A Stability-aimed PMS for Shipboard Zonal DC Microgrids: the C-HIL Tests on Real-time Platform

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***Abstract*—In future vessels, high reliability and flexibility in loads supply will be the main drivers in the power system design. To these aims, the zonal DC distribution is the most promising technology, as it enables the suitable and safe transfer of onboard power. Conversely, the large exploitation of filtered DC converters opens challenges, such as system stability. As large bandwidth controls on converters can reduce the stability margin of DC grids, the centralized Power Management System (PMS) can be programmed to supervise the stability status. In this paper, the Weighted Bandwidth Method (WBM) is implemented to configure the PMS when unstable conditions are foreseen. The smart PMS can tune the control gains in order to constantly ensure the stable operation of power distribution, regardless the system configuration. The capability of the reconfiguration algorithm is verified by performing a C-HIL test on a real-time platform.**

Keywords—stability, C-HIL, ship, DC microgrid, PMS, real-time

I. Introduction

As the future vessels will require high reliability and flexibility, the onboard power systems are to be improved as well [1]. The foreseen enabler technology is the Medium Voltage Direct Current (MVDC), capable to surpass the limits of the AC distribution, while opening the path towards new technological solutions [2]-[3]. The exploitability of DC solution is bounded to the development of power electronics interfaces, that have seen a huge boost in the last years [4]. The DC shipboard power system is indeed a converter-dense environment. This aspect guarantees advantages on the controllability and integration side, however leading to some drawbacks at system level. One of the most problematic is the DC system stability issue [5]-[6]. As known, each converter is provided of its LC filtering elements to assure the power quality requirements. The interactions among those elements and the tight controls on converters can trigger unstable behaviors [7]. When dealing with high bandwidth controlled converters, it is indeed of paramount importance that the ship central controller is always aware of the stability status of the distribution. To this aim, the centralized Power Management System (PMS) is responsible of coordinating the onboard power grid [8], to reach the ship's mission while ensuring safe and efficient operations.

From the context of zonal DC systems [9]-[10], in this paper the PMS of a shipboard microgrid is the case-study where introducing the stability assessment capability. Prior to each load modification, this PMS can check in real-time the stability status of the zonal DC controlled grid. Then, it can reconfigure the control settings on converters to avoid the instability arise. This stability assessment is computationally fast and simple, and takes advantage of the results in [11]. Although similar studies are also in [12]-[13], here the work is further improved by adding a real-time control logic platform. Indeed, a Controller Hardware in the Loop (C-HIL) setup is implemented to reach a higher degree of complexity and coherence with reality [14].

II. Shipboard Zonal DC Microgrid

The paper validates the design of a stability-aimed PMS by some tests on a C-HIL implementation. This PMS is in charge of managing a zonal DC system to ensure the system stability, even when connecting high-power destabilizing loads. As the PMS can modify the bandwidths on each controlled converter in real-time, stable operating conditions are always guaranteed whatever load is powered. The zonal DC microgrid is constantly supervised and configured by the PMS to avoid the instability, thus the intervention of protections and the consequent blackout.

A. Controlled DC power grid in zonal topology

The work is focused on the design of a PMS to configure a stable zonal DC system. The case of study has been already discussed in [12], thus only some considerations are here provided to recover the design considerations on the controlled DC grid. The power system on which synthesize the PMS is in Fig. 1. It is a zonal DC microgrid, where each lateral red input is the cascade of diesel generator, diode rectifier and DC-DC (buck/boost) converter. As other papers on DC stability [11]-[13], also here the bandwidth on each *h*-generating converter is much smaller than the control setting on each *k*-load converter (i.e. $\omega_h << \omega_k$). In this hypothesis, each power input is modeled by a constant DC voltage source feeding the RLC output filter, whose resistive term is small enough to be considered negligible. In this condition, the four filters are aggregated in a Thevenin equivalent, having L=0.764 mH, C=792 µF as in [12].

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TABLE I. Design data of power system and control, load section [12].

	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

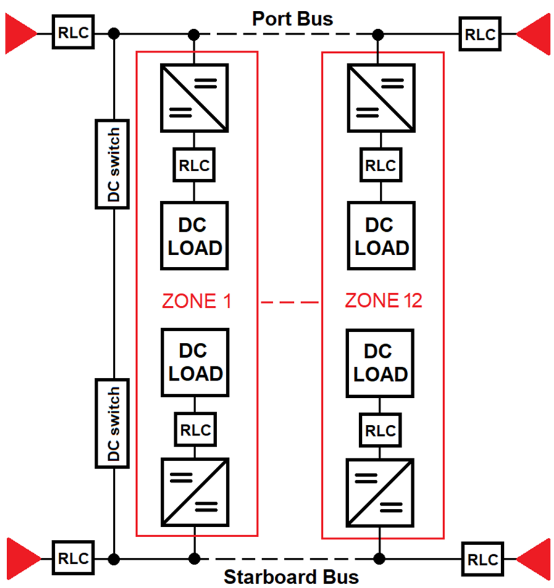

Fig. 1.Shipboard zonal DC microgrid [12].

B. Power system data & control settings

As in [12], also here the ZEDS microgrid (Fig. 1) is powered by four converters (i.e. red triangles) which gives a total rated power of 36 MW. This amount is distributed at 6 kV to the twelve *k*-zones. Each zone has two twins buck converters to feed the DC loads. The data in Tab. I are about each single load converter, so the power of each zone is doubled. About the converter function, the voltage control is assigned to all the interfaces, except the current controlled converters in zones 1, 8 and 10. Among the parameters [11]-[13], the ω_k bandwidths define the DC stability issue. The first eight (k=1⋯8) are smaller than 750 rad/s, while the ω_k >1000 rad/s in the final zones (k=9⋯12). In each zone, the LC filters are in accordance with the theory in [11]. In this condition, load filters do not influence the system stability, which conversely is due to the unfeasible combination of power inputs filters (i.e. Thevenin equivalent) and control settings. The WBM solver is adopted to identify this eventuality, later solved by the PMS reconfiguration on control.

C. WBM stability solver

In DC controlled systems with a large employment of power converters, the WBM method can easily find the proper control settings combination to preserve the system stability. The WBM is effective to aggregate the dynamics effects of controlled converters. Once subdivided the controlled loads in two sets [11]-[13], the WBM calculates a proper bandwidth reduction to constantly avoid the instability, even when feeding large power converters with destabilizing dynamics. In such a way, low-performance loads are made capable in balancing the stability detriment of high-bandwidth ones. The PMS is thus configured basing on the bandwidths reduction from the WBM solver, which is programmed to always ensure a sufficient stability margin. From the characterization of the DC microgrid, each controlled load (i.e. unfiltered DC-DC buck converter in charge of feeding a resistance) is then grouped in one of the two sets (i.e. stabilizing/destabilizing families), as in [11]-[13]. Once defined the aggregated control bandwidth for each set, the WBM allows to concentrate the dynamics effect of multiple power converters in a $Y_i(j\omega)$ single admittance. Then the DC stability is evaluated from the study on the product among $Z_o(j\omega)$ output impedance (i.e. from Thevenin equivalent) and $Y_i(j\omega)$ input admittance (i.e. from WBM modeling). In this regard, the Nyquist criterion can assess the DC system stability by verifying if the curve $Z_0(j\omega)\cdot Y_i(j\omega)$ clockwise-encircles the point (−1,0) on the Gauss plane. Named $-\psi$ the real term of this intersection, the DC system is certainly stable when Ψ<1. Conversely, the instability arises if Ψ is larger than 1.

D. Stability-aimed power management system

The zonal DC microgrid in Fig. 1 is provided of a centralized controller (PMS) which communicates with field and zonal controllers. The PMS changes the control setpoints in order to achieve the ship mission, while always checking for safe and efficient operations. Each time the zonal loads power is changed, the system stability can be potentially harmed, especially when the ratio between stabilizing/destabilizing loads varies [11]-[13]. To preemptively solve this issue, the WBM stability theory is integrated into the PMS control logics. SEach time the loads are changed to follow the ship mission, the stability status of the DC grid is checked before moving to the new operating condition. If the Ψ stability index becomes lower than -0.95, the PMS reconfigure the converter control bandwidths prior to the load change operation. In such a way, the stable evolution among operating conditions is constantly assured. As the control coefficients to be reconfigured are the ones of stabilizing loads only, the high performances of destabilizing (more demanding) loads are always preserved. The control setpoints are the outputs of an optimization process integrated into the PMS [12]. The goal is to minimize the distance between w_{Si} final control bandwidths and rated values in Table I, while moving the Ψ real intersection in a safe-stable zone. To this aim, the function in (1) is to be minimized while subjected to the (2) equality constraint. Particularly, to ensure a ψ index lower than -0.95, the equivalent stabilizing bandwidth should be equal to w_{Sobb}, previously identified by the PMS. Finally, the additional constraint in (3) defines the [w_{Simin}, w_{Simax}] acceptable range (e.g. ±5%) where placed the new control bandwidths. Basing on this procedure, the PMS can be configured to set safe-uninterrupted evolutions from stable operating points. Next Section describes the C-HIL platform to real-time modify the bandwidths, while the final tests to verify the stability-aimed PMS are in Section IV.

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

$$\frac{\sum_{i=1}^{8} P_1\omega_1}{P_S} = \omega_{Sobb} \quad (2) \qquad \sum_{i=1}^{8}\omega_{Si} \in [\omega_{Simin}, \omega_{Simax}] \quad (3)$$

III. Controller Hardware In the Loop Synthesis

The C-HIL tests are developed by interfacing two real-time systems. The controlled DC grid is hard real-time emulated on Typhoon HIL 604. Then, the soft real-time controller is implemented in Python code, executed in an external PC. The interaction between the two is obtained by an Ethernet communication interface.

A. *Real-time platform for C-HIL tests*

To evaluate the setting on stabilizing bandwidths in realistic conditions, a prototype of the PMS is developed to be externally interfaced to the real-time emulator of the plant. The accurate circuital modeling of the power system is performed on Typhoon HIL 604. The generating side of the DC microgrid is a constant voltage source supplying the LC Thevenin equivalent filter. Conversely, the load converters are modeled by means of step-down converters with PI regulators, whose control bandwidths are in Section II. The real-time emulation is obtained by running the controlled system on Typhoon HIL 604 with a simulation step of 10 µs. The controlling PMS works in a separate computing system, which is connected to the plant emulator via an IP network over Ethernet. For homogeneity with standards in electrical industry, the Modbus TCP is the communication protocol to read-write data. The Fig. 2 gives a representation on the developed systems for the C-HIL tests. The algorithm to train the PMS is written in Python language. It includes the calculation code to determine the parameters related to DC stability, and the interfacing part towards the plant simulator. For simplicity, a single Modbus client is implemented for the entire DC grid. A different solution can foresee a Modbus client for each device (converter or switch) in the grid. In this work, the single client is considered as a gateway of several real devices. The developed emulations tests have an experimental value, as they also potentially include communication delays.

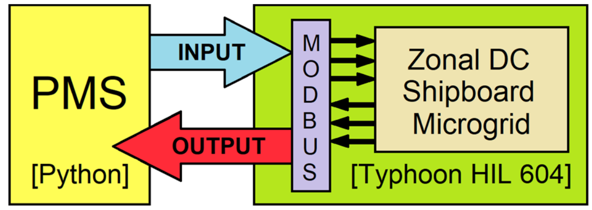

Fig. 2. Controller Hardware In the Loop test on PMS.

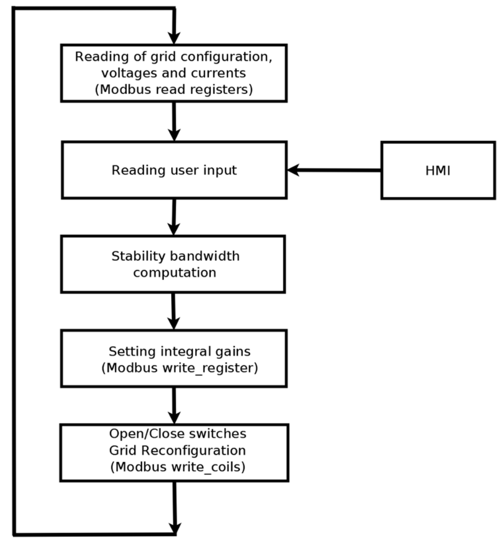

Fig. 3. Block diagram for the implemented code.

B. *Python Code*

The PMS action is programmed by Python as in Fig. 3. This language is chosen for its implementation simplicity and developed code portability. Modbus interfacing is implemented by standard communication libraries. The first tested library is the open source *pyModbusTCP*, instead the second comes from Typhoon HIL team. Basing on the first library, the second one provides some facilitations in converting 32-bit registers into floating point numbers according to the IEEE754 standard. From the reading of user requests on power system switches (i.e. 0/1 to model which power converter is called to action), the code evaluates the stability performance. Then, it can force the PMS in setting new control gains to prevent unstable conditions. The reading of switches status takes place by mapping the states in Modbus registers of the coil type. Each of these is commanded through single writes (*write_single_coil*). The gain values are mapped into *holding_registry* type registers, which are read and write. In these 32-bit registers (actually each consist of two pairs of 16-bit registers), floating point values are stored according to the IEEE754 standard. The conversion between floating point and 16-bit register pairs is implemented in some complementary functions to the PMS code. Eventually, it is also possible to use the wrapper library *typhoon.api.modbus* which already provides the *write_registers_adv* functions including the conversion. The algorithm calculates the control gains by the optimization. Particularly, the SciPy library provides the minimize function in (1). By different solvers, it finds the minimum of a scalar function on several variables. The Sequential Least Squares Programming is the solver used in the case of study. The PMS code reads the values from the plant simulator every 0.5 s.

IV. Real-Time Stability Tests

The performed tests are aimed at showing the capability of a trained PMS to identify and preemptively solve an incoming instability. Albeit these tests could be executed on a simulation only environment, a step further points to the C-HIL real-time tests, thus exploiting a Python controller interfaced through Modbus to the Typhoon HIL 604 platform.

A. Initial bandwidths configuration

The system is initially configured in a stable operating point. As in [12], all stabilizing (Zone 1-8) and destabilizing loads (Zone 9-12) are connected, and their control bandwidths are set in Table I. In this configuration, only half (i.e. 2.5 MW) of destabilizing load 9 is supplied. The overall load power is equal to 33.5 MW while m_D=13.5/33.5=0.4. For these initial control settings, the stability boundary is in Fig. 4. In this representation, an OC (i.e. dot) is stable if it stays below the related (i.e. same color) line, thus its stability boundary. From the theory in [11]-[13], now it is possible to find the w_S and w_D for this first OC (blue dot in Fig. 4). Then the Ψ value (i.e. -0.78) recognizes this OC as stable. From this operating state, the PMS commands different configuration changes. At first, the Zone 5 stabilizing load is reduced from 4 MW to 3 MW. As a consequence, the total power is 32.5 MW and the m_D coefficient goes up to 0.42 (i.e. green color). As the total stabilizing load is reduced, the new w_S-w_D crossing is characterized by a smaller Ψ (i.e. -0.8), which is still a stable condition. The third operating condition is reached when the Zone 9 destabilizing load is increased to its rated value (i.e. 5 MW). Now black line and black dot represents this case in the stability maps. As a notable quota of destabilizing load is connected, the Ψ stability index decreases to -0.94, definitely close to the stability boundary. The stability status variations during this test are visually appreciable in the Figs. 4, also including a zoom on the operating conditions. Some black arrows are used to explicitly define the sequence of the OCs.

B. Destabilizing perturbation

In the OC3 point, the system is very close to the stability boundary, meaning that even a small demanding perturbation can provoke the system instability. The next OC that is set by the PMS forces the disconnection of Zone 5 stabilizing loads, determining an overall load power of 32 MW and an m_D=0.5. This OC is represented by a red line in the stability maps of Figs. 4. If the converters control bandwidths are not tuned, the w_S-w_D crossing stays in an unstable zone (i.e. red dot in Fig. 4). On the other hand, if the PMS preventively checks the stability status, it can act to modify the control bandwidths of the converters to guarantee a stable evolution. In the case of study, the bandwidths remodulation is performed with an optimized stability solver, that acts only on the control coefficients of stabilizing loads. This ensures a stable evolution towards the OC4, represented by the red dot in Fig. 5, now clearly below the red line. In particular, the PMS always checks that the next OC to be reached is characterized by a $\Psi \geq -0.95$. If this condition is not verified, the PMS activates the optimization function and tunes the control bandwidths accordingly. Please note that in Fig. 5 both OCs and stability boundaries are identical to what proposed in Fig. 4. Only the last step to OC4 differently shows the desired requirement on stability.

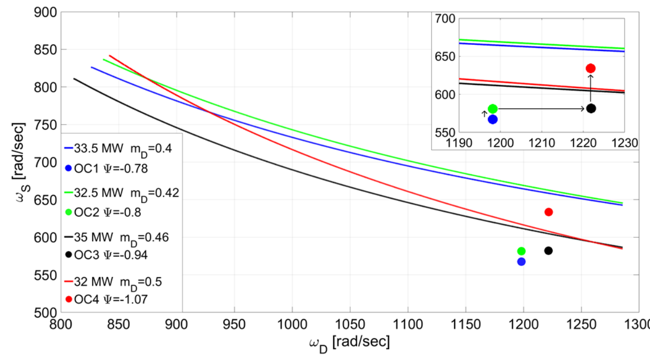

Fig. 4. Operating condition evolution during the unstable test.

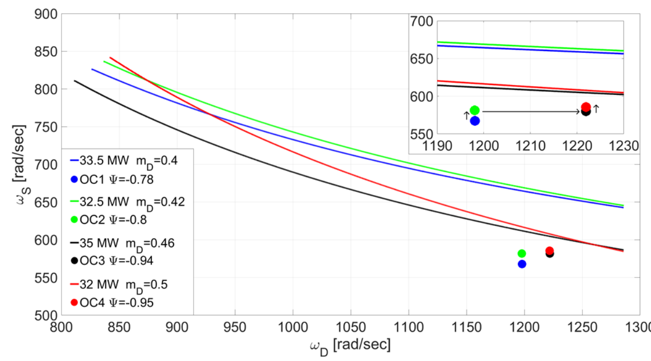

Fig. 5. Operating conditions evolution during the stable test.

C. Real-time transient responses

The analytical considerations and tests are verified through the real-time emulation. The optimized PMS is implemented with a Python code, while the power system is modeled in Typhoon HIL. The controller is interfaced to the DC system through the Modbus protocol in a C-HIL configuration, then achieving a higher degree of realism. The voltage and power transients of the controlled DC microgrid during the test are here proposed and discussed. The voltage transients in Fig. 6 are given both for unstable and stable case, so with/without the trained PMS. While the power transients (Figs. 7-9) are provided for only the stable evolution. The test starts with the DC grid at steady-state in the OC1, the stabilizing loads powers are in Fig. 7 and the destabilizing ones in Fig. 8. At approximately 1.5 s, the transition from OC1 to OC2 is commanded to force a reduction in Zone 5 load power (3 MW), as in Fig. 9. In this transient, the voltage remains stable (Fig. 6), thus the system is able to feed all the zones. The second stable evolution is imposed at 4.5 sec, when the Zone 9 destabilizing load is increased at 5 MW (Fig. 9). The last transient is commanded at 12.5 s, when the Zone 5 load is disconnected. Without the PMS reconfiguration, this event can provoke the instability, as in the cyan transient of Fig. 6. Conversely, if the PMS preemptively checks the stability status and reconfigure the bandwidths, the unstable behavior is avoided, as in the blue voltage transient of Fig. 6. Also after the disconnection of Zone 5 stabilizing load, the optimally reconfigured DC grid can maintain the supply of all the zonal loads (Figs. 7-8) without any interruption (not even transiently), while keeping the control bandwidth reduction inside the 5% range, as in (3).

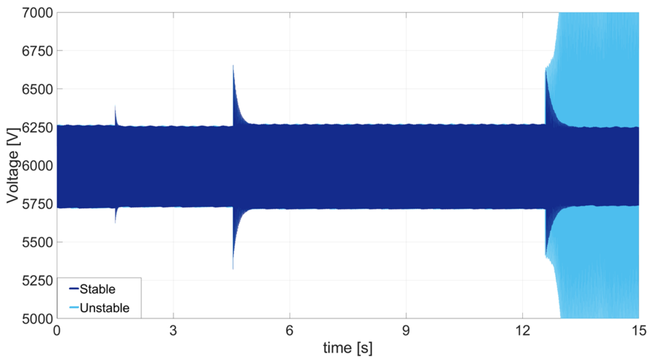

Fig. 6. Bus voltage transients.

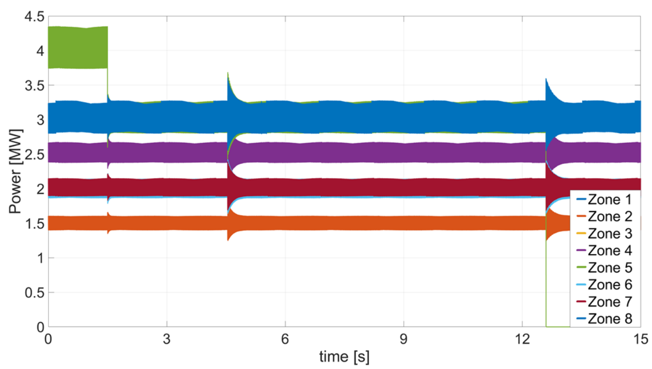

Fig. 7. Power transients of low-bandwidth stabilizing loads (stable case).

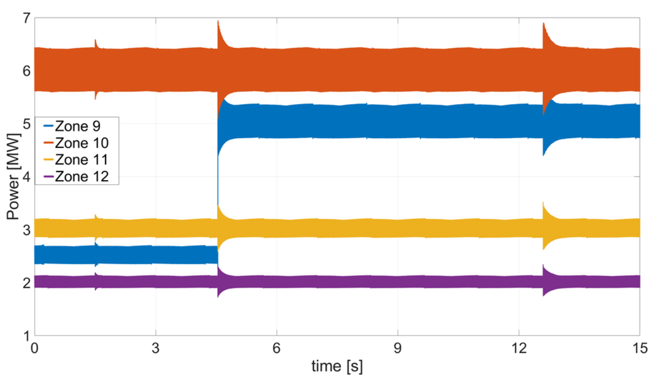

Fig. 8. Power transients of high-bandwidth destabilizing loads (stable case).

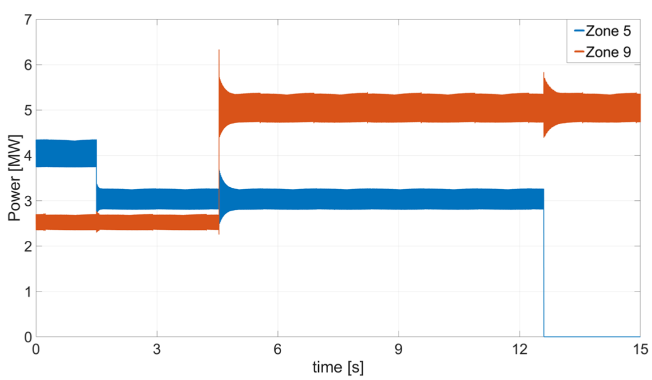

Fig. 9. Power transients in the Zones with OC changes (stable case).

V. Conclusions

The paper has presented the C-HIL tests on a real-time platform to show the potentiality of a smart PMS. The latter is capable of tuning the control settings on the power interfaces of a zonal DC system. The reconfiguration algorithm is based on the WBM, a simple and effective method to check the stability status of a controlled DC grid. Once identified an upcoming unstable operating point, the control retuning is optimized to ensure the DC system stability, while limiting the performance degradation on power converters. As the C-HIL tests ensure more coherence with reality (e.g. communication delays, measurement errors), the de-risiking activity is performed prior to the future implementation on control electronic boards.

Acknowledgment

The authors wish to thank Prof. Giovanni Giadrossi for his valuable contribution, and Typhoon HIL for providing the platform used in the development of this research work.

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