Optimized Tuning for Flexible and Resilient Control of Zonal DC Microgrids on Ships

Andrea Alessia Tavagnutti
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
andreaalessia.tavagnutti@phd.units.it

Daniele Bosich
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
dbosich@units.it

Giorgio Sulligoi
Dept. of Engineering and Architecture
University of Trieste
Trieste, Italy
gsulligoi@units.it

***Abstract*— Flexibility and resiliency are among the main features of next-generation zonal DC microgrids on ships. These paramount characteristics are enabled by the huge penetration of power electronics interfaces, whose presence is beneficial for the grid controllability. Conversely, the interactions among controlled converters and filtering stages can possibly trigger unstable behaviors, thus the ship blackout. Although DC systems are designed to ensure the stability in the operating conditions, the risk of instability is anyway not negligible, especially after faults or undesired disconnections. In this paper, an advanced Power Management System (PMS) is conceived to reconfigure the control parameters in order to avoid the instability. This control tuning is performed by integrating into the PMS an optimization procedure. The latter is able to maintain the system stability without any load shedding action, while limiting the dynamics performance worsening. The stable reconfiguration capability extends the flexible and resilient operation of zonal DC grids.**

***Index Terms*-- DC microgrid, ship, stability, ZEDS, optimization.**

I. Introduction

The flexible operation is a critical requirement to be attained in the more demanding and high performing All Electric Ships (AES) power systems [1]. The Medium Voltage Direct Current (MVDC) technology and the zonal topology are among the key enablers for such a hard task, especially in the navy context [2]. Not only the flexibility target can be achieved through advanced power system design choices, but also developing smart control logics. The power system of a ship can be compared to an islanded microgrid [3], indeed some strategies and issues as well can be directly transferred from the land-based network to the marine one. The huge penetration of complex power electronics interfaces in a DC microgrid [4] requires a proper control logic and architecture, capable of integrating all the loads, sources and storages. Moving onto marine power distributions, the control and optimal operations of a shipboard grid are usually supervised by the Power Management System (PMS) [5], where the decisions can be either taken by a human operator or with automatized/deterministic process. At this level, optimization algorithms can be exploited to gain economic advantages, such as fuel consumption minimization [6]. However, the ships PMS is not only responsible of managing the loads and sources power but also of assuring that the system is constantly working in a stable condition [7]. The stable operation of the power system is guaranteed during the design phase or by using specific stabilization techniques [8]. However, risky situations can occur, especially when feeding high-dynamics loads. To solve the arise of unstable conditions, a stability assessment tool may be integrated into the PMS to keep monitored the controlled system's operating points. This can be achieved either by online measurements, based on the impedance evaluation [9], or with analytical approaches, like the Weighted Bandwidth Method (WBM) [10]. Such a method is characterized by a reduced computational burden, thus it is particularly suitable for the integration in a centralized controller with reconfiguration capabilities. In a previous work this idea has been introduced [11], while in this paper a step further is made by defining a deterministic method to perform the stabilizing reconfiguration. To this aim, an optimization algorithm is included in the ship PMS. Such an algorithm is capable to adapt the converters control bandwidths accordingly to the DC grid's stability requirements. By adopting this smart control tuning, the stability is always ensured whatever the dynamics on highly-demanding loads, then extending the admissible operative scenarios.

II. Shipboard Zonal DC Microgrid

The paper discusses an optimized PMS reconfiguration for advanced zonal DC shipboard grids. This strategy is aimed at ensuring the on-board power supply even in critical conditions, when a PMS no-intervention means at best a consequent load shedding, at worst system instability then blackout.

A. Equivalent model of power inputs

As in [12]-[13], the ZEDS concept is based on the presence of open-system interfaces, where the power electronics is crucial to enable the flexibility in managing the power balance. To this aim, the multiconverter DC microgrid under study is in Fig. 1, while a similar structure is also discussed in [13]. Being this paper mainly oriented on the DC stability effect due to LC filters presence, the power inputs (red triangles) are not characterized. As usually adopted in DC marine microgrids, a single red triangle can represent the cascade of diesel generator,

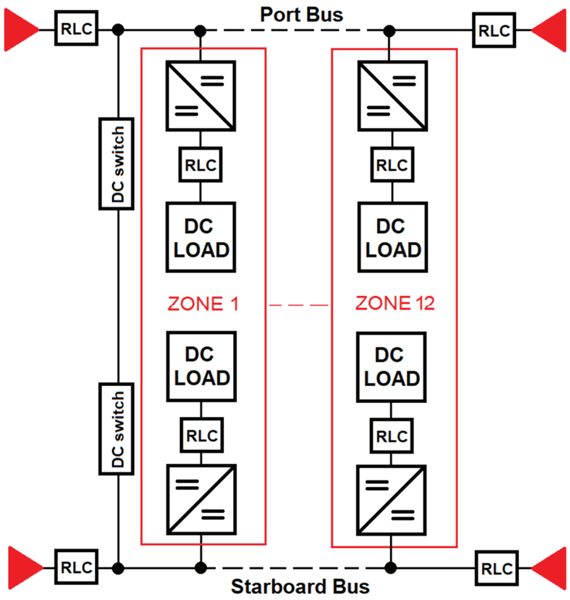

Fig. 1. Multiconverter zonal DC shipboard microgrid.

diode rectifier and DC-DC (buck/boost) converter. To discuss about DC stability on the load side, the generating part (red triangles) is supposed to operate in steady-state condition. This is true when the ω_h control bandwidths on generating converters are sufficiently smaller than the ω_k load converters control bandwidth, thus ω_h<<ω_k. In this case, each power input is modeled by a constant-ideal DC voltage source supplying the related RLC output filter. When the negligible filter resistors are ignored and the DC switches are assumed to be closed, a Thevenin equivalent can model the four generating filters in regarding to the DC stability issue [10]. The equivalent filter is designed on the rated power as in [10], thus resulting L=0.764 mH, C=792 µF, while $\omega_0=(LC)^{-0.5}$ is the resonance frequency.

B. *Power electronics in zonal interfaces*

In the ZEDS structure (Fig. 1), four red inputs provide a total power of 36 MW to feed twelve k-zones (i.e. k=1$\cdots$12) at 6 kV. Each zone is equipped with a couple of identical step-down converters, whose characteristics are in Tab. I (i.e. the zone power thus doubles the reported MW-value). Albeit the authors refer on [10] to explain the parameters, attention is to be put on the ω_k bandwidths. The first eight zones (k=1$\cdots$8) host low bandwidth controlled loads with ω_k<750 rad/s. Conversely, the high bandwidth converters (ω_k >1000 rad/s) are located in the final zones (k=9$\cdots$12). All the load converters are voltage controlled, except the ones in zones 1, 8 and 10 that are current controlled. In each zone, the ω_k bandwidth is sufficiently smaller than the ω_{fk} resonance frequency of output filter (thus ω_k <<ω_{fk}). When this inequality is true, the stability analysis can be performed by neglecting the LC filters as in [10].

III. Optimized Control Tuning

The paper proposes an advanced tuning to reconfigure the DC microgrids control in critical conditions, where a no-intervention means system instability or load shedding. In order to overcome these two negative eventualities, a smart bandwidths redefinition is conceived basing on the Weighted Bandwidth Method (WBM). The performed optimization is able to ensure the system stability, while keeping the converters control bandwidths as close as possible to the initial ones. In such a way, the dynamics performance is not downgraded when chasing the stability requirement in zonal DC microgrids.

A. *WBM stability solver*

In a complex zonal DC grid as in Fig. 1, the WBM has already demonstrated [10]-[11] its capability in identifying the system behavior regarding to the stability requirements. By grouping the controlled loads in two sets (i.e. stabilizing/destabilizing), the WBM can define which bandwidths combination does not impair the stable behavior in the steady-state condition. Evidently, when the stable operating

TABLE I. Design data of power system and control, load section.

	k=1	k=2	k=3	k=4	k=5	k=6	k=7	k=8	k=9	k=10	k=11	k=12
P_{nk} [MW]	1.50	0.75	1.00	1.25	2.00	1.00	1.00	1.50	2.50	3.00	1.50	1.00
V_n [V]	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000	6000
U_{k0} [V]	4500	3000	5000	5000	4500	3000	5000	5000	4500	3000	5000	5000
D_{k0} [·]	0.75	0.50	0.83	0.83	0.75	0.50	0.83	0.83	0.75	0.5	0.83	0.83
ω_k [rad/s]	650	750	700	550	300	500	600	700	1350	1200	1100	1150
I_{k0} [A]	323	240	192	237	285	320	194	285	528	950	285	190
f_{sk} [Hz]	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
$\Delta P_{\%k}$	3	4	4	5	3	4	3	5	5	5	5	5
$\Delta V_{\%k}$	7	7	7	7	7	7	7	7	7	7	7	7
$\Delta I_{\%k}$	30	30	30	30	30	30	30	30	30	30	30	30
R_k [mΩ]	430	521	1085	1108	323	391	797	923	449	166	923	1385
L_k [mH]	3.9	6.9	4.8	3.9	2.9	5.2	4.8	3.2	2.4	1.8	3.2	4.9
C_k [µF]	12.8	14.3	6.86	8.48	17.1	19.0	6.93	10.2	20.9	56.5	10.2	6.78
R_{Lk} [Ω]	13.5	12	25	20	10	9	25	16.7	8.1	3	16.7	25
ω_{fk} [rad/s]	4490	3175	5500	5500	4900	3175	5500	5500	4900	3175	5500	5500

points increase in number, the global ship management becomes more flexible , thus consequently improved. In this work, the WBM is adopted to perform a bandwidths reconfiguration to extend the system operative limits. By wisely tuning the control setting of low-bandwidth loads, a stable operating point is always ensured, also in heavy conditions. This means a notable advantage in power management, as high-performance loads can continually work in an extended region of stable operating points. The eventuality that a perturbation (i.e. load connection/disconnection) triggers an underdamped transient (i.e. bus voltage's limit cycle) is indeed prevented, as the control tuning is designed to constantly guarantee a sufficient stability margin. In this paper, only the loads that are identified as stabilizing by the WBM are part of the bandwidths redefinition. For the more demanding loads (i.e. destabilizing), the rated control bandwidth is conversely not-modified to constantly ensure the high-dynamics requirements. To do this, a stability tool based on WBM [10] is integrated into the shipboard Power Management System (PMS). In such a way, the PMS acquires the capability of reconfiguring the converters control bandwidths, if a possible system instability is foreseen by the WBM stability solver. When a connection/disconnection of loads is planned, thus the PMS preemptively checks the stability condition for the final controlled DC power grid. If the operating points are classified as unstable by the WBM method, then the PMS consequently modify the load converters control bandwidths to guarantee the entire power supply to the totality of loads. Differently from previous work [11], in this work the WBM rules are combined into an optimization procedure. The latter is conceived to reach the stability goal also in critical conditions, while keeping the control bandwidths as close as possible to the initial ones. The DC grid under study operates in the initial steady-state condition, characterized by a total power of 36 MW to be delivered to controlled loads (Table I). From this operating point, a planned PMS action is aimed at disconnecting 4 MW of stabilizing load in Zone 5. As disclosed by WBM method, this disconnection must be preempted by a bandwidths modulation to constantly assure the stability target.

B. Control Optimization

As in [10], the WBM solver determines the Ψ stability performance of a controlled DC system, once applied (1) on the two aggregated controlled loads (i.e. stabilizing/destabilizing). When the Ψ term is larger than 1, the optimization can identify the stabilizing bandwidths reduction to reestablish the stability target $\Psi \leq 1$. To this aim, the unique objective function to be minimized is the sum of distances (2) between old/new bandwidths (i.e. over-lined for optimized values), while the aggregated bandwidth to be attained is the constraint ω_{sobb} in (3). Additional constraints in (4) are also necessary to limit the admissible bandwidths variation in respect to initial values. By means of (1)-(4), the single-objective/constrained optimization is made available for the smart/easy integration on the onboard PMS. On the other hand, the computational burden behind the stability assessment is largely reduced thanks to the WBM simplifying hypotheses [10]. The optimal solution is unique, thus fostering the automation in system reconfiguration.

$$\begin{cases} \Im\left(\overline{Z}_o \cdot \overline{Y}_i\right) = -\dfrac{\omega_{cr}}{C\left(\omega_0^2 - \omega_{cr}^2\right)} \cdot \left[G_S \dfrac{\omega_S^2 - \omega_{cr}^2}{\omega_S^2 + \omega_{cr}^2} + G_D \dfrac{\omega_D^2 - \omega_{cr}^2}{\omega_D^2 + \omega_{cr}^2} \right] = 0 & \text{(1a)} \\ \Re\left(\overline{Z}_o \cdot \overline{Y}_i\right) = -\dfrac{2\omega_{cr}^2}{C\left(\omega_0^2 - \omega_{cr}^2\right)} \cdot \left[G_S \dfrac{\omega_S}{\omega_S^2 + \omega_{cr}^2} + G_D \dfrac{\omega_D}{\omega_D^2 + \omega_{cr}^2} \right] = -\Psi & \text{(1b)} \end{cases}$$

$$\min f(\omega_{Si}) = \sum_{i=1}^{8} (\overline{\omega_{Si}} - \omega_{Si})^2 \quad (2)$$

$$\frac{\sum_{i=1}^{8} P_1 \omega_1}{P_S} = \omega_{Sobb} \quad (3) \qquad \sum_{i=1}^{8} \omega_{Si} \in [\omega_{Simin}, \omega_{Simax}] \quad (4)$$

C. Two-variable Tuning

In order to graphically appreciate the bandwidths tuning, a simplified case is here discussed. For this example, the optimization works on only two variables, thus making possible the optimal point's representation on a 3-D graph. In the shown case, the Ψ stability target (1b) is on -0.8 while the destabilizing loads are modeled as a unique controlled load (i.e. P_D=16 MW) having the bandwidth ω_D=1220 rad/s as control requirement. On the stabilizing side, three loads are

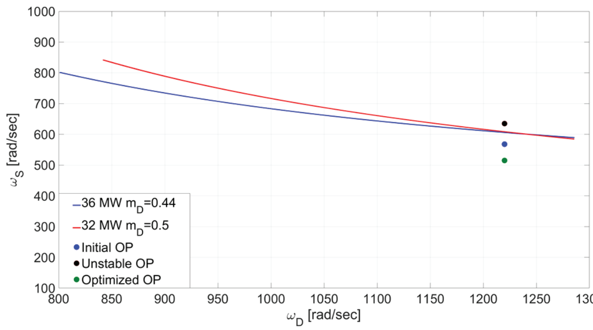

Fig. 2. Operating points on 2-D stability maps, simplified case of study.

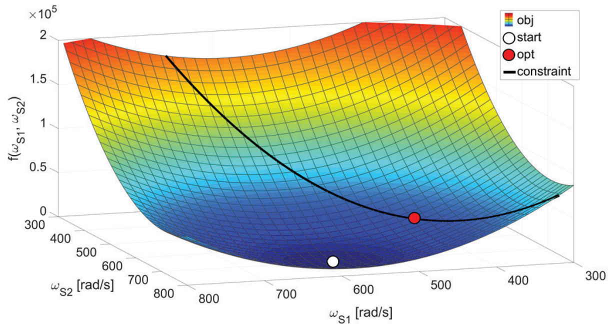

Fig. 3. Objective function and optimization constraint, 3-D solid.

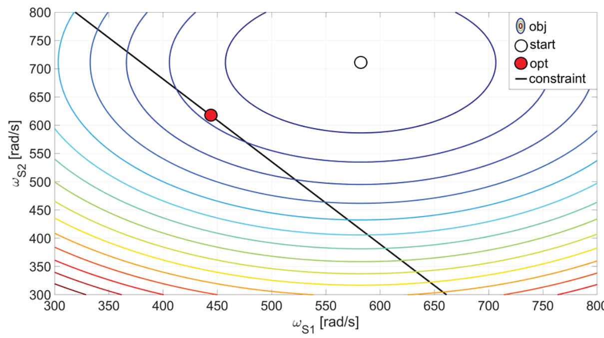

Fig. 4. Objective function contours.

hypothesized. An aggregated load (P_{S1}=9.5 MW, ω_{S1}=582 rad/s) to WBM-model the controlled loads in Zones 1, 4, 6 and 7. A second load of 6.5 MW as representative of the controlled loads in Zones 2, 3 and 8. Now the WBM identifies ω_{S2}=711 rad/s. Finally, the controlled load (i.e. ω_{S3}=300 rad/s) in Zone 5 requesting 4 MW. By reapplying the WBM on these three aggregated-stabilizing loads, a global ω_S=568 rad/s finally models the stabilizing effort whereas the total PS power is 20 MW. Thanks to the stability assessment of [11], this first example shows (Fig. 2) a blue stable operating point below the stability curve obtained for m_D=16/36=0.44. Conversely, when the stabilizing load quota of Zone 5 is removed, the black equilibrium point moves up (ω_S=634 rad/s) beyond the red stability curve (i.e. m_D=16/32=0.5). This equilibrium point is definitely unstable. To guarantee the system operation even in absence of load 5, the PMS must impose an optimized control tuning to reduce the bandwidths on stabilizing loads prior the Zone 5 disconnection.

$$\min f(\omega_{S1}, \omega_{S2}) = (\overline{\omega_{S1}} - \omega_{S1})^2 + (\overline{\omega_{S2}} - \omega_{S2})^2 \qquad (5)$$

$$\frac{P_1 \omega_{S1} + P_2 \omega_{S2}}{P_1 + P_2} = \omega_{Sobb} \qquad (6)$$

The bandwidth limitation is applied on the only stabilizing loads control requirement in order to avoid dynamics worsening on the high-performance destabilizing loads or load shedding maneuvers. For the simplified case, the objective function is offered in (5). The constraint is in (6) while assuming Ψ=-0.8 as stability target in (1b). In this optimization example, no limitations (4) are adopted in the bandwidths redefinition. The objective function in (5) is modeled by the surface of Fig. 3, where the black curve constitutes the constraint (6) on which the optimized solution lies (red dot). To give more details, the Fig. 4 provides the contours of the objective function as a 2-D graph. In last figure, not only the direction of function increase is highlighted, also the local minimum point coinciding with the combination of starting bandwidths is well recognizable. Also in this case, the red optimal point sits on the constraint line. At the end, the red solution is the point at minimum distance from the combination of initial bandwidths respecting the constraint. The so-optimized bandwidths combination on stabilizing loads (i.e. ω_{S1}=444 rad/s and ω_{S2}=617 rad/s) can assure two targets. Firstly, it limits the reduction on dynamics performance. Secondly, its application is effective in reestablishing the system stable operation (i.e. Ψ=-0.8). Now the green point is indeed well-below the stability limit-curve in Fig. 2. The optimization process is performed on Matlab optimization tool box (i.e. *fmincon* function). The adopted algorithm (i.e. interior-point) is the default provided by the function. As the focus is not on the optimization algorithm but instead on the method, the use of basic Matlab tools is proficient to get valid results but in a simple and fast way.

IV. Flexible and Resilient Control

The reconfiguration strategy for the two-variable case is now extended to a 12-zones DC microgrid. The controlled grid in Fig. 1 is assumed to be supplying in steady-state 36 MW to the shipboard loads, whose characterization is in Table I.

A. *Stability-aimed Optimized Control Setting*

The initial operating condition is represented as a blue dot (initial OP) in the stability map of Fig. 5. This OP is well-below the blue line, which constitutes the stability boundary. So the DC power grid works in a safe operating zone. From this point, the 4 MW of Zone 5 load are to be disconnected for operative reasons. Before this load removal, the PMS is trained to check where the next operating point will be located in the stability maps. In Fig. 5, the new stability boundary is depicted with a red line while the next OP with a black dot. Now this OP is unstable, being above its stability boundary. To solve this issue, the PMS must apply the optimized control adaptation before the Zone 5 removal. The PMS sets Ψ= -1 as stability requirement, while limiting the control bandwidths variation to ±5% of Table I rated values. After the loads bandwidths calculation, the PMS can adjust the new setting on the system control to ensure the final operating condition, where the Zone 5 load can be safely removed (green dot). Indeed, this stable OP is exactly laying onto the stability boundary, as set by the control (Ψ= -1). As WBM is a less conservative method, thus a not-stringent stability requirement wants to limit the reduction on stabilizing control bandwidths. This issue is emphasized in Fig. 6, where two bandwidths re-modulations are compared by assuming the less stringent requirement and a more severe one, thus Ψ= -0.7.

B. *Transient response*

Detailed emulations are performed on Typhoon HIL 604 platform to verify the PMS capability in reconfiguring stable systems. The tested DC shipboard microgrid in Fig. 1 is modeled by using basic buck converters and exploiting four cores of the FPGA board (time step of 5e-7 s). The zonal DC grid transient response after the Zone 5 removal is assessed with/without the optimized control setting. The dynamics

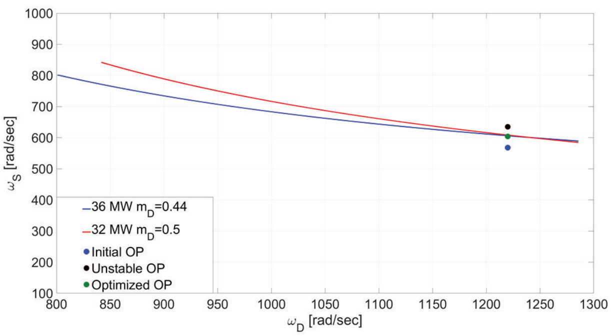

Fig. 5. Operating points on 2-D stability maps, 12-zones DC microgrid.

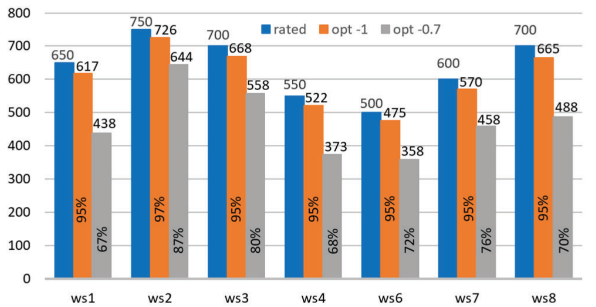

Fig. 6. Bandwidths re-modulations for two Ψ stability requirements (-1/-0.7).

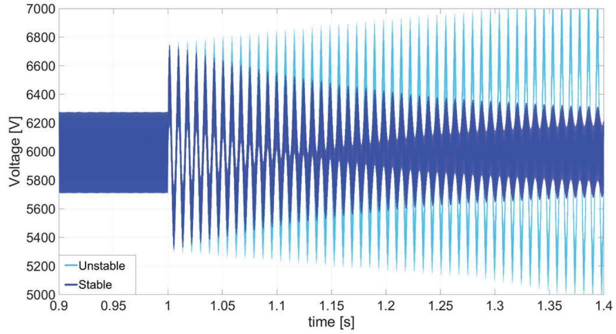

Fig. 7. Bus voltage transients, stable/unstable case (disconnection of Zone 5).

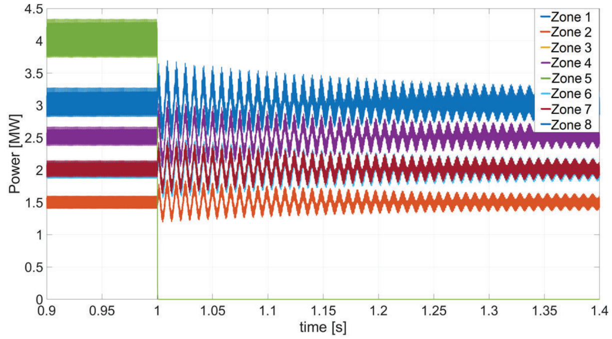

Fig. 8. Load power transients, stabilizing loads (disconnection of Zone 5).

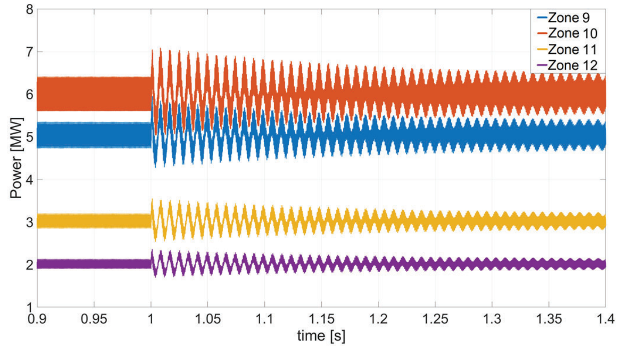

Fig. 9. Load power transients, destabilizing loads (disconnection of Zone 5).

effect on voltage transients (Fig. 7) demonstrates the importance of the stability-aimed control reconfiguration. The blue transient is about the DC system in which the PMS is aware of the upcoming instability. It acts to preemptively avoid the unstable behavior by forcing the optimal reconfiguration on reduced bandwidths. While the cyan transient is referred to the system in which the Zone 5 is disconnected with no preventive actions. In presence of Zone 5 removal at 1 s, only the bus voltage of the reconfigured system remains stable. For the DC grid based on PMS smart reconfiguration, the power transients of both the stabilizing and destabilizing loads are given in Fig. 8-9. In the last figures, the upgraded resiliency is made evident when the removal of Zone 5 load does not impair the continuous supply of other zones. The optimized modulation in bandwidths control extends the stable operating points, then making the zonal DC microgrids as preferable in the management of high-performance isolated grid [13].

V. Conclusions

The paper has investigated preventive PMS actions to avoid the arise of system instability, thus the consequent ship blackout. In the considered zonal DC microgrid, the advanced PMS is optimized to perform a stability-aimed reconfiguration when an unstable operating point is detected. By implementing the WBM stability assessment tool, the PMS can tune the control bandwidths to extend the stable region of operation, while maintaining all the loads powered. This feature makes the zonal DC microgrid flexible and resilient, then encouraging its adoption in the next-generation shipboard systems. The prize to be paid is a slight reduction in the converters control bandwidths, which anyway are kept very close to the initial values therefore ensuring the dynamics requirements on loads.

Acknowledgment

The authors would like to thank Typhoon HIL for providing the platform used in the development of this research work.

References

[1] S. Fang et al., "Toward Future Green Maritime Transportation: An Overview of Seaport Microgrids and All-Electric Ships," in *IEEE Trans. on Vehicular Technology*, vol. 69, no. 1, pp. 207-219, Jan. 2020.

[2] J. G. Ciezki and R. W. Ashton, "Selection and stability issues associated with a navy shipboard DC zonal electric distribution system," in *IEEE Transactions on Power Delivery*, vol. 15, no. 2, pp. 665-669, April 2000.

[3] A. Monti and M. Molinas, "A Ship Is a Microgrid and a Microgrid Is a Ship: Commonalities and Synergies [About This Issue]," in *IEEE Electrification Magazine,* vol. 7, no. 4, pp. 2-5, Dec. 2019.

[4] N. Salehi et al., "A Comprehensive Review of Control Strategies and Optimization Methods for Individual and Community Microgrids," in *IEEE Access*, vol. 10, pp. 15935-15955, 2022.

[5] D. Park and M. Zadeh, "Dynamic Modeling, Stability Analysis, and Power Management of Shipboard DC Hybrid Power Systems," in *IEEE Trans. on Transp. Electrification*, vol. 8, no. 1, pp. 225-238, March 2022.

[6] P. Xie et al., "Optimization-Based Power and Energy Management System in Shipboard Microgrid: A Review," in *IEEE Systems Journal*, vol. 16, no. 1, pp. 578-590, March 2022.

[7] D. Perkins, T. Vu, H. Vahedi and C. S. Edrington, "Distributed Power Management Implementation for Zonal MVDC Ship Power Systems," *Proc. IECON 2018 - 44th Ann. Conference of the IEEE Industrial Electronics Society*, 2018, pp. 3401-3406.

[8] M. Wu and D. D. -C. Lu, "A Novel Stabilization Method of LC Input Filter With Constant Power Loads Without Load Performance Compromise in DC Microgrids," in *IEEE Transactions on Industrial Electronics*, vol. 62, no. 7, pp. 4552-4562, July 2015.

[9] A. Riccobono et al., "Stability of Shipboard DC Power Distribution: Online Impedance-Based Systems Methods," in *IEEE Electrification Magazine*, vol. 5, no. 3, pp. 55-67, Sept. 2017.

[10] D. Bosich, G. Giadrossi, S. Pastore, and G. Sulligoi, "Weighted Bandwidth Method for Stability Assessment of Complex DC Power Systems on Ships," *Energies*, vol. 15, no. 1, p. 258, Dec. 2021.

[11] A. A. Tavagnutti, D. Bosich and G. Sulligoi, "The WBM Reconfiguration to Prevent the Instability on DC Shipboard Microgrids," *Proc. 2022 International Conference on Smart Energy Systems and Technologies (SEST)*, Eindhoven, The Netherlands, 05-07 September 2022.

[12] "IEEE Standard for Power Electronics Open System Interfaces in Zonal Electrical Distribution Systems Rated Above 100 kW," in *IEEE Std 1826-2020*, vol., no., pp.1-44, 25 Nov. 2020.

[13] M. Chiandone, A. Vicenzutti, D. Bosich, A. A. Tavagnutti, N. Barbini and G. Sulligoi, "Open Source Hardware in the Loop Real-time Simulation of Zonal DC systems," *Proc. 2022 Open Source Modelling and Simulation of Energy Systems (OSMSES)*, Aachen, Germany, 04-05 April 2022.