Analysis of Interoperability between DC-Voltage-Droop-Controlled MMCs with Grid-Forming Functionality in a MTDC Grid

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***Abstract*—In this article, the interoperability between droop-controlled Modular Multilevel Converters (MMC) with Grid-Forming (GFM) functionality in a 3-terminal DC grid is investigated. Two possible implementations of GFM control, namely Virtual Synchronous Machine (VSM-GFM) and matching-GFM, are combined with two implementations of DC voltage droop. A small-signal analysis on a three-terminal asymmetrical monopolar DC grid is conducted to identify the limitations of the control parameters related to system stability and dynamic performance. Time-domain simulations are conducted to analyze the effect of control parameters on system response. The results demonstrate the interoperability between the two control options, subject to some control parameter limitations.**

***Index Terms*—HVDC, Small-Signal Analysis, Interoperability, MMC, Grid-forming**

I. Introduction

Recent developments in offshore wind farm connections have led to a growing interest in Multi-Terminal DC (MTDC) grids, which provide an efficient solution to transferring large-scale offshore wind power to onshore AC grids. Compared to existing point-to-point links, MTDC grids provide several advantages, including increased power transfer capacity, reduced transmission losses, and enhanced system reliability [1]. However, MTDC systems also present challenges related to control and protection, especially considering that future large-scale MTDC grids are likely to be constructed by different manufacturers [2]. This presents the challenge of coordinating control schemes from multiple vendors and managing potential interactions.

The Modular Multilevel Converter (MMC) is the most suitable converter technology for MTDC grids. The MMC offers the advantages of modularity, scalability, and high efficiency. Different MMC control structures exist in the literature, and their choice depends on the required functionalities. From an AC grid perspective, the MMC can operate in either Grid-Forming (GFM) or Grid-Following (GFL) mode. On the one hand, GFM control mimics the behavior of a synchronous generator, providing frequency and voltage support to the AC grid. Different GFM controls have been widely analyzed in the literature [3], [4], such as the Virtual Synchronous Machine (VSM-GFM) [5] and matching GFM [6]. On the other hand, GFL control relies on a phase-locked loop to synchronize the converter with the AC grid, effectively operating as a current source from the AC grid perspective hence offering limited grid support functionalities.

From a DC grid perspective, the MMC can be controlled to regulate either its active power output or the DC voltage at its DC Point of Connection (DC-PoC). Among various DC voltage control strategies, DC voltage droop control is particularly suited for MTDC systems due to its decentralized nature and ability to facilitate power sharing among converter stations [7]. This control method enables the MMC to regulate its DC voltage through a proportional action. Different DC voltage droop control schemes have been proposed [8], with similar static characteristics but different dynamic responses.

In most existing literature on GFM control, a constant DC voltage source is assumed on the DC side, and the MMC is controlled to adjust its AC power output in order to provide frequency support, such as inertial support and primary frequency support. However, this assumption ignores important dynamics related to the DC side of the converter. It also limits the possibility of combining DC voltage regulation and AC frequency support. According to [9], it shall be possible to activate GFM control and DC voltage droop by the HVDC converter station. This drives the need to investigate possible control solutions that can provide both functionalities simultaneously. The stability limitations of combining GFM control with DC voltage droop have been studied in [10]. The authors show that the interaction between GFM control and DC voltage droop can lead to low-frequency instability.

This paper studies the interoperability of two possible control implementations of GFM control and DC voltage droop control in a three-terminal DC system. A small-signal analysis is conducted to identify the limitations of the control parameters and their impact on the system performance and stability.

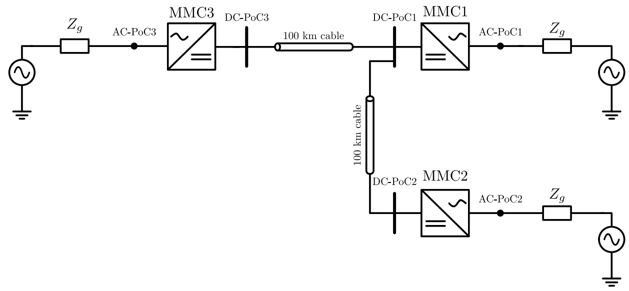


Fig. 1: Three-terminal MMC-MTDC grid configuration.

TABLE I: MMC parameters.

Parameter	Value
Nominal Power [MVA]	1000
Nominal DC voltage [kV]	525
Nominal Primary AC voltage [kV]	400 RMS L-L
Transformer resistance [pu]	0.5%
Transformer inductance [pu]	18%
MMC arm inductance [pu]	15%
MMC arm capacitance [μF]	48.4

Time-domain simulations are then performed to validate the small-signal analysis and investigate the system response to different control parameters variations.

The rest of the paper is organized as follows. Section II describes the system configuration and the considered MMC control structures. Section III presents the small-signal analysis on the three-terminal grid. Section IV presents the simulation results. Finally, Section V concludes the paper findings.

II. System Description

A. Grid configuration

The three-terminal asymmetrical monopolar DC grid shown in Fig. 1 is considered for this study. It consists of two onshore stations, MMC1 and MMC2, and an offshore station, MMC3. Each AC grid is modeled as a Thévenin equivalent, with a short-circuit ratio of 5, representing a strong AC grid connection. On the DC side, the three MMCs are connected radially with two cables of 100 km, one between MMC1 and MMC2, and the other between MMC1 and MMC3. Table I provides the physical parameters of the MMC.

B. MMC model and control

The Arm Average Model (AAM) is used to model the MMC, with each arm represented by an equivalent capacitor, as in Fig. 2. To obtain a state-space representation of the MMC linearized with respect to an equilibrium point, the approach in [11] is adapted, where the Σ-Δ variables are considered to represent the MMC arm capacitor voltages and currents. The reader is advised to refer to [11] for more details about the modeling of the MMC in state space for small-signal analysis.

Fig. 3 shows the overall MMC control structure and Table II gives the control parameters of the three MMCs. Two GFM control structures are considered, namely VSM-GFM and matching-GFM. While these GFM controls have been

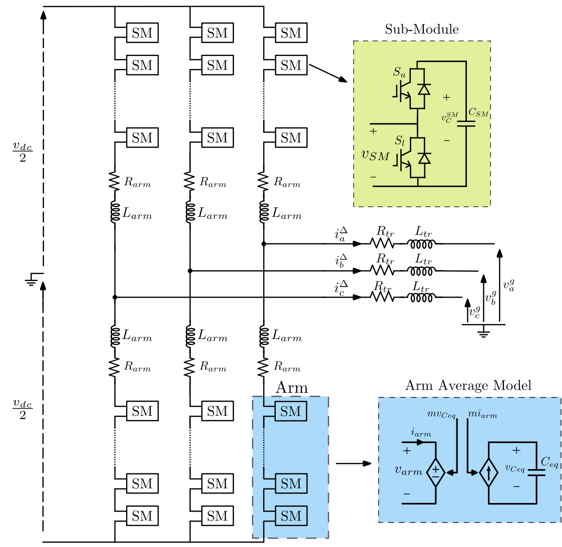


Fig. 2: MMC and its Arm Average Model (AAM).

studied individually in the literature, our study focuses on their combination with DC voltage droop control. In MMC1, the VSM-GFM control is combined with the DC-voltage droop scheme A, which adjusts the AC power reference proportionally to the DC voltage deviation. such a control structure is similar to the one presented in [12]. In MMC2, the matching-GFM control is combined with DC voltage droop scheme B, which adjusts the DC voltage reference proportionally to the AC power deviation. These two combinations are imposed by that fact that the output of the droop scheme A, the AC-power reference, is also the input of the VSM-GFM, while the output of the droop scheme B, the DC-voltage reference, is also the input of the matching-GFM.

In both GFM structures, a constant voltage reference is used for the modulation of the internal AC voltage.

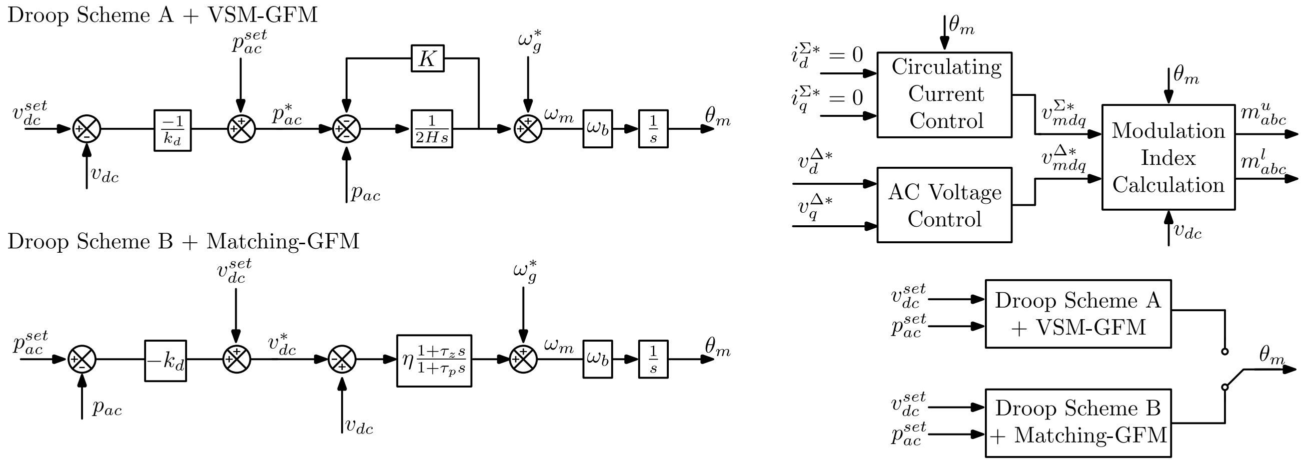
Our previous study [13] investigated the interoperability between droop schemes A and B using a GFL control structure, highlighting potential stability limitations of droop scheme A. Building on this, the present study incorporates GFM control into to MMC1 and MMC2. The three MMCs are following the non-energy based control strategy, where the circulating currents are controlled to zero [14], [15].

1) MMC 1: The VSM-GFM structure [5] provides the inertial support for the AC grid by mimicking the response of a synchronous generator. The active power dynamics of the VSM-GFM is described by

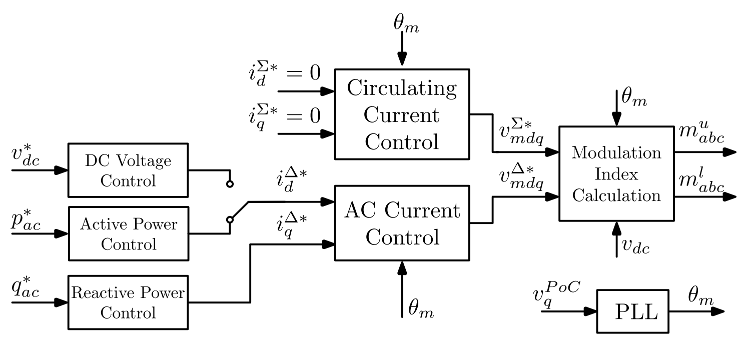
$$p_{ac} = p_{ac}^* - 2H\frac{d\omega_m}{dt} - K(\omega_m - \omega^*) \qquad (1)$$

where p_{ac} is the active power output, p_{ac}^* is the active power setpoint, ω_m is the modulated frequency of the MMC, ω^* is the nominal grid frequency, H is the inertial constant and K is the frequency damping coefficient.

2) MMC 2: The matching-GFM control [6], [16] adjusts the converter's frequency in response to DC voltage variations to achieve synchronization with the AC grid. Specifically, the



(a) GFM control structure



(b) GFL control structure

Fig. 3: General control structure of the MMC considered for this study. MMC1 operates under VSM-GFM and DC voltage droop scheme A. MMC2 uses matching-GFM control and DC voltage droop scheme B. MMC3 operates in GFL control structure, with constant active power control mode.

frequency is modulated such that the transfer function from the DC voltage error to the frequency deviation becomes:

$$G(s) = \frac{\Delta\omega(s)}{\Delta V_{dc}(s)} = \eta\frac{1+\tau_z s}{1+\tau_p s} \tag{2}$$

where η defines the static relationship between the DC voltage deviation and the frequency deviation, τ_z is lead time constant and τ_p is the lag time constant. The DC voltage controller generates the reference for the synchronization angle θ_m, which is used for the abc-to-dq transformation. In this study, we extend the matching-GFM control structure to include DC voltage/AC power droop control, thus enabling primary DC voltage support for the connected DC grid at the DC-PoC.

3) MMC 3: MMC3 operates as a GFL-controlled MMC, with its AC power maintained at a constant setpoint using a conventional cascaded control structure, see Fig. 3b. The AC power control loop sets the reference for the d-axis AC current, while the AC current control loops generate the references for the modulated AC voltages.

C. Cable model

To obtain the state-space representation of the cable model, the approach in [17] is followed. A single π section with three parallel RL branches are considered to model the cable, as shown in Fig. 4. This representation effectively captures the cable's frequency dependence within the study's relevant frequency range, which is below 150 Hz. The cable parameters are adapted from [18].

TABLE II: Control parameters.

MMC1	H [s]	5
	K	100
	k_{d1}[p.u]	0.1
MMC2	η	0.2
	τ_z [ms]	5
	τ_p [ms]	0.3
	k_{d2}[p.u]	0.1
MMC3	AC power response time [ms]	50

D. Small-signal model validation by EMT simulations

To obtain the model of the entire 3-terminal DC grid for the small-signal analysis, the state-space models of the sub-systems (MMCs, cables, and AC grids) are first connected by identifying their respective inputs and outputs. Then, a linear time-invariant state-space model is obtained by linearizing the

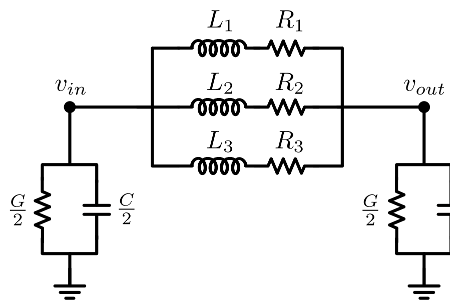


Fig. 4: State-space representation of the cable model [17].

TABLE III: Initial power flow.

Converter	Control Mode	v_{dc}^{init} [pu]	p_{ac}^{init} [pu]
MMC1	Droop A + VSM-GFM	1.003	0.5
MMC2	Droop B + Matching-GFM	1	0.472
MMC3	P-mode + GFL	1.007	-1

nonlinear system around the equilibrium point defined in Table III, with the positive power corresponding to the inverter mode.

To validate this small-signal model, a comparison with a non-linear model of the same 3T grid built on EMTP-RV is performed. In this EMT model, the MMCs are represented by the AAM, and the DC cables by the wideband frequency-dependent model. A 0.2 pu step change in AC power setpoint of MMC3 is considered at t=5s. The results in Fig. 5 show that the linearized model's response closely matches that of the EMT model, thus validating its suitability for further analysis.

III. Small-Signal Analysis

The small-signal analysis examines how droop gain affects GFM-controlled MMC dynamics and overall DC system stability. For this, a variation of the DC voltage droop gain of MMC1, k_{d1}, from 0.01 to 0.2 is considered, while all the other control parameters are kept constant. The eigenvalues obtained, as shown in Fig. 6, indicate that decreasing the droop gain k_{d1} below 0.06 p.u renders the system unstable for the considered operating point. In fact, high inertial support for the AC grid slows AC power dynamics, which conflicts with the need for fast MMC response in DC voltage regulation. In this case, even for $H_1 = 1$s, a relatively low inertia constant for MMC1, instability already occurs when the DC voltage support is increased by reducing k_{d1} below 0.06 p.u . This confirms the findings in [10], where the authors showed the interaction mechanism between VSM-GFM control and DC-voltage droop scheme A, and introduced a phase compensator in the droop control loop to mitigate this low-frequency instability.

For the pair of poles that migrate to the right half plane, a participation factor analysis shows that the states participating in the unstable modes are the GFM angle, frequency of MMC1, and the DC component of the internal MMC capacitor voltages. This indicates the low-frequency coupling between the dynamics of different converters.

For the MMC2, the trajectories of the system poles in Fig. 7 show that the system remains stable for $0.01 \leq k_{d2} \leq 2$. This indicates the advantage in terms of stability when combining scheme B droop control with the matching-GFM control, especially for a low value of droop gain, which is more relevant from the point of view of limiting the DC voltage steady-state variation for a droop-controlling station.

IV. Simulation Results

Time-domain simulations of the 3T DC grid are conducted to investigate the influence of the control parameters on the response of the system, with the same initial power flow in Table III. The disturbance introduced is a 500 MW step increase in the AC power setpoint of MMC3. The droop gains of MMC1 and MMC2 are set to 0.01 p.u. and 0.1 p.u., respectively, while all other control parameters remain the same as in Table II. The result in Fig. 8 shows the system becomes unstable with growing oscillations after the disturbance, which confirms the small-signal analysis results.

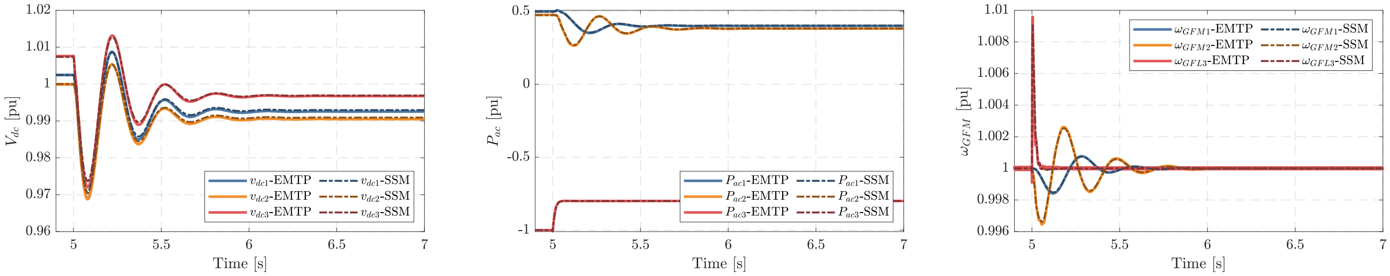
The impact of the VSM-GFM control parameters on the frequency dynamics is intuitively clear, with H as the inertial constant, K as the damping coefficient. On the other hand, the impact of the matching-GFM control parameters, namely τ_z and τ_p, on the system needs to be further studied. For this purpose, we check the system response for different values of the matching-GFM control parameters.

For η, Fig. 9 shows that η has a strong impact on the damping, with a higher value of η providing a better damping to both the DC voltage and frequency oscillations. For τ_z, Fig. 10 shows that increasing τ_z improves the damping of both the DC voltage and the frequency. In addition, the response time is highly reduced as τ_z increases. Finally, for τ_p, Fig. 11 shows that, even though the difference in system response between $\tau_p = 0.3$ ms and $\tau_p = 3$ ms is not significant, the system becomes unstable when $\tau_p = 30$ ms. This implies that a proper controller design is needed to find the range of parameters that satisfies dynamic requirements and ensures system stability.

From Figs. 9 to 11, it can be concluded that a low-frequency coupling between the MMCs is present. Indeed, low-frequency oscillations originating from the control setting of one MMC can propagate to the other MMCs through the DC grid.

V. Conclusions

This paper investigates the interoperability of droop-controlled MMCs with GFM functionality in a three-terminal DC grid. Two GFM implementations, VSM-GFM and matching-GFM, are combined with droop control schemes A and B, respectively. A small-signal analysis identifies control parameter limitations affecting system stability, validated by time-domain simulations. Results show that a low value of droop gain for scheme A can lead to system instability, whereas scheme B, combined with matching-GFM control, is more robust, maintaining system stability for a wide range of droop gains. The study demonstrates that both GFM implementations can be effectively combined with droop control in a three-terminal DC grid. While it is important for converter



(a) DC voltage (b) AC Power (c) Frequency

Fig. 5: Time-domain validation of the linearized model against the non-linear EMT model.

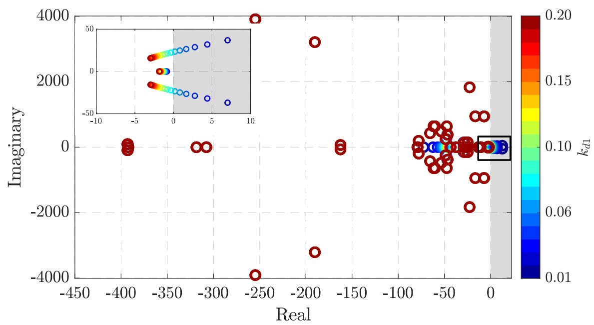


Fig. 6: System poles when varying the droop gain of MMC1.

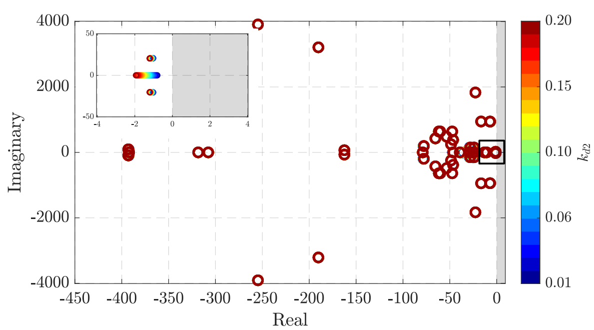


Fig. 7: System poles with varying the droop gain of MMC2.

manufacturers to implement their respective control solutions, a generalized testing framework should be developed to evaluate the required AC and DC grid support functionalities early in multi-vendor HVDC projects, de-risking interoperability issues.

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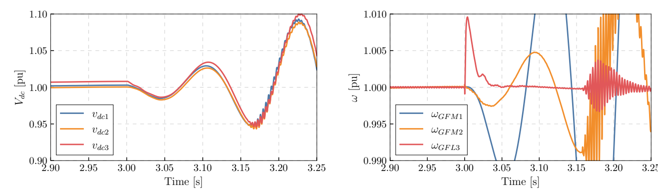
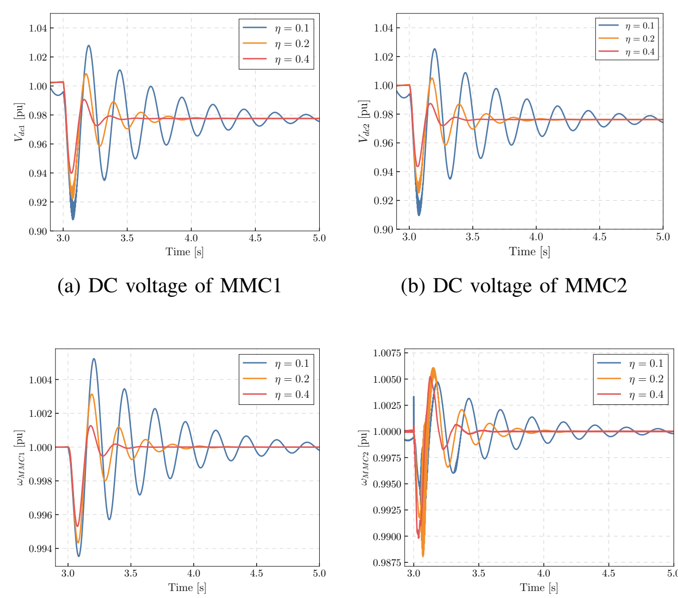


(a) DC voltage (b) Frequency

Fig. 8: System response with $k_{d1} = 0.01$ pu and $k_{d2} = 0.1$ pu.



(a) DC voltage of MMC1 (b) DC voltage of MMC2

(c) Frequency of MMC1 (d) Frequency of MMC2

Fig. 9: System response to a 500 MW decrease in MMC 3 AC power setpoint with different Matching-GFM control gain values.

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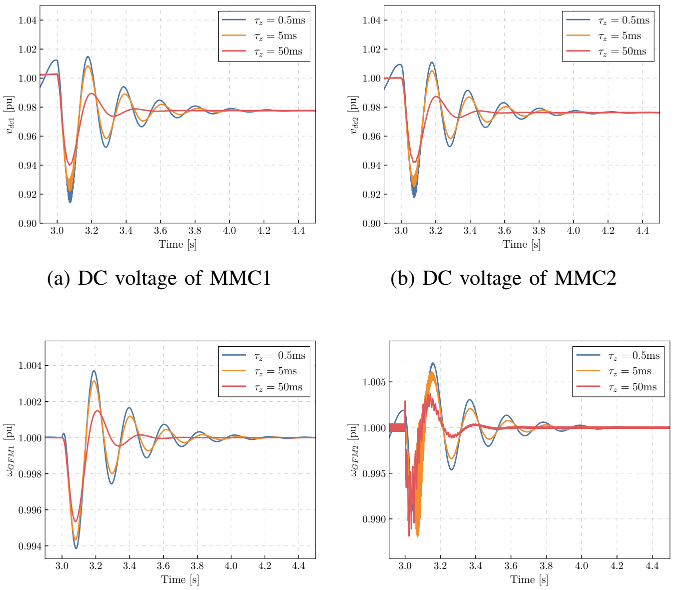


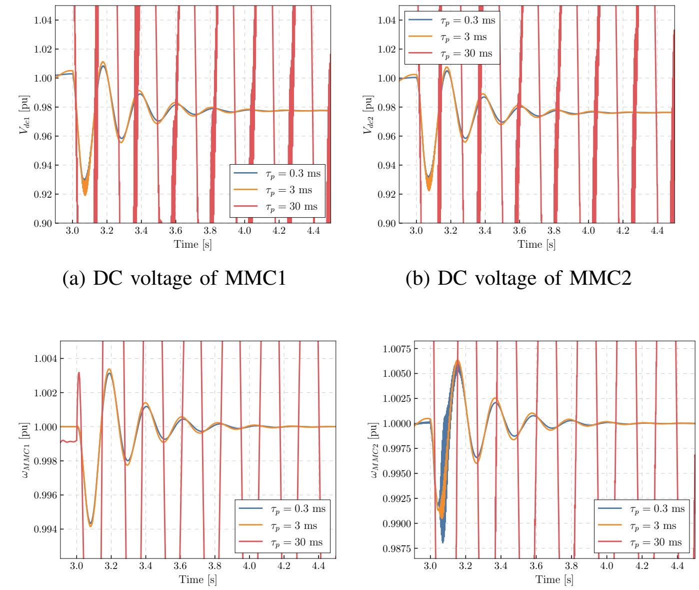
(a) DC voltage of MMC1

(b) DC voltage of MMC2

(c) Frequency of MMC1

(d) Frequency of MMC2

Fig. 10: System response to A 500 MW step decrease in MMC 3 AC power setpoint with different matching-GFM control lead time constant τ_z.



(a) DC voltage of MMC1

(b) DC voltage of MMC2

(c) Frequency of MMC1

(d) Frequency of MMC2

Fig. 11: System response to A 500 MW step decrease in MMC 3 AC power setpoint with different matching-GFM control lag time constant τ_p.

can be held responsible for them.

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