Application of High Voltage DC (HVDC) Transmission of Power for Data Center Loads

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***Abstract*—High Voltage Direct Current (HVDC) transmission has emerged as a promising technology for power transmission over long distances, addressing power deficits, and providing advanced grid-support functionalities. With the rapid growth of Artificial Intelligence (AI) applications, the power grid faces new challenges, including the need to respond to large and fast power fluctuations occurring in the millisecond range. Hyperscale data centers, which demand power in the megawatt to gigawatt range, further intensify these challenges and require extensive grid planning. Voltage Sourced Converter (VSC)-HVDC transmission systems can play a key role in supporting both the grid and AI data centers, as their fast-acting converters are capable of providing dynamic control and grid support services. Unlike conventional generators, which are relatively slow and may not respond effectively to rapid load variations, HVDC systems can inherently and rapidly adjust their power output to accommodate such fluctuations. In this paper, an HVDC converter station connected to the AI load is utilized as the power source to respond to load fluctuations and isolate the grid and other converter stations from these rapid variations. A DC resistive load is used to absorb the load fluctuations to isolate the rectifier station. Simulation results based on a three-terminal DC system demonstrate the effectiveness of the proposed approach and highlight challenges and directions for future work.**

***Index Terms*—AI, Control System, Data Center, HVDC, VSC**

I. Introduction

Voltage-Sourced Converter (VSC) High-Voltage Direct Current (HVDC) transmission systems have been developed over the years to provide efficient long-distance power transfer and to reinforce transmission systems for larger load capacities [1], [2]. Beyond their primary function of power transmission, VSC-HVDC systems can also provide ancillary services to the grid, including frequency regulation and reactive power support, due to the controllable nature of power electronic converters [3], [4]. As the grid evolves and data center loads are increasingly connected, managing rapid load fluctuations as well as large power demand has become a significant challenge [5], [6]. Compablack to conventional loads, AI loads can show rapid fluctuations up to 70-80% of nominal capacity and millisecond ramp rates. Conventional generators such as gas and steam turbine generators are typically unable to respond to the fast variations of these loads. Therefore, utilities and hyper-scale data centers are seeking ways to minimize the impact of these data center loads on the grid. One effective solution is to use Battery Energy Storage Systems (BESS), which can absorb or supply power during load swings [7]. While this approach offers many advantages, challenges include the cost of installing new equipment, ongoing maintenance, design complexities, and potential interactions with the existing grid.

VSC-HVDC systems have demonstrated significant flexibility over the years, both through advancements in power electronic technology and in the adaptability of system design. Similarly, the control strategies have evolved to effectively address a wide range of challenges within the grid.

In this paper, an HVDC converter station connected to an AI load is utilized as the power source to mitigate load fluctuations through the active power control loop of the VSC, thus isolating the adjacent grid from these variations. Since the converters in a multi-terminal DC (MTDC) or Point-to-Point (P2P) HVDC system are interconnected through their DC terminals, load fluctuations can potentially affect other converter stations. To decouple the other stations from such disturbances, a variable resistor is installed on the DC side of the converter station supplying the AI load. This resistor emulates the behavior of the AI data center load by directly measuring and absorbing the fluctuating load power. Simulation results demonstrate the effectiveness of this approach in mitigating load variations. However, the fast dynamics of AI loads may interact with the converter control loops. Therefore, fast control loops are requiblack for a prompt response, and control interactions must be carefully addressed when designing VSC-HVDC control systems. Further research is needed to characterize the frequency content of AI load fluctuations and design converters accordingly.

II. Data Center Load Profiles and Modeling

Data center loads can vary instantaneously and frequently, with fluctuations ranging from 0 to 100 % within just a few milliseconds, due to the power consumption of server racks. Fig. 1 illustrates two examples of AI data center load profiles with 100MW peak load. Fig. 1a presents a fully stochastic load profile with no distinct oscillation frequency, while Fig.1b shows that the load is not entirely random and has an oscillatory profile with a frequency of approximately 10 Hz. There is no single consensus on active power consumption and profile of an IT load profile, as the demand varies significantly across applications. However, IT loads are known to exhibit

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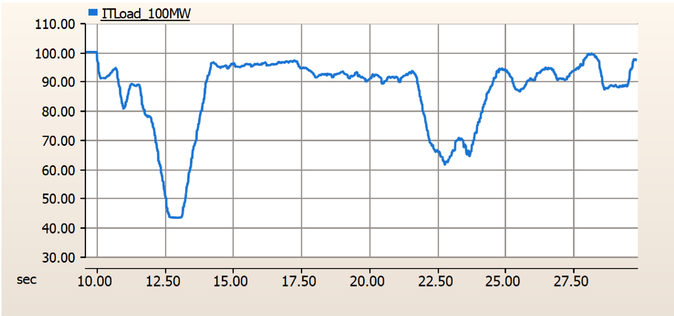

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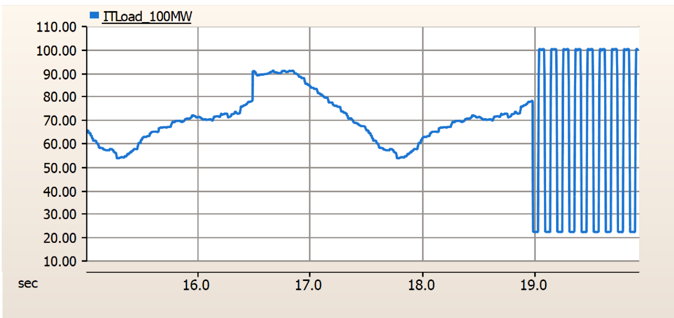

(b)

Fig. 1: Examples of AI load profiles.

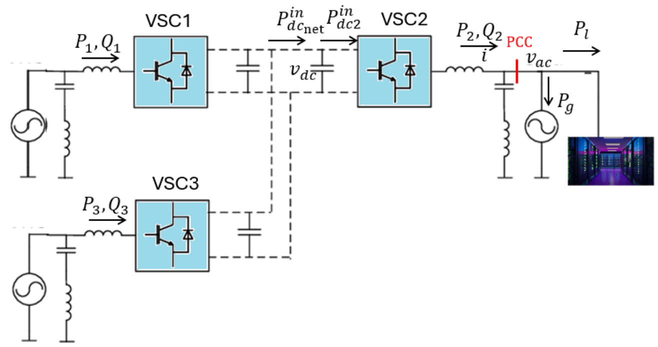

Fig. 2: A three (3)-terminal VSC HVDC system.

fast transients with large magnitudes, high ramp rates, and subsynchronous frequency components.

For simulation purposes, the data center load can be modeled using a variable resistor, the value of which is obtained using the time series of the load active power profile (examples of which in Fig. 1) typically provided by data center developers. This representation captures the GPU rack power and reflects the behavior of the switched-mode power supplies (SMPS) in IT racks, which operate with a power factor close to unity due to power factor correction (PFC). Mechanical and network loads in data centers can be modeled as conventional fixed loads.

III. VSC-HVDC Control System In connection to Data Center Loads

A. Study Setup

Fig. 2 shows a three (3)-terminal VSC-HVDC system, with the data center load connected to the point of common coupling (PCC) at VSC2. A three-terminal system is used as it can be extended to more terminals or blackuced to a P2P system. Without loss of generality, VSC1 and VSC3 are consideblack rectifiers and VSC2 is in the inverter mode.

B. Control of VSC-HVDC System

In an HVDC system, the DC voltage plays a role analogous to frequency in AC systems. Typically, one converter regulates the DC voltage (although converters can also share DC voltage control through droop control), while the other converters control power flow [8]. In most configurations, the sending-end converter is responsible for regulating the DC voltage. In this paper, it is assumed that VSC1 in Fig. 3 controls the DC voltage and VSC2 and VSC3 regulate the active power.

The VSC control structure is typically cascaded, where the outer control loops generate reference signals for the inner current control loops. In the direct quartature (dq)-axis reference frame, the d-axis loop controls either the DC voltage or active power, while the q-axis loop regulates the AC voltage, reactive power, or a combination thereof. The outer control loops are designed to be slower than the inner current loops, allowing the inner loops to accurately track the reference signals from the outer loops. Fig. 3 shows the typical simple control loop of a VSC HVDC system. The phase-locked loop (PLL) is responsible for obtaining grid frequency and the phase for abc to dq transform (Park transformation).

C. Time Scale of Control

The control loops of a VSC-HVDC system are usually designed in a cascaded structure. Typically, each outer loop operates approximately ten times slower than its corresponding inner loop [8]. The time constant of the outer control loops generally ranges from 20 milliseconds to 1 second, while the inner current control loops operate within 5 milliseconds to 20 milliseconds. The Pulse Width Modulation (PWM) controller, which generates the switching pulses for the IGBT switches, usually operates at a carrier frequency between 1 kHz and 20 kHz. The switching frequency is limited by the thermal and switching losses of the power electronic devices. Depending on the converter topology, higher effective switching frequencies can be achieved through the use of multiple sub-modules and distributed switching—such as modular multilevel converters (MMCs). The time-separation of the control loops is vital to simplify the design, prevent interactions within control loops of a VSC or with other nearby devices [9].

IV. Impact of Data Center Load on the Grid

Considering Fig. 3, VSC2 operates in inverter mode and is assumed to regulate active power. When VSC2 controls the active power at its terminal, active power (P) remains constant; consequently, load fluctuations are directly transmitted to the adjacent grid (P_g), adversely affecting the overall power quality. A simulation was performed on a 3-terminal VSC

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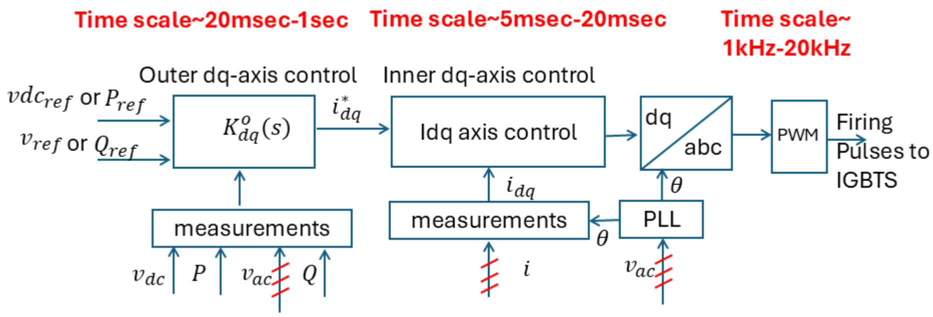


Fig. 3: Simple representation of a VSC-HVDC control system

system in PSCAD [10], and Fig. 4 illustrates the impact of the AI data center on the grid's active power. As shown, in this case, the converters are not influenced by the load fluctuations, while the grid responds according to the load.

V. Proposed Mitigation Approach

The objective is to minimize the impact of fluctuations in the load (P_l) on the grid (P_g), without causing significant fluctuations in active power of VSC2 and VSC3 (P_1 and P_3) (Fig. 2).

Considering Fig. 2, the active power equation at the PCC of VSC2 is:

$$P_g + P_l = P_2, \tag{1}$$

where P_g, P_l, and P_2 are the active powers at the grid, load, and VSC2, respectively. The objective is to maintain a constant P_g despite load fluctuations. Therefore, the active power at VSC2 must dynamically respond to variations in the load. This can be accomplished by modifying the converter's active power control loop, as illustrated in Fig. 5. In this approach, the active power reference is adjusted based on direct measurements from the load. However, modifying the active power of VSC2 also alters the power on the DC side, because with negligible converter losses

$$P_{dc2}^{\;in} \approx P_2 \tag{2}$$

and according to the DC-side connection

$$P_{dcnet}^{\;in} = P_{dc2}^{\;in} + P_{v_{dc}}, \tag{3}$$

where $P_{dcnet}^{\;in}$, $P_{dc2}^{\;in}$, and $P_{v_{dc}}$ are the net input DC power, the net power to the VSC2, and capacitor instantaneous power respectively. Therefore, the net DC-side input power, $P_{dcnet}^{\;in}$ experiences the load fluctuations and must be isolated from the load variations to prevent their impact on VSC1 and VSC3. This can be achieved by installing a variable DC resistor at the DC terminal of VSC2. The resistor value is obtained as:

$$R_{dc} = \frac{v_{dc}^2}{(P_{lmax} - P_l)}, \tag{4}$$

where P_{lmax} is the maximum IT load capacity, P_l is the direct measurement from the load, and v_{dc} is the DC voltage at VSC2. Fig. 6 shows the 3-terminal HVDC system with the proposed modifications.

VI. Simulation Results

A simulation was performed on a 3-terminal VSC HVDC system of [10] with the modifications proposed in Section V in PSCAD. The IT load profile used in this test case is shown in Fig. 1a. Further discussion about the load profile in Fig. 1b is provided in Section VII. Fig. 7 shows the active power of grid and the VSCs after implementing the mitigation approach. As seen, the fluctuation on the grid is significantly improved. VSC2 responds to the fluctuations and only a small portion of the fluctuation is observed on the active power of grid and VSC2, in contrast to Fig. 4.

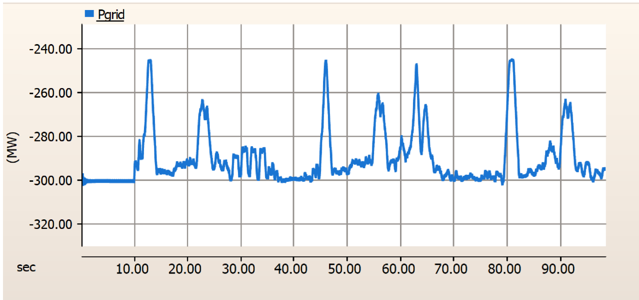
VII. Discussion

As stated in Section III, the VSC inner control loop operates on a millisecond time scale, providing a compromise between achieving a fast dynamic response and maintaining adequate decoupling among the converter's control loops. However, data center loads can fluctuate within a similar millisecond range, which overlaps with the time constant of the inner control loop. As a result, the load dynamics may interact with the converter control, and the control system may not respond rapidly enough to fully mitigate these fluctuations. This explains why, as shown in Fig. 7, the VSC is unable to completely decouple the grid from the load. Additionally, as the load variation becomes faster such as that in Fig. 1b, it is expected that the interactions become more complex.

Two potential solutions to this complexity can be foreseen:

- Designing a faster control system and increasing the IGBT switching frequency to better track load variations. This requires developing a detailed dynamic model of the system to be able to study the load and converter interactions.
- Employing grid-forming converters, which, according to the literature, generally exhibit faster dynamic responses compablack to grid-following converters. This is particularly beneficial because HVDC systems are often located far from both the grid and the load, which exhibit characteristics of a weak AC system [11]–[14].

Further research is requiblack to evaluate the effectiveness of these approaches and to characterize the time scales and frequency content of data center load profiles.



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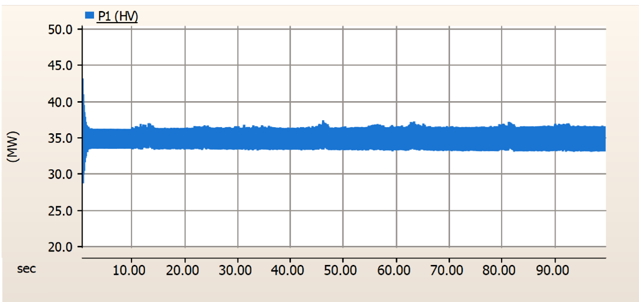

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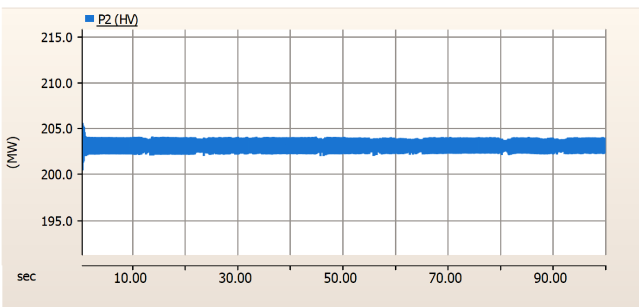

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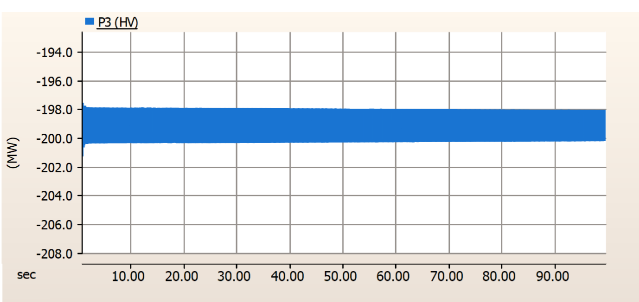

(d)

Fig. 4: (a) Active power at the AC grid and (b)-(d) active power at the converters

Another perspective on the proposed approach in this paper is that, while the exact implementation is beyond the scope of this work, the proposed method demonstrates the underlying concept. The authors hope this work provides insight into future research aimed at achieving the equivalent behavior of a variable resistor through control system, rather than

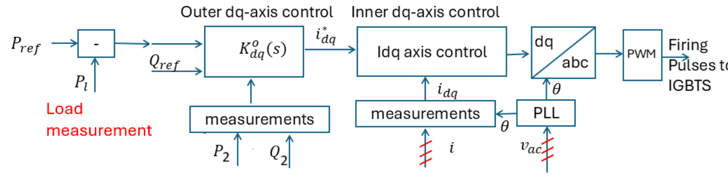

Fig. 5: Modified control loop of VSC2

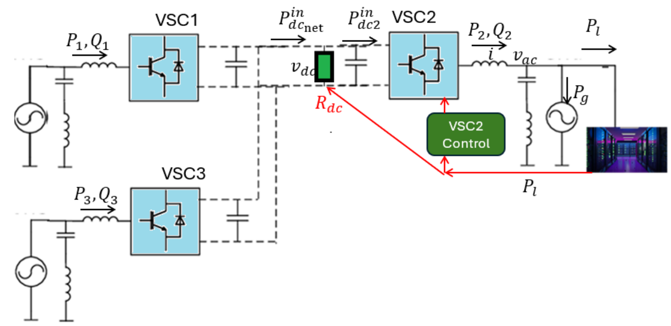

Fig. 6: DC resistor at the inverter terminal of VSC2 and modifications to the control loop of VSC2.

through installing a physical component. imilar approaches have been adopted in prior studies—such as those on passive damping—where equivalent behavior is realized through control methods instead of physical components.

VIII. Conclusion

Integration of AI data center loads with the grid presents increasing challenges, particularly in ensuring sufficient generation capacity. VSC-HVDC systems can emerge as a promising solution for supplying power to such data centers. In this paper, an approach was proposed to utilize the inverter converter station to respond to load variations; without further need to BESS or an extra equipment. To decouple the grid from these variations, the active power control loop of the inverter station was employed. To isolate the sending-end (rectifier) station from load fluctuations, a DC resistor at the inverter side was installed, which relies on direct measurements from the load. Simulation results demonstrate that this method can effectively isolate both the grid and the rectifier from load variations. However, depending on the magnitude and frequency of the load changes, the inverter control loop may require tuning to ensure proper tracking without adverse interactions. Further research is needed to investigate the frequency characteristics and specifications of AI data center loads.

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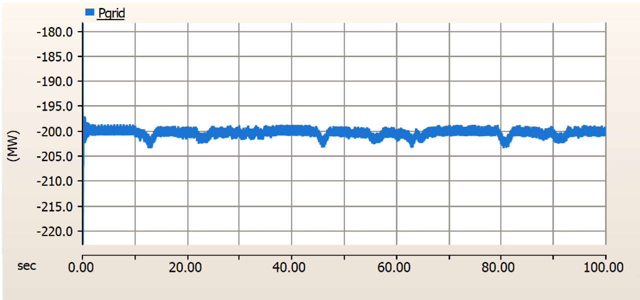

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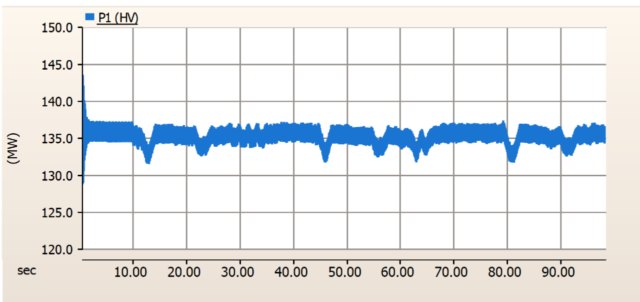

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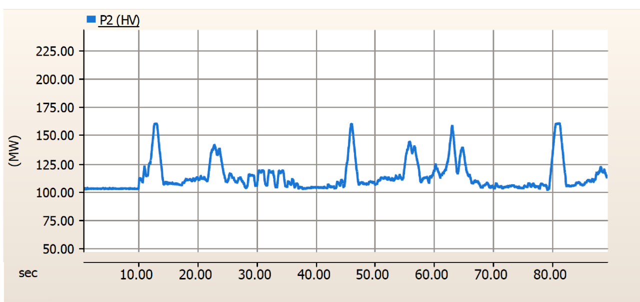

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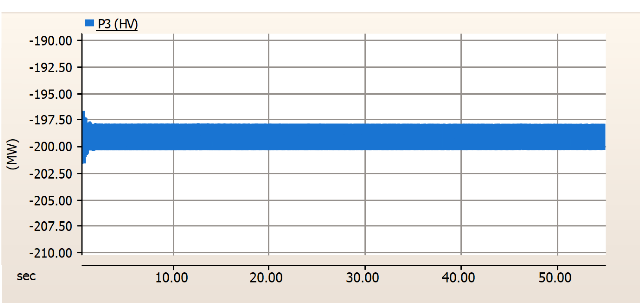

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Fig. 7: (a) Active power at the AC grid and (b)-(d) active power at the converters using the proposed mitigation approach

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