Coordinated Power Control for Flexible and Sustainable Operation of DC microgrids in Yacht Marinas

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***Abstract*—The innovation towards sustainable solutions is involving all the industrial sectors. In this context, the marine world is going through a great transition. The integration of renewable energy sources and the adoption of flexible power systems, like DC microgrids, are some powerful solutions to develop advanced and sustainable marine grids. These concepts are not only adopted in the onboard shipboard distribution, but also when conceiving supplying platforms and marinas. In this paper a flexible DC microgrid is proposed for a yacht-marina, and a coordinated power control is presented. The ships at berth, renewable sources and energy storages are all connected through multiple power converters. A centralized controller is demanded in managing sources and loads. By properly coordinating the photovoltaic modules, landed/embarked storage and power flows to/from the main grid, the attained goal is the sustainable operation of the yacht-marina DC microgrid.**

***Keywords*—DC, microgrid, PV, PMS, power, marina, storage.**

I. INTRODUCTION

Nowadays, the environmental concerns are a key issue in the global interests. The efforts of the scientific and industrial world are addressed to develop innovative solutions as well as to exploit the yet existing ones, in order to contribute to a sustainable growth and to the ecological transition. The transportation sector is one of the more impacting in terms of energy consumption and greenhouse gasses emissions [1]. Indeed, in recent years we are witnessing a great development of electric transportation, both in terrestrial and marine applications. In the maritime world, the electrification embraces several aspects, from the onboard power distribution [2]-[4] to the cold-ironing [5]-[7] concept. By foreseeing an increasing number of electric ships, the newest marinas infrastructure has to adapt to this great change, both on the recreational and commercial side [8]. To guarantee full environmental benefits, there is the need to exploit green energy coming from Renewable Energy Sources (RESs). Nonetheless, sources like PV plants do not guarantee constant and uninterrupted power supply, thus they need to be assisted by proper energy storage systems [9]. In this way, when the production exceeds the demand, the energy can be stored, and when there is a lack of production, the storage can fulfill the power request. A DC microgrid [10]-[12] is one of the most promising solutions to be employed both in onboard distributions, ports as well as marinas. This kind of power system is capable to easily combine RESs, storages and hybrid-electric ships inside a marina. All these elements are to be properly managed to achieve goals such as optimization of the produced and consumed power or economic benefits (by selling the eventual excess of power). For such a reason, the coordination of the control tasks is of paramount importance and adequate control strategies are to be developed [13].

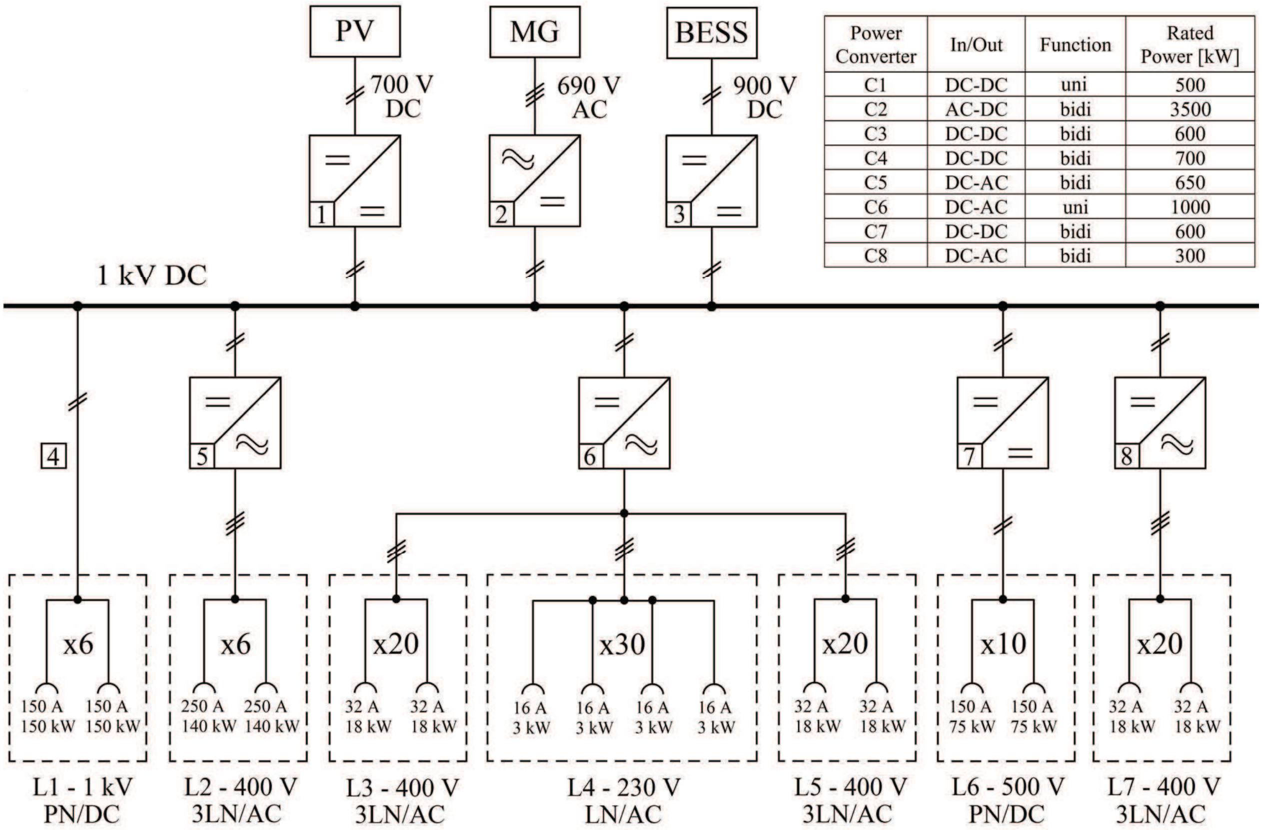
In this paper, a DC microgrid for a yacht marina is proposed and its control strategy described. The power system includes PV modules, Battery Energy Storage Systems (BESSs) and several electrical connections available for the docked ships. The connection to main grid is also present, this guarantees the power supply also if the green energy sources are not available and at the same time allows to sell energy to the terrestrial network. The flexible and sustainable operation of the microgrid is managed by a Power Management System (PMS), that coordinates the power flowing through the different power electronics converters. The controlled DC microgrid is emulated by a real-time HIL platform and the results of the nigh-day transition management are discussed.

II. DC MICROGRID IN YACHT MARINA

In this Section, a DC microgrid is envisaged to optimize the yacht-marina operation, thus increasing its sustainability in accordance to the green deal scenario. The large employment of controlled power converters is not only able to increase the flexibility in microgrid operation. At the same time, the smart management of the marina can enable the profitable sale of PV energy to the main electrical distribution.

A. Green marina for sustainability

The marinas are of paramount importance for territories in which the blue economy represents a fundamental source of income. In particular, they are crucial to support the development of tourism and recreational activities; consequently, their number has significantly increased in the last years [14]. Due to all the services they must be able to provide to customers and boat owners, marinas are great energy consumers. Furthermore, pleasure crafts have been undergoing a deep revolution as regards their propulsion and generation systems: over recent years, electrification has been the absolute trend also for marine applications [15]-[16]. As a result, the energy need of marinas has increased and new sources are to be researched and integrated. In addition, the environmental aspect is also fundamental in this analysis: green energy production is one of the key factors of Industry 4.0, as well as one of the most challenging achievements [17]. Sustainability has become a crucial driver for economy and it is currently able to influence customers' attention and choices. As far as marinas are concerned, the possibility of



Power Converter	In/Out	Function	Rated Power [kW]
C1	DC-DC	uni	500
C2	AC-DC	bidi	3500
C3	DC-DC	bidi	600
C4	DC-DC	bidi	700
C5	DC-AC	bidi	650
C6	DC-AC	uni	1000
C7	DC-DC	bidi	600
C8	DC-AC	bidi	300

Fig. 1. The controlled 1 kV-DC microgrid of green marina.

implementing technologies for low-impact energy production by exploiting renewable sources must represent the ultimate goal [18]. Being able not only to behave as load, but also to provide energy, smart-marinas would economically benefit by both lowering berthing costs and providing additional services. In such a way, the system comprising marinas as energy hub and electric vessels would assess itself into the green logistics trend [19], with advantages in terms of both environmental sustainability and return of image. From an economic point of view the potential market is enormous. The global nautical fleet has more than 33 million of pleasure crafts and only 13% is moored in equipped marinas [20].

B. *Hosted Vessels*

The electrification of transportation has also reached the motor boat sector. Indeed, several are the important advantaged. The electric navigation is silent, clean, comfortable and relaxing. There are no vibrations, there are no harmful emissions. The world market for electric powered boats in 2020 reached $ 4.5 billion. Electric boat market is a fast growing industry having a compound annual growth rate (CAGR 2021-2026) estimated at around + 12.65%. The Covid-19 pandemic hampered the growth of electric boat and ship market owing to shut down of manufacturing facilities and trade restrictions imposed worldwide [21]. However, with relaxations allowed by governments to improve economic conditions, the market is expected to revive in the next future. There are already over 100 manufacturers of electric boats and pleasure ships. The market for hybrid and pure electric boats and ships will rise rapidly to over $20 billion worldwide in 2027 for non-military versions. Recreational boats is the largest and fastest growing electric marine market in sales number, followed by underwater leisure and autonomous underwater vehicles. Hybrid and pure electric marine vessels (EVs) with electric propulsion (some or all of the time) have been around for over 100 years. The electric boat Lady Lena dates from 1890. Currently, the market for electric and hybrid watercraft is still significantly low with about 1-2% of the addressable market. All-electric propulsion systems consist of an electric motor being powered by a battery pack. Hybrid electric systems consist of a fueled engine and energy storage used to propel the craft sometimes (parallel hybrid) or to charge the battery (series hybrid). The choice of a hybrid-electric propulsion configuration or the other is not linked to the overall size of the boat/ship. What changes, according to the size of the boat/ship, is the capacity of the storage system on board. In particular, the Table I shows the average capacity of the battery packs according to the length overall for traditional pleasure craft, while Table II shows the same values for hybrid-electric propulsion boats. The future smart marina must not only ensure that the battery packs of traditional boats are kept charged, but must also provide adequate energy for charging those with hybrid-electric propulsion. The number of the latter is constantly growing, especially in the "up to 10 m" segment and in the "over 60 m" segment.

TABLE I. BATTERY PACK CAPACITY FOR TRADITIONAL PLEASURE CRAFTS.

Type of pleasure vessel	**Approximate battery packs capacity [kWh]**
Up to 10 m	5.0
From 10.01 m to 12.00	8.0
From 12.01 m to 18.00	12.00
From 18.01 m to 24.00	25.00
From 24.01 m to 35.00	75.00

TABLE II. BATTERY PACK CAPACITY FOR HYBRID-ELECTRIC PLEASURE CRAFTS.

Type of pleasure vessel	Approximate battery packs capacity [kWh]
Up to 10 m	15.0
From 10.01 m to 12.00	21.0
From 12.01 m to 18.00	42.00
From 18.01 m to 24.00	350.00
From 24.01 m to 35.00	700.00
From 35.01 m to 60.00	1500.00
Over 60.00 m	3000.00

C. *Controlled power system*

The DC microgrid in Fig. 1 is capable of enabling the advanced power management of the green marina. This smart strategy can indeed promote the exploitation of PV source and the bidirectional power flow from/to the berthed vessels. Both the outcomes are well-received when fostering the marina sustainability and the sale of green energy to the external distribution system. In the 1kV-DC grid of the marina, eight power converters are installed to ensure the power balancing among sources, loads and storage. The converters data are defined in the table included in Fig. 1. Three converters (i.e. C1, C2 and C3) are referred to the upper part of power scheme. The C1 is a unidirectional DC-DC boost converter to interface the PV field (i.e. 50m x 50m is the covered surface) to the DC bus. Conversely, the C2 is a bidirectional AFE rectifier to alternatively supply the harbored vessels from outside or to address the marina power surplus to the 10/0.69 kV-main grid. The C3 is the DC-DC converter responsible for managing the Battery Energy Storage System (BESS), thus its charge/discharge in accordance to the 500 kWh capacity. In the lower part of Fig. 1, five converters are defined once hypothesized their power sizing. Each rated power is found by combining the total power of jetties' electrical sockets (i.e. dashed boxes) and an utilization-contemporaneity factor of about 0.4. Unlike the other lower converters, the C4 is supposed to be installed on the moored vessel. It is a bidirectional DC-DC converter to interface the mega-yachts having 1 kV-DC onboard distribution. Also the C5 is a bidirectional module, where AC is the stage towards the shipboard power system. On the other hand, the C6 is a unidirectional DC-AC converter to charge both 3-phases and single-phase sockets. Given the complexity in managing a bidirectional power flow from/to an entire distribution, now the unidirectional interface (i.e. from grid to ship) is preferred. Finally, both C7 and C8 works to transmit power in both directions. The first one is aimed at working with DC ships, while the second again is an AFE inverter from/to AC vessels. All the data on the power grid are expressed in Fig. 1, while the x multiplied by a number is used to replicate the same jetty for a certain number of time in the marina installation. In regards to the bidirectional converters, each socket on the 1 kV DC mega-yacht is related to 0.5-1 MWh of battery. Same order of capacity, also for each socket supplied by C5. Smaller the capacity when talking about the C7, where 0.25-0.5 MWh is the storage on each socket. Only 40 kWh is finally the capacity to be related to each socket fed by C8 converter.

D. *Advanced control strategy for flexibility*

The operation of the green marina in Fig. 1 is managed by a centralized [22] Power Management System (PMS) that receives all the signals from the field components and coordinates the power flow to/from each converter. The PMS optimizes the power production and consumption inside the microgrid, guaranteeing economic benefits to the ship owners and proper exploitation of the green energy as well. To this aim, the PMS sends the change in control signal and power references to the different converters. In this paper the focus is on how to manage the night-day transition by using the C2 grid converter and the C3 BESS converter, to balance the available power. Both converters can be operated in power or DC bus voltage control mode. If the power control mode is selected the central controller sends the power reference to the converter, if the bus voltage control is selected instead, the PMS sends the voltage reference and the eventual droop signal. If both the converters are in voltage control mode, the power sharing is managed by changing the droop signal. Smooth transitions between the two can be achieved by the adoption of a dynamic droop [23]-[24]. The BESS converter is always demanded of the bus voltage control, indeed the batteries work to absorb the voltage fluctuations on the DC feeder [25] and to assist the microgrid operations during transitions from one operating condition to another. Being the bus voltage always regulated, the other converters can be operated in power control mode, and their power reference is increased with a ramp-rate of 100 kW/s. In the test described in the next Section, the night to day transition of the green marina is presented. Before the sun starts rising, the bus voltage is controlled in droop mode by the C2 and C3 converters, the PV converter is disconnected, and the ships converters are all power controlled. Some ships are supplying the bus and other ones are being charged instead. The amount of generating power that is lacking is fully supplied by the grid. This option is ensured by properly setting the droop gain ratio between C2 and C3. By foreseeing the oncoming sunrise, the droop ratio between the voltage-controlled converters is changed dynamically, to smoothly switch the power supply from the grid to the batteries. At this point the sun is up and the PV converter is connected. Its power output exceeds the loads needs, therefore this excess of power is automatically delivered to the batteries. When these storages are sufficiently charged, the grid converter is switched to power control mode and the excess of power is sent to the terrestrial grid.

III. COORDINATED POWER MANAGEMENT

The flexible DC microgrid is smartly controlled to ensure a time-varying power management, then increasing the marina sustainability. On one hand, the combined exploitation of photovoltaic RES and battery storage can minimize the energy purchase from the main grid. On the other, it also can enable the sale of no-emissions energy from the marina when low is the power demand of charging vessels. A specific scenario is conceived to glimpse the marina's potentiality in supporting the green deal. The investigated scenario is about a night-day transition, when the PV power plant is regulated to start its power providing to the controlled electrical grid.

A. *Scenario under test*

The scenario here proposed foresees the coordinated power control to be adopted on the DC microgrid. In the 60 seconds under investigation, the proposed controlled grid is supposed to modify its operation in order to receive the renewable energy from the rising sun on PV. The initial steady-state condition is during the night (i.e. idle C1 converter), when the main grid (i.e. C2 converter) is providing 100 kW to feed two aggregated loads (i.e. 800 kW) by means the action of C5-C6 converters. The missing quota (i.e. 700 kW) comes from the C4-C7-C8 converters, whose bidirectional operation exploits the stored energy in the onboard batteries of resting vessels for the entire scenario. From the night condition, at 1.2 s the PMS acts to address the 100 kW-supply to the C3 battery-converter, then nullifying the energy purchase from the main grid. Once the second steady-state is achieved at *t*=3 s, an extended stop of 32.5 s is required to verify, thus ensure, the sun-availability. Then, at 35.5 s the C1 power-controlled converter is appointed in feeding 400 kW from PV by following the 100 kW/s ramp-rate. When the second transient is ended at 39.5 s, part of the PV energy (i.e. 100 kW) is necessary to power the vessels on charge, while the remaining 300 kW-quota is stored in the microgrid battery. After a dead-time of 16 s, at 55.5 s the C2 power-controlled converter provides a 100 kW/s ramp-rate to the main system. At 58.5 s, the C2 starts to entirely sell its 300 kW of green power to the external grid, while the buffering function of battery is finally concluded.

B. Hardware In the Loop platform

The DC microgrid is emulated by Typhoon HIL 604 real-time platform to verify the coordinated power control. By adopting the Software-In-the-Loop approach, the eight controlled converters of Fig. 1 are implemented in Typhoon HIL schematic editor to check the microgrid operation. In this environment, seven core coupling subdivide the numerical task in eight cores, then guaranteeing real-time transients with a time-step of 1 µs. By compiling the system-control code, real-time emulations are run to depict the regulated switching behavior of power converters as in Figs. 2-13.

C. Tests on HIL platform

The DC microgrid behavior during the night-day transition is highlighted in twelve figures. Such figures are subdivided in three groups to show the voltage-power transients triggered by three relevant actions of PMS. The first PMS activity is aimed at smoothly inverting the droop coefficients on the two parallel-controlled supplying converters, C2 and C3. In night configuration, a very large droop coefficient on C3 voltage control resets the power contribution from the battery. Conversely, C2 is controlled by a tiny droop coefficient to force the entire load supply from the external grid in no-sun hours. Opposite functioning after the first transient, where the dynamics smooth inversion in droop resistances nullifies the grid contribution with no consequences on the bus voltage (Fig. 2). The two droop values swap in about 0.4 s to cut-off the power furniture from main grid (Fig. 3). At 2 s, the battery is able to autonomously provide the power request by the loads (i.e. 100 kW), while the bus voltage regulation is anyway demanded to C2-C3 parallel-connected converters. For what concern the plugged ships, the ones interfaced by C4-C7-C8 provide their power quota to the DC microgrid, as in Fig. 4. Differently, C5-C6 converters behave as loads, while charging the battery on hosted vessels (Fig. 5). After a time-break to confirm the PV availability, at 35.5 s the PMS forces the second transient, where the C1 power-controlled converter starts to supply the system by its 100 kW/s ramp-rate. Evidently, the battery inverts its operation, thus storing the 300 kW-energy surplus at the end of PV entry. This operation change is testified by the bus voltage in Fig. 6. Here, a slight increase in the filtered value (about 1%) is given by the input current to BESS. The microgrid's battery charging is also depicted in Fig. 7, where the steady-state condition is reached at 39.5 s. Both in supplying (Fig. 8) and load converters (Fig. 9), the coordinated control shows it capability in avoiding power perturbations. In the last transient, the PMS forces a power injection to external grid, testified by the negative voltage droop in Fig. 10. At 55.5 s, the available power from PV is dynamically split between battery and C2 converter (Fig. 11). Now this converter is power-controlled to provide 300 kW after 3 seconds (i.e. 100 kW/s). The input power to the BESS is coherently reduced towards zero. Again, the Figs. 12-13 do not show any effect on generating-load converters power.

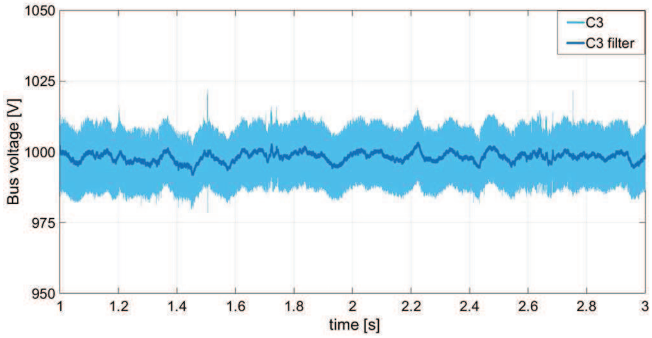


Fig. 2. Storage system voltage (first transient).

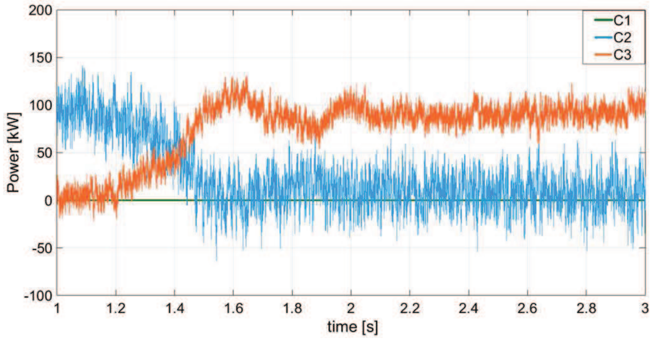


Fig. 3. Upper converters power (first transient).

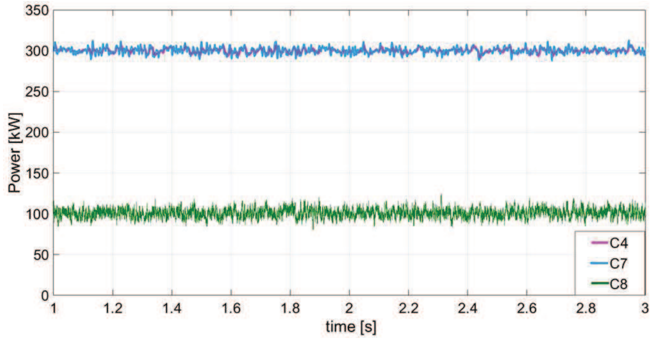


Fig. 4. Generating converters power (first transient).

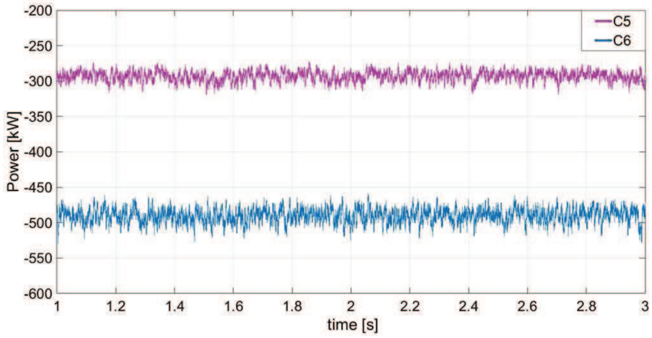


Fig. 5. Load converters power (first transient).

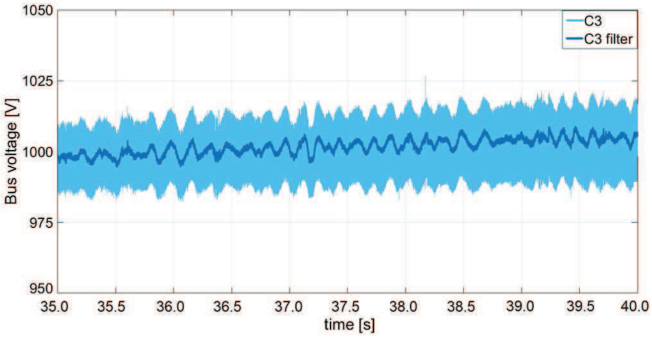


Fig. 6. Storage system voltage (second transient).

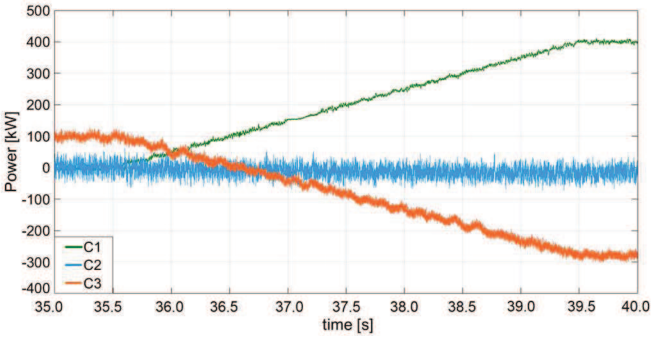


Fig. 7. Upper converters power (second transient).

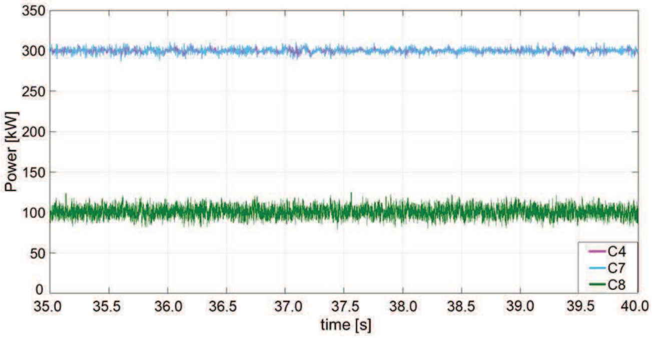


Fig. 8. Generating converters power (second transient).

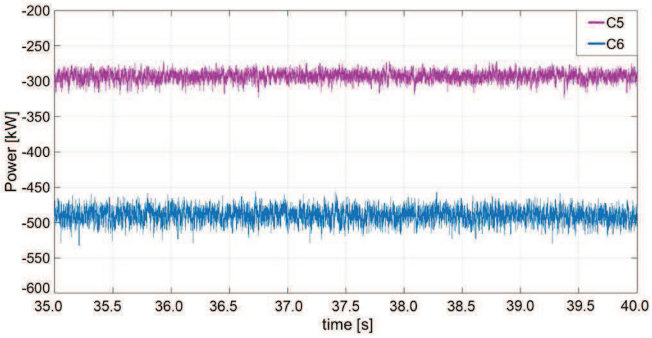


Fig. 9. Load converters power (second transient).

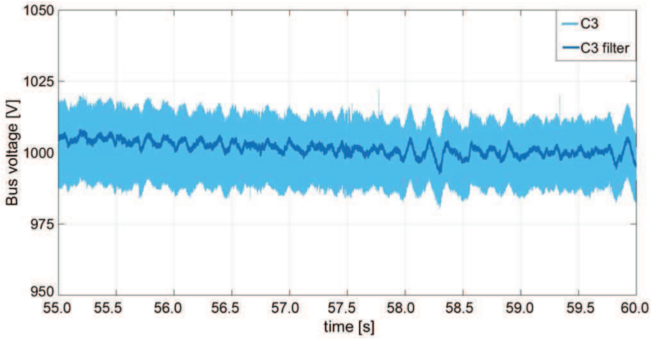


Fig. 10. Storage system voltage (third transient).

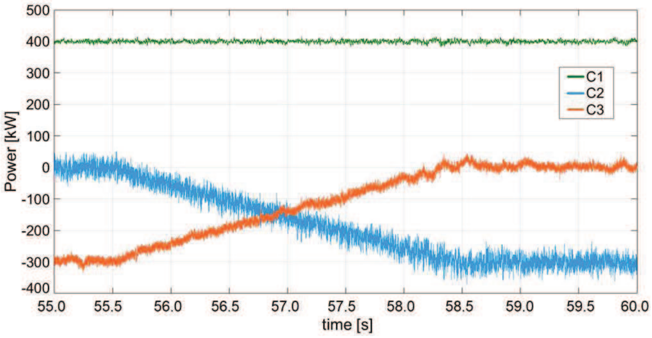


Fig. 11. Upper converters power (third transient).

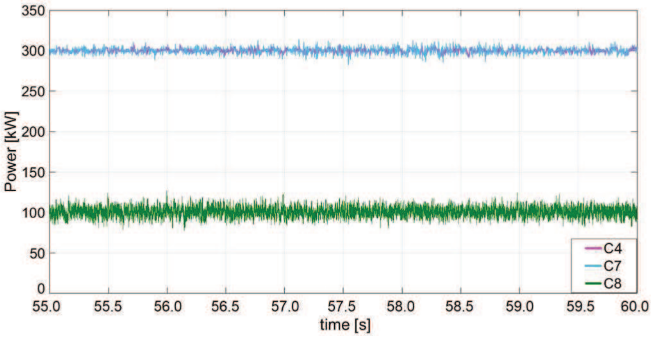


Fig. 12. Generating converters power (third transient).

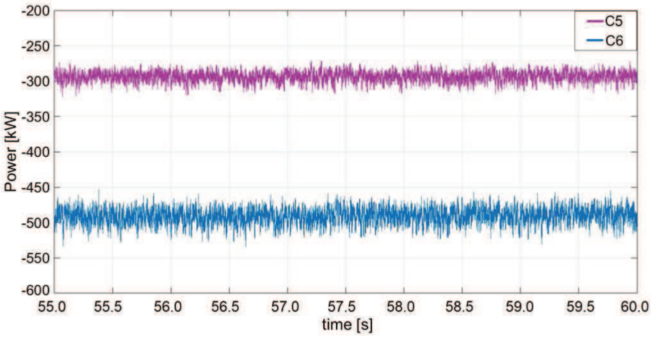


Fig. 13. Load converters power (third transient).

IV. CONCLUSIONS

The paper has presented the coordinated power control of a DC microgrid to improve the flexibility of a yacht-marina. This important outcome is ensured thanks to the real-time management of photovoltaic source and battery storage. The Power Management System (PMS) acts as a centralized controller to optimize the marina operation. By collecting the power-voltage field measurements, the PMS dynamically adjusts the control settings on multiple power converters. In this way, both vessels charging and bidirectional flow from hosted ships are ensured then increasing the marina value in terms of sustainability. To prove the capability of the controlled DC microgrid in managing source-loads-storage, several transients have been developed in HIL platform. The emulation of the night-day transition has indeed demonstrated how the photovoltaic (PV) plant can not only provide sustainable energy for the vessels charging, but at the same time it can increase the marina income by selling its green energy to the main grid. This profitable ancillary service will be analyzed also in the future by studying the whole day power flow as well as the strategies to manage the days with no PV power output and the nighttime.

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