Analysis of Sub-Synchronous Oscillations Induced by AI Data Centers and Damping Enhancement Using Grid-Forming Inverters

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***Abstract*—The rapid growth of AI data centers introduces large scale, highly variable demands that can excite sub-synchronous oscillations (SSOs) in modern power systems. These oscillations, if undamped, can potentially threaten grid stability. This paper investigates the mechanisms by which AI data center load fluctuations induce SSOs. Furthermore, this paper evaluates mitigation strategies by co-locating a grid-forming (GFM) battery energy storage system (BESS) that integrates power oscillation damper (POD) techniques documented in the available literature. Detailed electromagnetic transient simulations in PSCAD/EMTDC demonstrate that the GFM-BESS with POD can significantly suppress the oscillations induced by AI data centers. These results demonstrate the effectiveness of GFM inverters in improving power system resilience and offer guidance for the secure integration of AI data centers into low-inertia grids.**

***Index Terms*—AI, data center, sub-synchronous oscillation, grid-forming inverter, power oscillation damper**

I. Introduction

While sub-synchronous oscillations (SSOs) have traditionally been studied in generation-dominated contexts, highly variable large loads, such as data centers, can also induce similar phenomena. Artificial inteligence (AI) data centers, in particular, show rapid and fluctuating power consumption due to diverse workloads and short bursts of demand. These rapidly changing patterns in power consumption can interact with system dynamics and excite poorly damped sub-synchronous modes in the surrounding grid. In this paper, we demonstrate that such variations in AI data center loads can give rise to SSOs. To mitigate these oscillations, a grid-forming (GFM) battery energy storage system (BESS) with an integrated power oscillation damper (POD), implemnted according to the techniques in [1] and [2], is co-located with the data center, which improves damping and enhances system stability.

II. Data Center Model

As shown in Fig. 1, a typical data center facility comprises several components, including (i) an emergency generator to maintain critical operations during outages or severe voltage sags, (ii) cooling system loads such as chillers, pumps, fans, and compressors, (iii) static loads including lighting and office equipment, and (iv) power electronic load. Among these, the power electronic load is the primary component supplying and conditioning power to the critical IT infrastructure and exhibits highly nonlinear, fast-acting dynamics that strongly influence the facility's transient and overall dynamic behavior. As illustrated in Fig. 1, the power electronic load consists of N racks with M vaults per rack, integrating IT equipment such as servers, storage arrays, and processor units, together with power conversion hardware. The power conversion architecture typically includes back-to-back AC/DC/AC converters and a DC/DC converter for the UPS system, shown along with their respective control systems in Fig. 2.

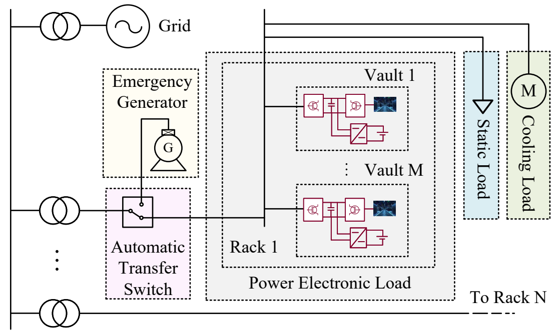

Fig. 1. The structure of a data center facility.

III. Sub-Synchronous Oscillations in Power Systems with AI Data Centers

SSOs are oscillatory phenomena in power systems that occur at frequencies below the nominal system frequency and can result from interactions among generators, network elements, and control systems. The increasing deployment of inverter-based resources (IBRs) has broadened both oscillation characteristics and potential causes [3]. In IBR-rich systems, fast-acting controllers can amplify poorly damped sub-synchronous modes, with a single "bad actor" potentially triggering widespread oscillations [3]. This underscores the need to understand, diagnose, and mitigate SSOs in modern low-inertia grids. The next section examines how AI data center load fluctuations can trigger SSOs, followed by a mitigation strategy.

A. SSO Excitation by AI Data Center Load Fluctuations

Large-scale AI data centers exhibit substantial active power fluctuations primarily due to the highly synchronized operation of graphical processing units (GPUs). During large model training tasks, GPUs operate in repeated cycles of intense

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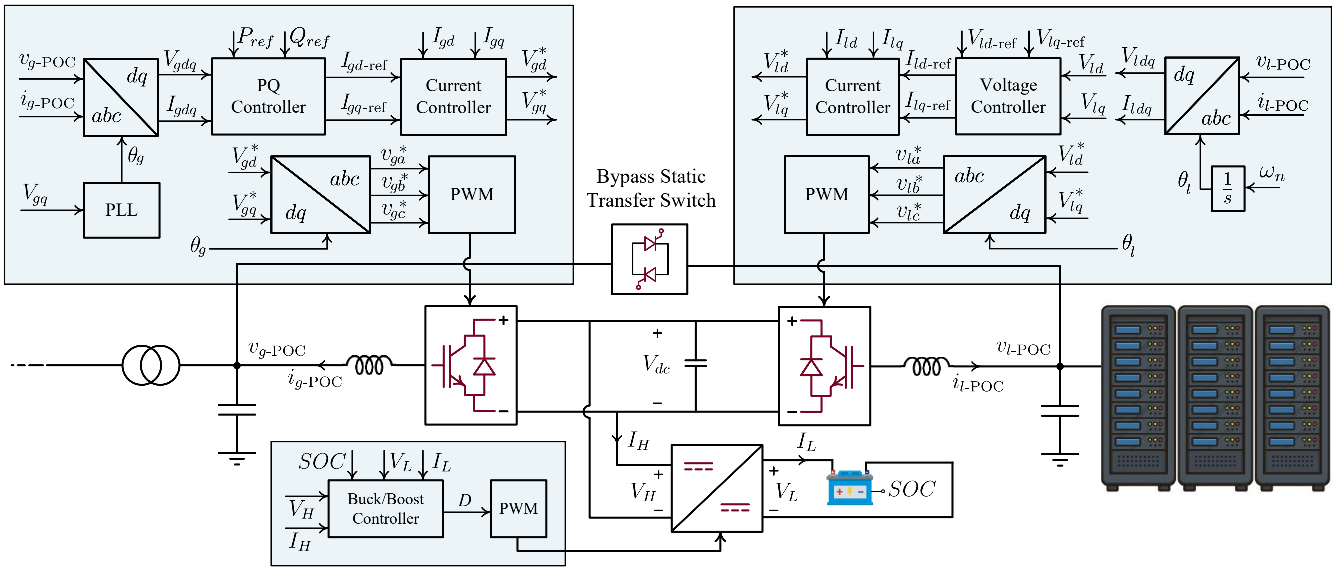

Fig. 2. The structure of the power electronic load within a data center facility.

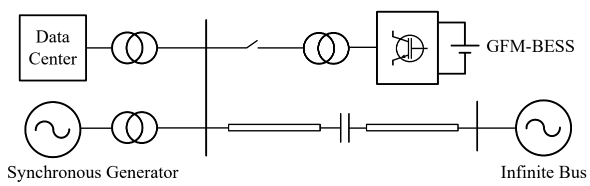

Fig. 3. The IEEE benchmark for sub-synchronous resonance augmented with a data center and a GFM-BESS.

computation followed by collective communication and memory synchronization phases, referred to as bulk-synchronous parallelism [4]. During the compute-intensive phases, GPUs operate near their maximum thermal design power, driving the instantaneous power demand of individual servers and the broader compute cluster to high levels, whereas during communication or checkpointing phases, GPU utilization drops significantly, causing the aggregate power draw to fall correspondingly [4]. These swings typically manifest at low frequencies, approximately 0.1 to 20 Hz [4]. The following explains how these low-frequency power variations in AI data centers can resonate with the natural frequencies of generators and other components of the electrical network, possibly inducing oscillations in the power system.

Following grid disturbances, in this case AI data center's large power fluctuations, the multi-mass mechanical system of the synchronous generator exhibits torsional oscillations at its natural frequencies. The corresponding electrical frequencies propagate throughout the network. These oscillations induced by the synchronous machine, in addition to the fluctuation of the load itself, excite the natural frequency of a network containing series-compensated transmission lines. This situation resembles an RLC circuit subjected to perturbations, with both machine-induced oscillations and repeated step changes from the data center acting as disturbances. Consequently, the network begins oscillating at its natural frequencies, and the resulting voltage and current variations feed back into the generator's air-gap torque, exciting additional torsional modes. This electromechanical interaction between the generator and the excited network can establish a positive feedback mechanism. The resulting oscillations can grow uncontrollably, leading to instability reflected as rising oscillations in electrical power, voltage, or shaft's torque, ultimately requiring protective actions to isolate affected components. The above scenario is illustrated through a case study below.

Case 1: In the test system of Fig. 3, the synchronous generator, series-compensated transmission line, and the infinite bus represent the IEEE benchmark for sub-synchronous resonance (SSR) analysis [5]. We have expanded this benchmark with the addition of the data center model from Figs. 1 and 2, along with a GFM-BESS, both connected to the synchronous generator's point of interconnection (POI). The ratings of the data center, GFM-BESS, and the synchronous generator are 1 GW, 800 MW, and 1800 MVA, respectively. The complete test system, shown in Fig. 3, has been modeled in PSCAD/EMTDC to capture detailed electromagnetic transients.

Assume that the GFM-BESS is out of service, and the data center load is operating at its peak power of 1 GW. At $t = 4$ s, the load starts oscillating at 10 Hz between 750 MW and 950 MW. These fluctuations persist for 4 s, after which, at $t = 8$ s, the load returns to its steady-state peak value of 1 GW. Fig. 4(a) shows the active power consumed by the data center load, including a zoomed-in view of the oscillations for better observation. Figs. 4(b)-(d) illustrate the synchronous generator's power and electrical torque, and the system's frequency, respectively.

As observed in Figs. 4(a)–(d), the load fluctuations induce sustained oscillations that increase in magnitude over time. At $t = 50$ s, the synchronous generator's active power exhibits oscillations of approximately 0.22 pu (equivalent to 396 MW),

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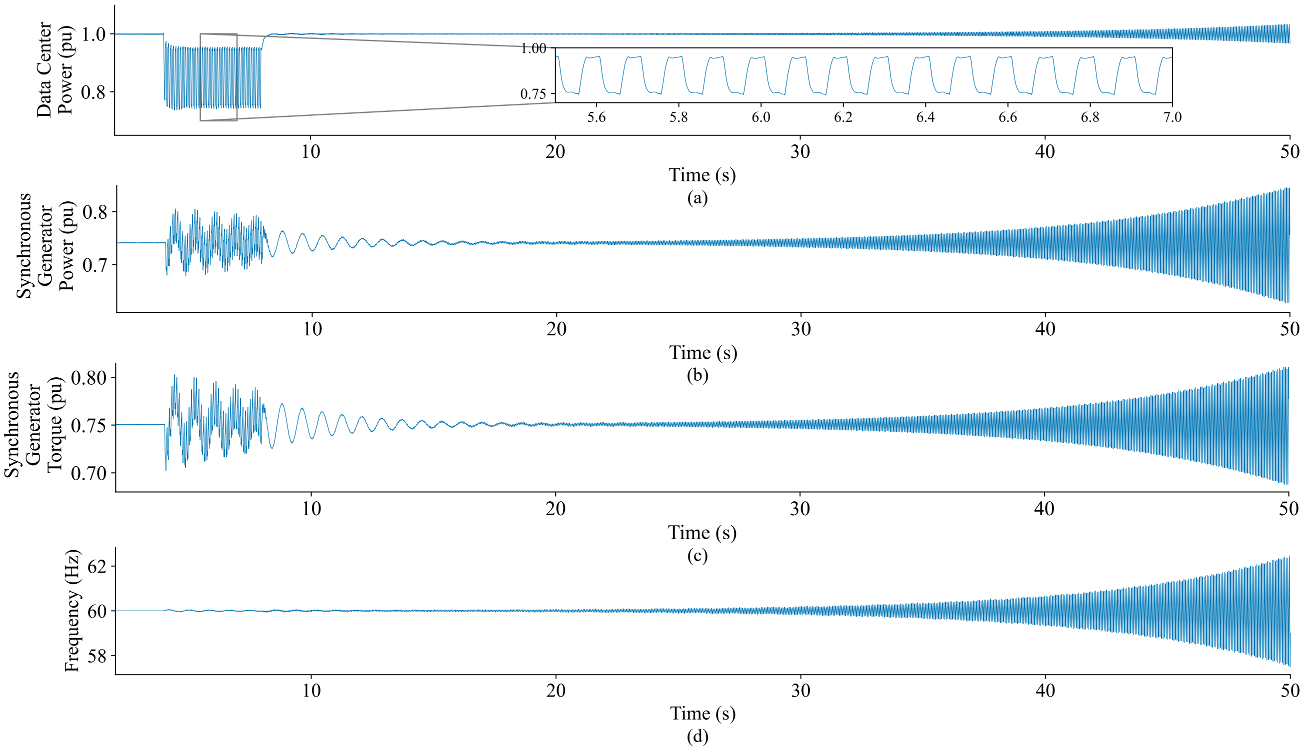

Fig. 4. Measurements for Case 1, (a) Data center power, (b) Synchronous generator power, (c) Synchronous generator torque, (d) Frequency.

while the system frequency varies between 57.5 Hz and 62.5 Hz. Such severe oscillations are indeed unacceptable, and in practice, protective relays would operate well before this point to prevent the system from experiencing widespread instability or damage to rotating machines and other grid equipment.

B. Damping Enhancement via GFM-BESS Co-Location

To mitigate AI-data-center–induced SSOs, we employ a twofold strategy [1], [2]: (i) a GFM-BESS to provide active damping, and (ii) augmentation of the inverter control with a power oscillation damper (POD). These techniques improve system stability by providing additional damping of low-frequency oscillations in power networks [1], [2]. Fig. 5 illustrates the control architecture of a GFM inverter implementing a virtual synchronous machine (VSM) strategy [6], with an integrated POD controller [2]. Note that due to the space limits, Fig. 5 shows only the active power control of the GFM inverter and excludes the voltage and current control loops.

<u>*Case 2:*</u> Consider again the test system of Fig. 3, now with the GFM-BESS in service. The same disturbance scenario used in Case 1 is applied. The measurements for this case are shown in Fig. 6. A comparison with the Case 1 results in Fig. 4 makes the effect of the GFM-BESS immediately clear. In Case 1, the synchronous generator's active power oscillations reached approximately 0.22 pu (396 MW) by the end of the 50-second simulation window. In contrast, with the GFM-BESS and POD active, the synchronous generator shows no noticeable oscillations in Fig. 6(b) and (c). A detailed zoom of the generator's power (not shown in Fig. 6) indicates a residual

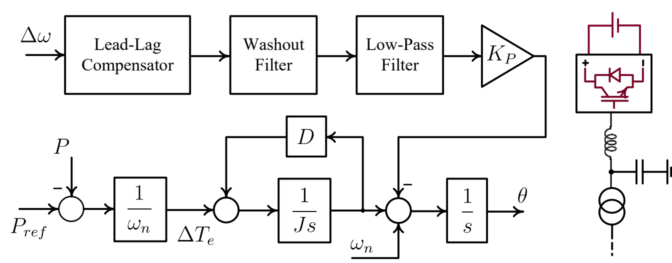

Fig. 5. The control structure of a VSM-controlled GFM-BESS augmented with a POD.

oscillation of only 0.00173 pu (3.1 MW). This represents more than a two-orders-of-magnitude reduction compared to the 396 MW power oscillation of Fig. 4(b), demonstrating that the GFM-BESS with POD nearly eliminates power oscillations.

Although the system frequency in Fig. 6 still exhibits a small, slowly growing oscillation (see the zoomed view in Fig. 6(d)), its magnitude is greatly reduced compared to Case 1. By the end of the 50-second simulation, the frequency varies only between 60.03 Hz and 59.97 Hz, representing a significant improvement over the severe 57.5–62.5 Hz excursions in Fig. 4(d). While a residual low-rate oscillation remains, the GFM-BESS effectively suppresses the dominant power oscillations and slows their buildup. This is important because many real-time damping mechanisms—such as POD-enabled STATCOMs and PV inverters, wide-area remedial action schemes, and adaptive damping controllers—require sufficient time to engage. The strong stabilizing effect of the GFM-BESS with

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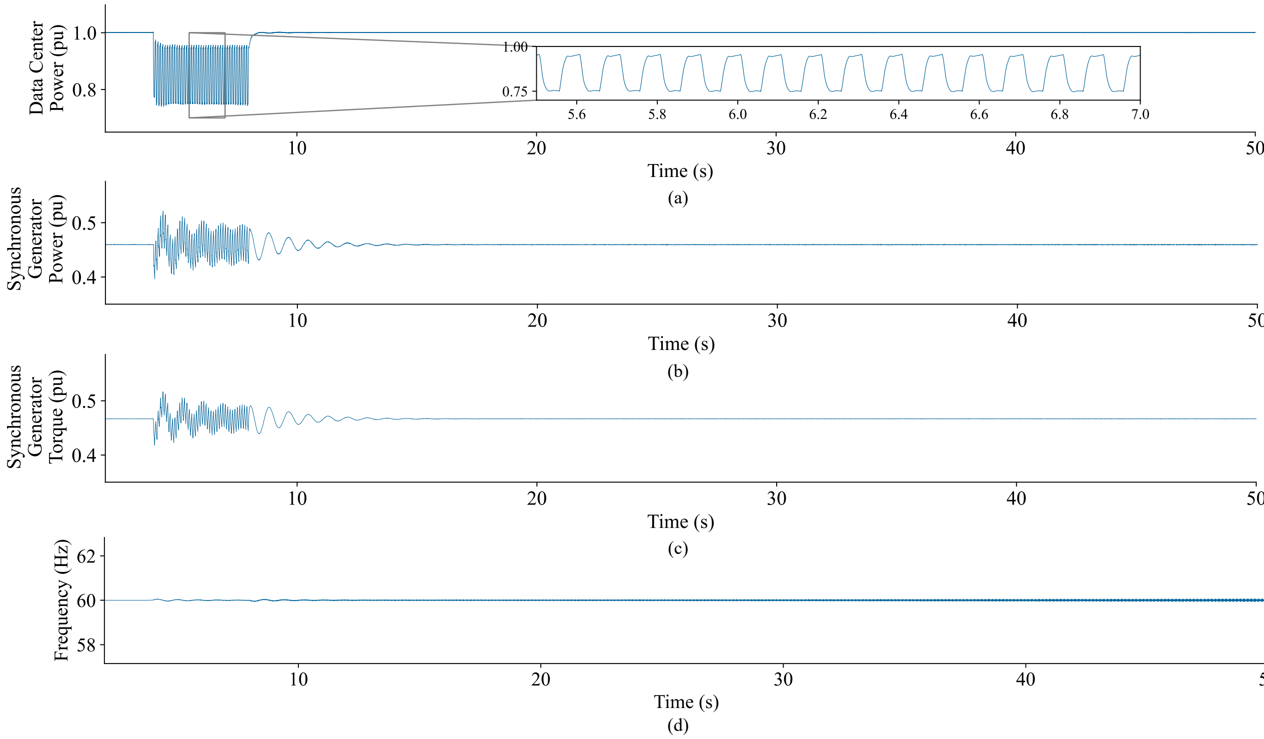

Fig. 6. Measurements for Case 1, (a) Data center power, (b) Synchronous generator power, (c) Synchronous generator torque, (d) Frequency.

POD therefore provides valuable response time, prevents rapid entry into protective thresholds, and reduces mechanical stress on the synchronous generator. Overall, the GFM-BESS with POD improves system robustness under data-center-induced disturbances. Additional mitigation measures, such as tuning the generator PSS, adding STATCOMs, and reducing series compensation, can further eliminate the remaining oscillations.

C. Frequency Scan Analysis of Data Center–Induced SSO

Figure 7 presents the frequency scan results for the system, data center, and co-located GFM-BESS. Figs. 7(a) and 7(b) show the resistance and reactance obtained from the system's passive frequency scan, where multiple reactance crossover points or low-reactance regions associated with negative damping are observed in the ranges of 30–55 Hz and below 10 Hz, indicating potential SSO-prone resonance frequencies. The data center's active frequency scan, shown in Figs. 7(c) and 7(d), reveals negative damping primarily in the 38–47 Hz range, which overlaps with the system resonance regions and can therefore amplify sub-synchronous oscillations. At lower frequencies, the data center provides only limited positive damping, which is insufficient to fully suppress existing oscillatory modes. In contrast, Figs. 7(e) and 7(f) demonstrate that co-locating the data center with the GFM-BESS introduces positive damping over most of the sub-synchronous frequency range, leading to a substantial improvement in system stability. Although slight negative damping persists at very low frequencies and near the fundamental frequency, explaining the small residual oscillations observed in the time-domain results of Fig. 6(d), the overall oscillation magnitude is significantly reduced. These findings are consistent with the EMT simulation results and confirm the interaction between data center load dynamics and network resonances, as well as the effectiveness of the GFM-BESS in mitigating SSO.

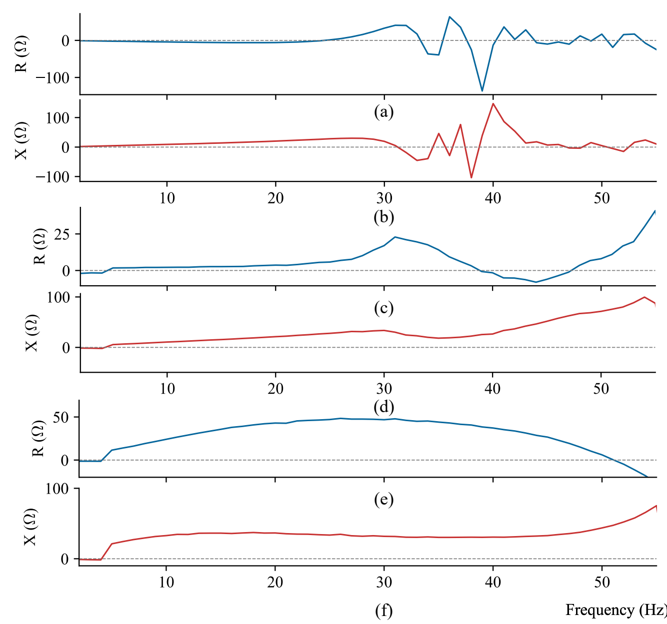

Fig. 7. Frequency scan results for the components of the test system shown in Fig. 3, R and X measured in: (a) and (b) System's passive frequency scan; (c) and (d) Data center's active frequency scan; (e) and (f) Active frequency scan of the data center co-located with GFM-BESS.

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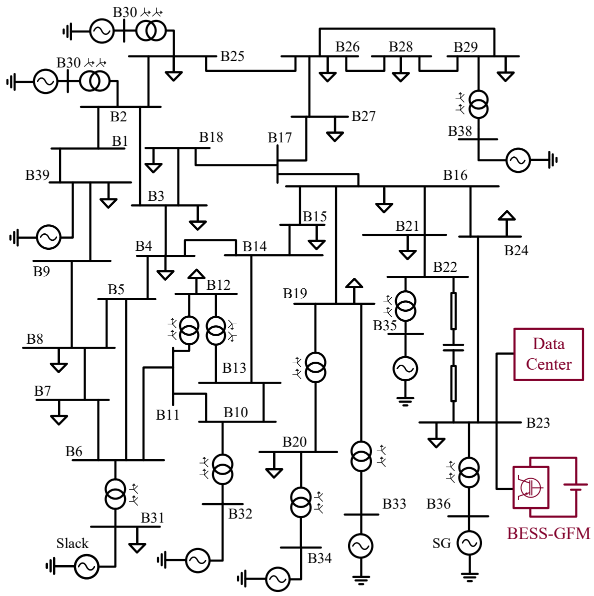

Fig. 8. The IEEE 39-Bus test system augmented with a data center and a GFM-BESS.

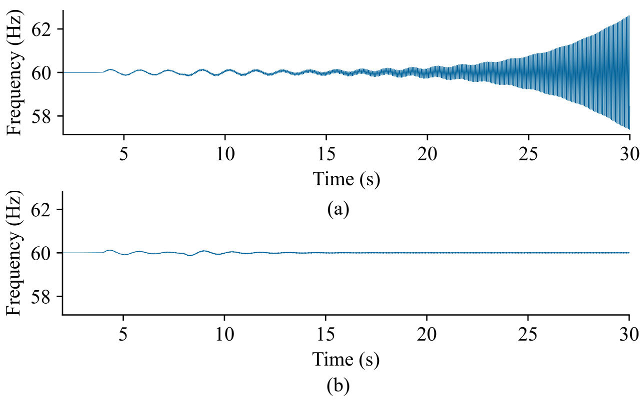

Fig. 9. Frequency measurements in the IEEE 39-Bus test system, (a) when GFM is out of service and (b) when GFM-BESS is in service.

D. Extended Validation on the Standard IEEE 39-Bus System

To further validate the proposed approach, simulations were conducted on the IEEE 39-Bus system shown in Fig. 8, where a data center co-located with a GFM-BESS is connected to Bus B23, with series compensation on the line between B23 and B22. The data center and GFM-BESS adopt the same configurations and control structures as in Figs. 2 and 5. Following an N-1 contingency, the line between B23 and B24 is tripped. Assume that the data center load oscillates at 10 Hz between 750 MW and 950 MW for 4 s. Without the GFM-BESS, sustained oscillations occur and the frequency varies between 57.4 Hz and 62.6 Hz by t = 30 s, as shown in Fig. 9(a). With the GFM-BESS and POD enabled, the frequency remains within 59.98–60.02 Hz, as illustrated in Fig. 9(b). Only frequency results are presented due to space limitations. These results confirm the effectiveness of the proposed damping strategy on an IEEE benchmark system.

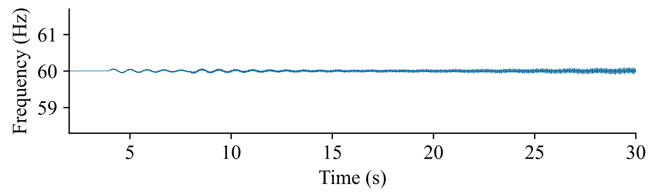

Fig. 10. Frequency measurements when a STATCOM with POD is co-located with the data center.

E. Comparison of STATCOM and GFM-BESS Damping Performance

A STATCOM with built-in POD was modeled in PSCAD and co-located with the data center in Fig. 4, with the GFM-BESS disconnected. Fig. 10 shows the system frequency, indicating that the data center's load fluctuations induce sustained oscillations. By the end of the 50-second simulation, the frequency varies between 60.4 Hz and 59.6 Hz, improving over the severe 57.5–62.5 Hz excursions without the GFM-BESS. Although the STATCOM provides significant damping, it is less effective than the GFM-BESS, where the frequency varies only between 60.03 Hz and 59.97 Hz. This superior damping arises because, in addition to the POD in both systems, the GFM control inherently provides extra damping through the constant D in the VSM control system shown in Fig. 5.

IV. Conclusion

AI data center load fluctuations can induce significant SSOs in power systems, leading to large power and frequency deviations. This paper demonstrates that a grid-forming BESS with an integrated POD dramatically reduces generator's power and system's frequency oscillations by over two orders of magnitude. While a small residual oscillation remains, the GFM-BESS provides valuable time for other real-time damping mechanisms to act, prevents protective trips, and reduces mechanical stress on the generator. Combined with additional mitigation strategies, the approach can enable fully secure and reliable integration of large AI data centers into modern grids.

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