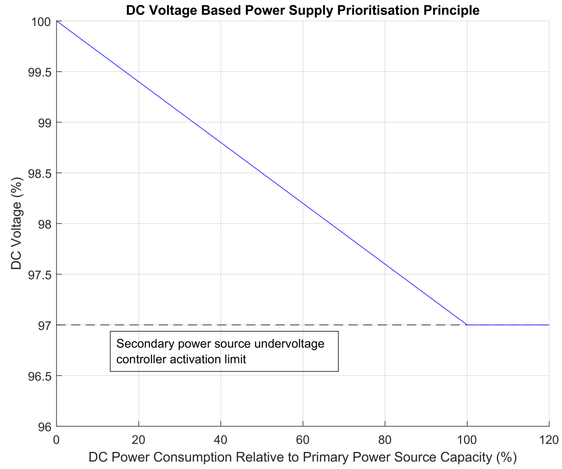

Fig. 4. Graphical representation of the principle of the DC power source prioritization functionality, with 3% DC drooping in the primary power source.

$$U_{\text{SystemDCRef}} = \begin{cases} U_{\text{GenDCRef}}\left(1 - D_{\text{Gen}}\frac{P_{\text{Gen}}}{P_{\text{GenMax}}}\right), & \text{for } P_{\text{Load}} < P_{\text{GenMax}} \\ U_{\text{GridUV}} = U_{\text{GenDCRef}}\left(1 - D_{\text{Gen}}\right), & \text{for } P_{\text{Load}} \geq P_{\text{GenMax}} \end{cases} \qquad (1)$$

errors. To this end, there are two main factors in the operation (see also Fig. 4 and equation (1)):

1) The primary DC power source (shaft generator side inverter in Fig. 3) is initially responsible on maintaining the voltage in the DC circuit with DC drooping active to adjust the DC voltage level according to the load.
2) The secondary power source's (ship AC grid side inverter in Fig. 3) undervoltage controller activation limit is set to the level where the primary power source is at full power.

This enables the DC voltage level to be used as form of communication tool between the inverters, where the secondary power source knows from the DC voltage level when to start feeding power to the DC circuit. The inverter's under voltage controller then manages how much power needs to be injected to the DC circuit from the ship's AC grid to keep DC voltage stable without separate input from external controller.

III. FUNCTION IN OPERATION

This described new functionality is implemented in shaft generator systems for MV Tasmanian Achiever II and MV Victorian Reliance II sailing mainly in Australia. Both ships are equipped with two 1.7 MW shaft generator systems with one 2.0 MW thruster located in the intermediate DC circuits of both shaft generator inverter systems as shown in Fig. 3. Data on the operation of the functionality were gathered during November 2019 from MV Victorian Reliance II.

A. Equipment Used

The combined shaft generator and thruster inverter system is based on liquid cooled VACON NX inverters (Danfoss) and the shaft generator itself is type PMM1000 permanent magnet generator (The Switch). The generator's basic information can be found in Table I.

TABLE I
SHAFT GENERATOR BASIC INFORMATION

Name	Value
Nominal Voltage	500 V
Nominal Frequency	23 Hz
Nominal Speed	115 rpm
Nominal Current	2300 A

B. Data Gathering

Data were gathered from the inverters with laptops using inverter service busses. Data from shaft the generator side and ship AC grid side inverters were gathered concurrently with the same laptop utilizing CAN bus type service bus with 7 ms sampling interval and the data from the thruster drive were gathered using serial communication and 50 ms sampling interval. The data gathering setup with different sampling rates, communication busses and separate laptops was due to practical limitations. The thruster inverter control unit did not have space for the option board for the CAN bus type service bus which would have enabled concurrent data gathering from all inverters with single computer.

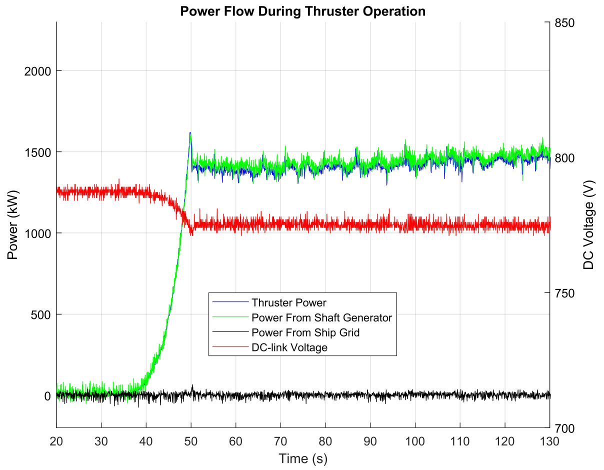

Fig. 5. Monitoring data from normal thruster use.

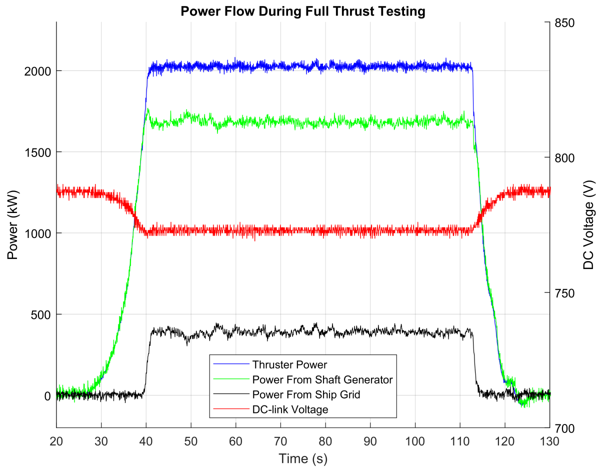

Fig. 6. Monitoring data from the first thruster full power test.

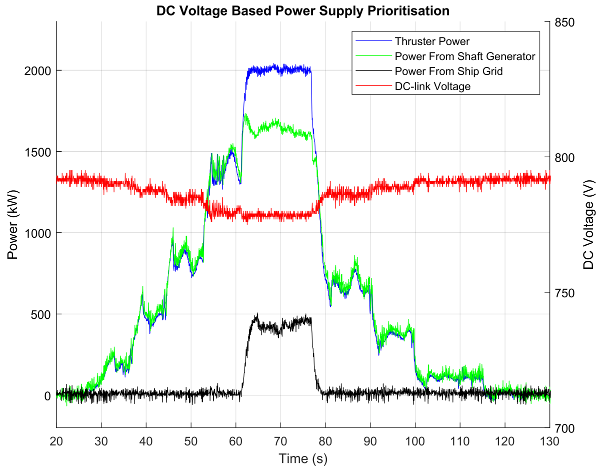

Fig. 7. Monitoring data from the second thruster full power test.

The data comprised of the loads of the inverters and the measured DC circuit voltages during sailing from Melbourne, Australia, to Burnie, Australia, and again back to Melbourne. The data was combined and synchronized by time in Matlab during the analysis by utilizing the recorded DC circuit voltages as reference.

C. Power Flow During Normal Ship Operation

Figure 5 shows shaft generator system's power flow during normal ship operation, in which the usage naturally depends heavily on the operator and the wind conditions outside the ship. According to the data the power consumption of the thruster is roughly between 1.3 – 1.6 MW in relatively calm sea. As 1.7 MW are prioritized to come from the shaft generator, in this situation auxiliary generators do not have any load increase due to thruster usage at all.

D. Power Flow During Full Thrust Testing

During full thrust testing in Fig. 6 – 8, the effect of the DC voltage–based power supply prioritization can be clearly seen when power from the ship grid stays at zero until the thruster load reaches the specified 1.7 MW. In Fig. 6 and 7 it can also be seen that when thruster load is decreasing, the power from the ship AC grid decreases back to zero, before power from the shaft generator starts to decrease.

Figure 7 shows full thrust testing of the ship's second thruster in little bit rougher waters than in the first test (Fig. 6). The DC circuit voltage where the grid side inverter starts feeding power to the DC circuit is little bit different, but operation–wise the system behaves the same way as the first thruster. The grid side inverter stats feeding power when the generator inverter power reaches nominal and decreases the feed before the generator inverter as the thruster load decreases.

Figure 8 shows the different stages of the operation in more detail from the first thruster full power test. At point A the thruster speed reference ramp–up is started and load starts to increase. At point B the load has reached the generator inverter's nominal power and feed from the AC grid starts to increase. At point C thruster is at its maximum power and all required power production has been transferred to grid side inverter. The generator inverter was loaded little bit above nominal momentarily, while the grid side inverter's undervoltage controller was ramping the power production up and thruster power consumption was increasing faster than it.

As for the stability of the ship AC grid during thruster full power loading, Fig. 9 shows AC voltage and frequency during the first full thrust test. The voltage, in red, has no visible fluctuations in it when thruster load is changing. Frequency, in cyan, dips < 0.2 Hz as the thruster load is increased rapidly. If the 2.0 MW thruster would have been located in the AC grid, the disturbance would have been considerably larger and it would have been noticed e.g. by flickering lights.

IV. DISCUSSION

This paper introduced DC voltage–based power supply prioritization in multi–inverter system, based on DC drooping and undervoltage controller of primary and secondary power sources respectively. Using these inverters' built–in functionalities in a novel manner enabled the DC circuit voltage to be used as form of communication tool between the inverters, which was used to indicate to the secondary power source when to start feeding power to the system. The functionality was shown in operation by presenting inverter monitoring data from a ship with 1.7 MW shaft generator system combined with 2.0 MW thruster in its DC circuit. The data was gathered during normal operation as well as full thrust testing.

During normal ship operation, the thruster load did not reach the level where the primary power source, i.e. the shaft

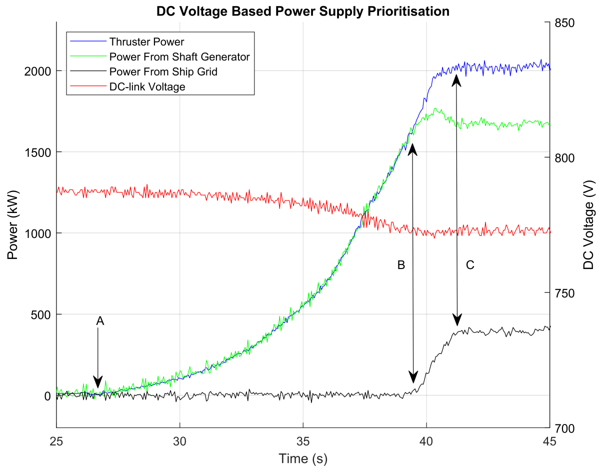

Fig. 8. More detailed graph from the first thruster full power testing, where A: speed reference starts increasing; B: DC voltage reaches the grid side inverter's undervoltage controller limit; C: thruster is at full power and power production between the generator and grid side inverters has been balanced.

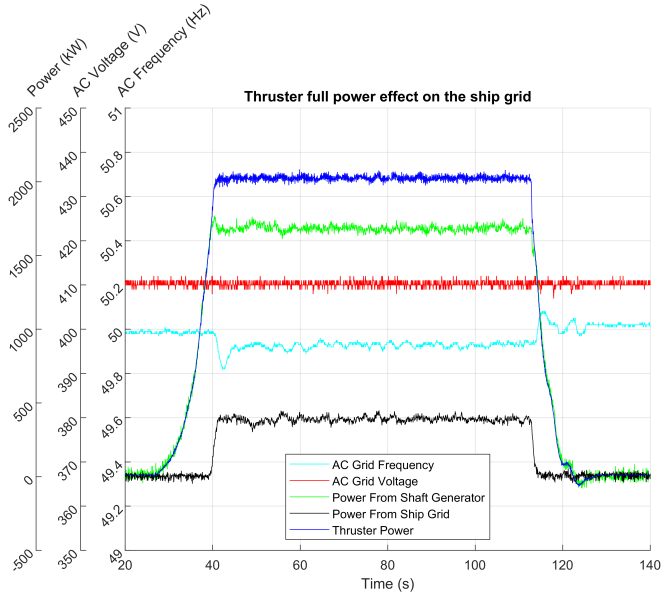

Fig. 9. Thruster full power load effect on the ship AC grid voltage & frequency.

generator, would have been at full power. From this follows that the secondary power sources, i.e. auxiliary generators in ship AC grid, were not used at all to power the thruster. This enabled to take full benefits of the shaft generator and as the AC grid was unaffected by the thruster usage there were also no disturbances on the hotel grid.

Full thrust testing showed the thruster load increasing to full 2.0 MW and only when the shaft generator load reached its specified maximum value of 1.7 MW, the grid side inverter started to compensate and take on the rest of the required power production. When thruster load was decreased, first the grid side inverter was fully unloaded before the shaft generator, thus showing the functionality working also in reverse.

The effects on the ship grid voltage and frequency were shown to be minimal during full power testing. This is as instead of the full 2.0 MW thruster load, only 0.3 MW was taken from ship AC grid.

Referring to in Section I.A, the research questions were how to fully utilize thruster in the shaft generator system intermediate DC circuit, while it was not practical for the shaft generator itself to be fully dimensioned to cover the power requirements alone. The power supply prioritization for loading the shaft generator first to full and only then feed the rest of the power from auxiliary generators was also to be done in system control–wise as simply as possible, i.e. without external controllers outside the inverters themselves controlling the power flows from different power sources. These points give possibility for the ship itself to be fuel and cost effective, while having the required maneuverability to safely operate the ship and the system to be as simple as possible to minimize the possibility of errors in the operation.

V. CONCLUSIONS

The solution gives good and practical option for utilizing the shaft generator to the fullest, prior to utilizing the less fuel efficient power sources. This lowers the ship's overall fuel consumption and shows the shaft generator does not necessarily have to be dimensioned to alone cover the full power of the loads on the DC circuit, while still maintaining control–wise simple system. The solution's implementation involves no external controllers but utilizes the DC circuit voltage as form of communication between the power sources, which lowers the complexity of the control system. After the tests on–board MV Victorian Reliance II, it can be said that the research questions have been fully satisfied.

As this method utilizes fundamental functionalities built–in to the inverters themselves, the implementation is fully transferable to other use–cases outside marine industry and shaft generators. Next step in our power supply prioritization / management related research is to look in to the possibilities that energy storages bring to multi–inverter systems and how to utilize them dynamically as power sources and consumers, i.e. prosumers, with other dedicated power supplies and loads connected parallel in to the same DC circuit.

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