Fault Response and Protection System Impacts of Large Electronic Loads Considering Emerging Ride-Through Requirements.

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***Abstract*—The prevalence of large, transmission-connected electronic loads is rapidly increasing; these loads must remain connected during faults to support system stability. In this work, we evaluate how the fault currents produced by large electronic loads may interact with transmission line protection and provide guidelines for transmission planners and protection engineers to manage these interactions. We present field experiences that highlight ongoing operational challenges as well as a detailed electromagnetic transient study exploring how different load-side solutions for fault ride-through interact with the transmission system, from both a protection and stability standpoint. The result is a set of design tradeoffs which planners, protection engineers, and load developers can use as part of a holistic approach to maintaining system reliability.**

***Index Terms*—data center, inverter, transmission line protection, power system modeling.**

I. Introduction

The prevalence of gigawatt-scale large electronic loads, such as data centers, on the grid is rapidly increasing [1]. The fault ride-through behavior of these loads can significantly impact system stability, prompting transmission service providers (TSPs) to begin developing ride-through requirements that specify how the loads should respond to faults. Just as is the case with inverter-based resources, the fault ride-through requirements set by TSPs for large loads can affect the performance of transmission system protection. Depending on how large loads implement under-voltage ride-through controls, fault current contributions from large electronic loads can be comparable to those from generation, especially if nearby generation is primarily inverter-based.

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Recent grid events involving the tripping of large numbers of data centers [2]–[4] highlight a need for improved coordination between site-level protection at data centers and transmission system protection. Conventionally, data centers have been too small and distributed for this to be necessary. Broadly speaking, the MV and LV networks of data centers are protected using approaches conventional to industrial power systems [5], [6]. Mission critical equipment is protected by double-conversion uninterruptible power supplies (UPS) with battery backup capable of supporting the load on a ten-minute timescale, reducing the need for sophisticated high-speed transfer schemes or networked systems. Any networked systems downstream of the UPS are protected using current differential (e.g., [7]) or pilot protection. Historically, data centers disconnecting during grid disturbances has gone largely unnoticed by TSPs, and site-level transfer schemes are often set sensitively, with a preference to disconnect proactively at signs that the grid is facing issues in order to minimize the risk of process interruptions. For these reasons, prior work on coordination between transmission system and data center site-level protections is minimal.

That said, some valuable work on data center modeling has already been done. In [8], authors present an approach for EMT modeling of a conventional data center, an approach which we have adopted and tailored in detail to better fit system-level fault studies. In [8], authors present a crypto-miner power supply. The model is appropriately detailed for fault studies and experimentally validated, but not representative of the more traditional data centers that are the focus of this work. This work leverages a set of open-source data center models for use in PSCAD/EMTDC [9], [10]. Much other modeling and analysis of grid impacts from data center dynamics has focused on the effects of rapidly fluctuating power demands associated with training and inference processes for large language models [11]–[13].

The primary contribution of this work is to define a set of design practices and trade offs for low-voltage ride through requirements and implementation which TSPs, data center developers, and data center suppliers can incorporate into their designs and requirements in order to ensure system stability and protection coordination. Studies are performed using electromagnetic transient (EMT) analysis with detailed protective relay and load electronics models. Effects on step distance protection, line current differential, directional elements, and reclosing are considered. We also discuss approaches for studying data center protection impacts with short-circuit models (rather than a detailed EMT model). We include field data and experiences from transmission system operators and protection engineers actively involved in the integration of large electronic loads.

II. Operational Experience with Data Center Fault Response

In this section, we summarize some of our real-world experience with data centers and their interactions with transmission-level protection systems. Event data is shared to highlight the practical relevance of the subsequent studies.

A. Experience in the Texas Region

ERCOT has had many events over the past few years involving crypto currency mining facilities either tripping or significantly reducing consumption during normally cleared system faults. Since the mining equipment is typically single-phase constant power devices, disturbance monitoring equipment from the transmission side monitoring the facility usually records current spikes in the faulted phase(s) during the voltage sags. Although this performance has not caused any transmission protection systems to operate during previous events, ERCOT is concerned that these current spikes during voltage transients could potentially cause misoperations and voltage stability issues. Fig. 1 illustrates a significant increase in current magnitude during an A-B fault, in which the current magnitude in the phase with the deepest voltage sag increases to over 160% of the pre-disturbance current (top graph).

B. Experience in the Virginia Region

In Virginia, the rapid proliferation of data centers constructed by only a handful of companies has led to repetition of facility designs. The repetition of design becomes detrimental when multiple facilities located both geographically and electrically close to each other are nearly identical—similar equipment, similar configuration, similar settings, etc. This results in a single disturbance causing several facilities to respond similarly. At a low density, this issue is not readily apparent or relevant, but at high density, this aggregate behavior can lead to large power swings when the data center's protection is not coordinated with the automatic reclosing on the transmission system. The onset of this problem has been so rapid that many projects have been approved and are in

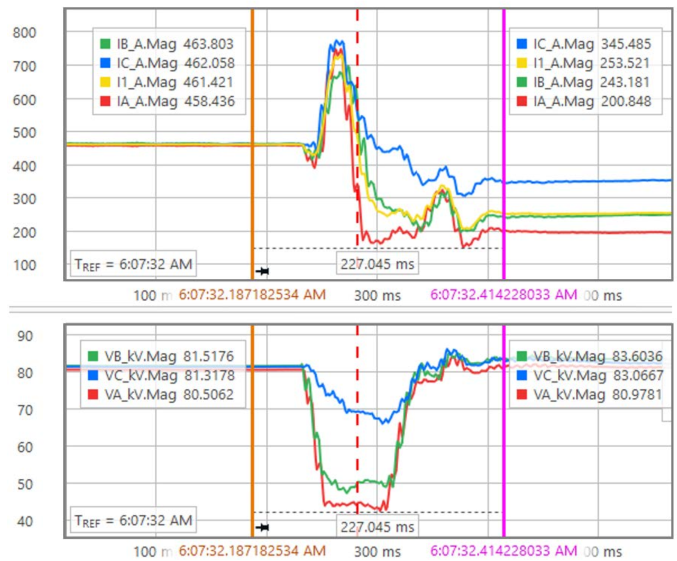

Fig. 1. Response of crypto mining facility to A-B fault, illustrating significant overcurrent for several cycles.

various stages of completion making correction difficult. In the first load loss incident [3], a common fault on Dominion Energy Virginia's (DEV's) transmission system in an area with high data center density made it clear that DEV and the data center owners had little understanding of how their equipment and practices affected one another: over a gigawatt of voltage-sensitive load disconnected suddenly and did not return for several hours (Fig. 2). The automatic reclosing practices that DEV conventionally uses on the transmission system involve multiple fault testing attempts, which cause voltage depressions. Data center protection at several facilities interpreted

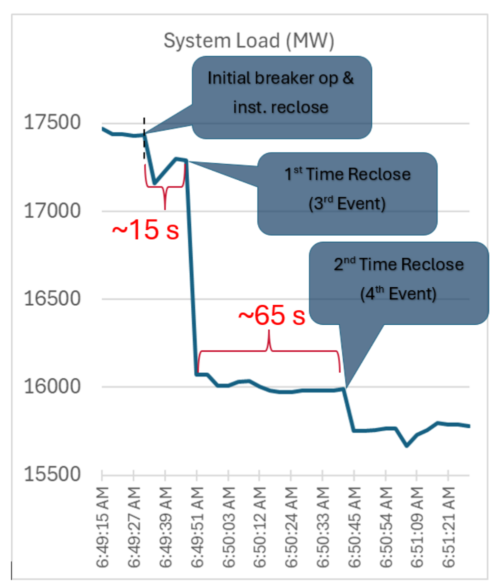

Fig. 2. DEV active power demand during load loss event in response to reclosing, illustrating additional load loss at each reclosing shot.

these voltage depressions in a way that caused their protection to disconnect from the grid. The resolution required DEV and the data center owners working together to implement an initial version of load ride-through by exchanging information and the data center owners altering protection settings to improve their response to common system events.

DEV suggests that other transmission owners:

- Require distribution providers to include detail about the nature of the load they are connecting—as much detail as possible upfront, but it should be a requirement when the facility commences operation.
- Discuss automatic reclosing practices and customers' load ride through capabilities for large industrial or commercial customers.
- Replace electromechanical relays near voltage sensitive loads with microprocessor relays to ensure consistent, high-speed clearing times.
- Explore historical event records to ensure that automatic reclosing practices provide reliability benefits.
- Require customers to install high-fidelity power quality monitoring as close to the large load facility as possible. The meters should measure and record the following data at high resolution:
  - Active and reactive power, with time-synchronized logging to track fast fluctuations or ramping behavior.
  - Energy Usage: both by phase and total.
  - Voltage and current harmonics up to the 50th harmonic.
  - Flicker severity, both short-term and long-term.
  - Magnitude, frequency, and duration of voltage dips, sags, and swells.
  - Voltage and current imbalance.
  - High-resolution (e.g., >1 ksps) capture of transient voltage and current waveforms resulting from switching events, faults, or equipment operations.
  - Frequency deviations.
- Implement load ride-through requirements in facility interconnection requirements [14]. Specifically, consider:
  - Coordinating under-voltage threshold for nominal line-to-neutral voltage to count a depression as an event; threshold should be set as low as possible while respecting load equipment capabilities to reduce likelihood that common fault-related depressions will be counted.
  - Setting a voltage depression event detection timer to approximately 80–120 ms or more to handle automatic reclosing schemes.

III. System Under Study

Studies are performed using an open-source EMT model based on the IEEE 39-bus transmission system [15]. Several loads, which are modeled simply as constant power loads in the base case, have been replaced by detailed data center models based on an open-source data center modeling library

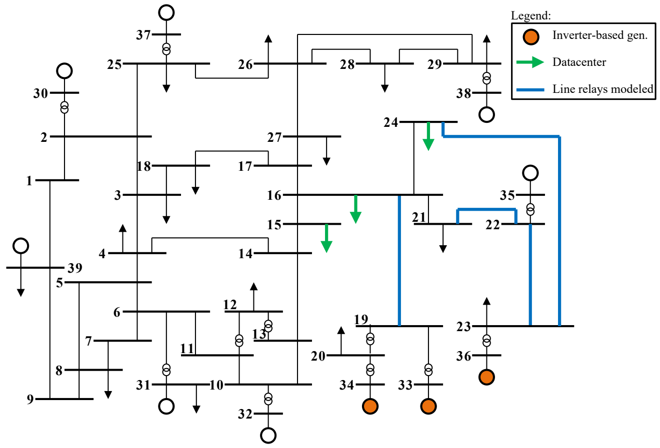

Fig. 3. Variation of IEEE 39-bus test system used to study protection system impacts from data center ride-through.

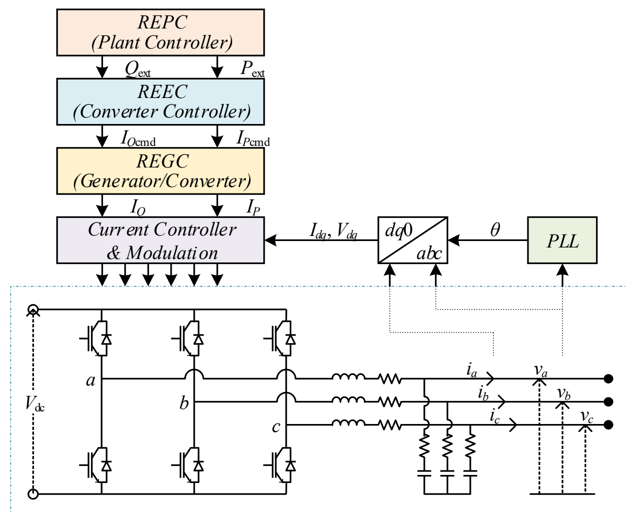

Fig. 4. Control design for inverter-based generation.

[9], [10]. Additionally, models of transmission line protective relays have been added to protect a selection of transmission lines, selected to allow for targeted study of areas where the data center's fault contribution will be most impactful to the fault currents and voltages measured by the relays.

A. Inverter Model

Inverter-based generation is represented using WECC-approved generic models [16], [17], which are publicly available for download [18]. The REPC component implements a plant-level controller, regulating active and reactive powers at a remote bus. The REEC represents the outer control loops of the inverter control, implementing active and reactive power control loops to generate current commands. The REGC models the inner control loops, and its main function is to limit the current commands based on the local voltage conditions measured at the IBG terminal.

B. Protection System

Line protection relays use a detailed model of typical protective relay signal processing including sampling, zero-crossing-based frequency tracking, and cosine filtering. Protection quantities are calculated 16 times per power-system cycle. The lines indicated back in Fig. 4 are protected using distance elements with direct transfer trip but no pilot protection. Mho characteristics are used for both phase and ground elements. Positive-sequence memory polarization with a time constant of four cycles is used [19]. Table I summarizes the reach and timer settings used. Line impedance data are taken directly from the system model data.

TABLE I
SETTINGS USED FOR STEP-DISTANCE PROTECTION

Parameter	Value	Parameter	Value
Zone 1 Reach	0.8 pu	Zone 1 Time Delay	0 s
Zone 2 Reach	1.2 pu	Zone 2 Time Delay	0.5 s
Zone 3 Reach	2.1 pu	Zone 3 Time Delay	1.5 s

The distance elements are supervised by directional elements; phase, negative-sequence, and zero-sequence directional elements are implemented. The negative- and zero-sequence directional elements operate by projecting the corresponding apparent sequence impedance onto the line's sequence impedance (1) [20]:

$$z[k] = \frac{Re[V_{[k]} \bullet (I_{[k]} \bullet 1\angle\theta_{Z_L})^*]}{|I_{[k]}|^2}, \tag{1}$$

where $[k] = 0, 2$, corresponding to either a zero- or negative-sequence quantity and θ_{Z_L} is the impedance angle of the protected line. Additionally, dynamic forward and reverse thresholds ($Z[k]FTH$ and $Z[k]RTH$) are computed to improve security when the apparent sequence impedance magnitude is large ((2) and (3)):

$$Z[k]FTH = \begin{cases} 0.75 \bullet Z[k]F - 0.25 \bullet |\frac{V_{[k]}}{I_{[k]}}| & Z[k]F \leq 0 \\ 1.25 \bullet Z[k]F - 0.25 \bullet |\frac{V_{[k]}}{I_{[k]}}| & Z[k]F > 0 \end{cases} \tag{2}$$

$$Z[k]RTH = \begin{cases} 0.75 \bullet Z[k]R + 0.25 \bullet |\frac{V_{[k]}}{I_{[k]}}| & Z[k]R \geq 0 \\ 1.25 \bullet Z[k]R + 0.25 \bullet |\frac{V_{[k]}}{I_{[k]}}| & Z[k]R < 0 \end{cases} \tag{3}$$

Incorrect directional indications during transients are avoided using a pickup timer. Some vendors obtain higher speed and security using more sophisticated approaches (e.g., a counter of forward and reverse indications [21]), but this approach is sufficient for our case studies.

TABLE II
SETTINGS FOR NEGATIVE- AND ZERO-SEQUENCE DIRECTIONAL ELEMENTS

Parameter	Value	Parameter	Value
$Z[k]F$	-1.375 Ω_{pri}	Min. Current Mag.	10 A
$Z[k]R$	1.375 Ω_{pri}	Pickup Time Delay	10 ms

The phase directional element operates only for three-phase faults and provides a directional indication when all three apparent line-to-line impedance angles are within +/-80°of θ_{Z_L} (forward fault) or $-\theta_{Z_L}$ (reverse fault). Both phase and ground distance elements are armed whenever at least one of the directional elements issues a forward indication. While practical relays use more sophisticated logic to handle possible discrepancies between directional elements (e.g., [21]), this simplified approach provided proper selectivity and security for the case studies performed.

To accurately represent the transient performance of distance protection during close-in faults, coupled capacitive voltage transformers are modeled, using the extra-high C parameters given in [22]. It is assumed that current transformers have been adequately sized to avoid saturation.

C. Data center Model

Fig. 5 depicts a single-line diagram of the data center model used. Information technology equipment (ITE) is interfaced with the grid through a double-conversion UPS. In such a case, the response of the ITE to grid disturbances is primarily determined by the dynamics of the UPS input rectifier, which is commonly a three-phase inverter similar to those used in inverter-based generation. Data center fault response is varied by modifying the fault controls used in the UPS, which is the primary source of electronic load in most data centers. The following fault responses are considered:

- Tripping
- Constant Power Ride Through
- Momentary Cessation (MC)
- Reactive Power Support

Other than tripping, which is included as a base case, all of these behaviors could arguably constitute "riding through" a fault, but each has different implications for power system stability and both site- and grid-level protection systems. TSPs may further restrict allowable behaviors by placing constraints on large load current and/or power consumption during under- or over-voltage conditions, but most load ride-through requirements are still early in their development stage.

1) Double-Conversion UPS: Fig. 6 illustrates the main control algorithms used in the double-conversion UPS. Both the UPS rectifier and inverter are voltage-source converters represented by an average value models (AVM) [23]. The input rectifier control is grid-following (GFL) with current vector control; the active current reference is controlled by a DC bus voltage regulator and the reactive current reference is controlled by a reactive power regulator with a power reference of 0 MVAR, giving unity power factor operation. Rectifier current is limited to 1.25 pu using a dq-domain current limiter with active power prioritization. The output inverter control is GFM with droop control; the active power reference is set equal to 0 and the reactive power reference is controlled by an AC voltage regulator. The inverter current magnitude is limited to 1.5 pu using hysteresis-based current clipping [24]. The UPS battery is represented as a DC voltage source with a magnitude of 800 V. The battery converter is a bidirectional buck-boost

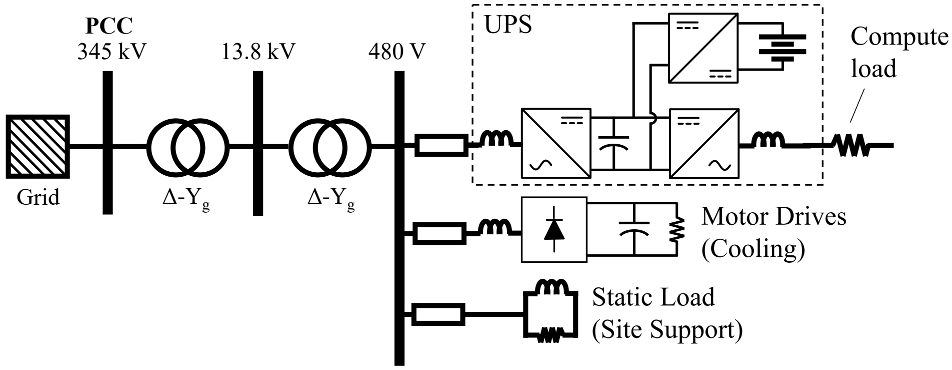

Fig. 5. Single-line diagram of data center model.

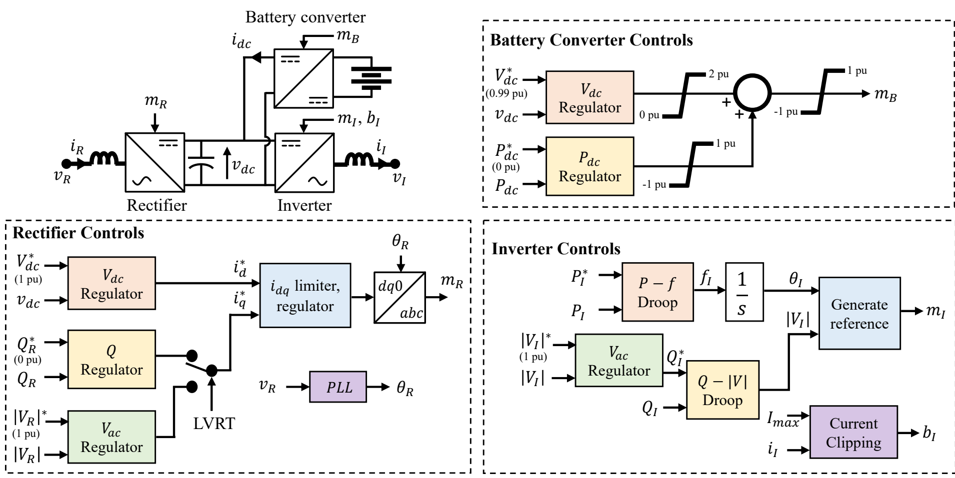

Fig. 6. Overview of controls for uninterruptible power supply model.

converter. The modulation index of the converter is controlled using both an active power regulator (to manage charging and discharging) and a DC voltage regulator. Coordination between the two DC link voltage regulators is achieved by operating the battery converter at a slightly lower DC voltage reference (0.99 pu) and limiting the DC voltage regulator to contribute only to the boost operating mode. With this arrangement, the DC voltage regulator of the battery converter participates actively in DC voltage regulation when the DC link voltage is below 0.99 pu. This allows the UPS to maintain tight DC voltage regulation even when the rectifier is operating at its current limits, thereby minimizing the effect of deep voltage sags in the rectifier AC voltage on the inverter AC voltage.

IV. Simulation Results

In this section, faults throughout the transmission system are simulated and the data center fault response is varied. For each scenario, we discuss how the data center's fault response affects transmission system protection and short-circuit modeling. Implications for system stability and site-level protection are discussed as well, but are not the central focus.

While a variety of fault types and locations were studied, our presented results revolve around an A-B fault on Line 22-23; this particular case clearly illustrates the challenges encountered in the larger set of studies. A pickup time delay of 100 ms has been added to the Zone 1 distance element for the Line 22-23 relays, purely to allow the system's fault response to be shown more clearly and to verify that the adjacent line protections do not overreach.

Fig 7. illustrates the response of the A PH current at the bus 24 data center to the previously mentioned A-B fault on line 22-23. The response is shown for the four LVRT controls discussed in Section (III-C-1), illustrating their operation. In the case where the UPS trips (the trace labeled "Trip") or enters MC ("MC Enabled"), the current drops significantly during the fault as only the drive and static load is connected. However, in cases where the UPS operates in either constant power ("Const. P") or reactive power support ("Q. Supp.") mode, the site current magnitude increases to roughly 1.5 times the pre-fault load current magnitude for the duration of the fault; the UPS input stage is operating at its maximum current consumption in these cases.

Fig. 8 illustrates the active (top) and reactive (bottom) power consumed by the bus 24 data center for the previously men-

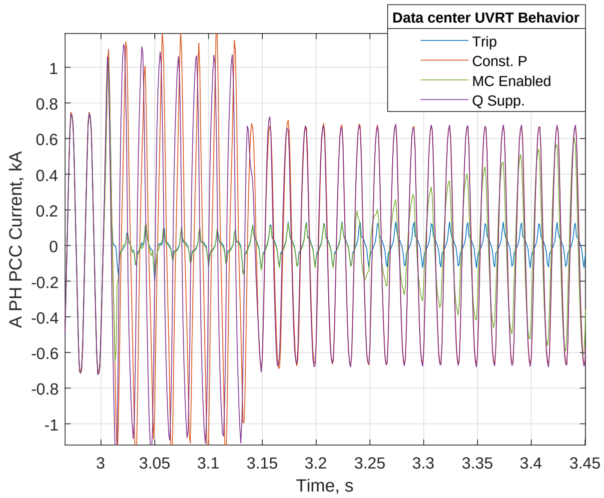

Fig. 7. A PH current at bus 24 data center in response to A-B fault on line 22-23.

tioned fault. The significant oscillation in power consumption during the fault period is the result of the negative-sequence voltage produced by the A-B fault. Observe that the quantity of reactive power contributed when reactive power support is enabled ("Q Supp.") is quite significant. The additional contribution raises the voltage magnitude (not shown) sufficiently to allow the UPS to maintain its active power consumption while remaining within the converter current limits. Thus, in regions where there is significant data center capacity, enabling reactive power support in data center UPS may significantly improve the ability of the UPS (and other electronic loads) to ride through voltage sags.

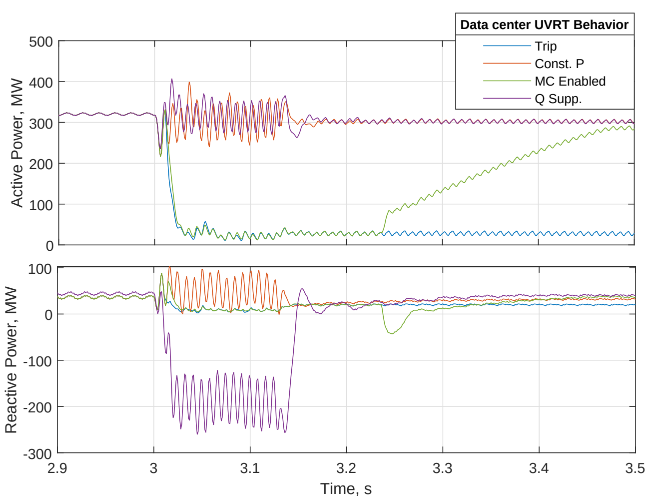

Fig. 8. Active power at bus 24 data center in response to A-B fault on line 22-23.

Fig. 9 and 10 illustrate the positive- and negative-sequence current flowing into line 21-22 for the previously discussed A-B fault. We examine line 21-22 rather than 22-23 as the fault current on line 22-23 is dominated by the synchronous generator placed at bus 35. The line 21-22 contributions are more influenced by the nearby data centers and inverter-based generators.

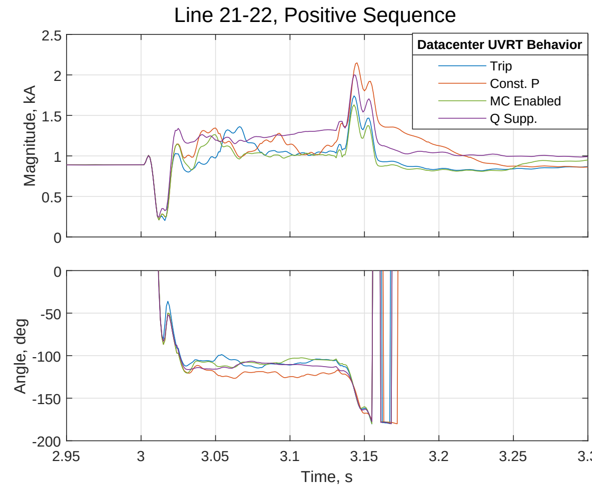

Fig. 9. Positive-sequence current on Line 21-22 in response to A-B fault on line 22-23.

The fault current contribution is not significantly greater than the pre-fault load current; observe that the positive- and negative-sequence fault currents have approximately equal magnitude. Because this is a bolted L-L fault, such a result suggests that the positive- and negative-sequence source impedance are roughly equal. Given that neither the IBG nor the UPS contribute significant negative-sequence current (i.e., they have a high equivalent negative-sequence impedance), the fact that the positive- and negative-sequence impedances are nearly equal suggests that the system's synchronous generators, despite the fact that most are electrically distant, continue to dominate the fault current contribution.

Synchronous machines dominate the system's fault response for faults on nearly every line in the test system (an exception, line 16-19, will be examined shortly), and the penetration of grid-following IBG is near its practical limit in this case. For example, replacing the bus 35 generator with an IBG results in a system where even normally-cleared L-L faults can cause system-wide collapse. In other words, this is a relatively conservative case when it comes to studying the degree to which the data center fault current contribution may be significant from the perspective of transmission line protection. As is evident in Fig. 9 and 10, the ride-through behavior of the data center does not significantly alter the fault currents

To further verify that the transients visible in the fault currents do not have any unexpected adverse effects on the line protection, the response of the negative-sequence directional (Fig. 11) and apparent impedance (Fig. 12) trajectories were considered.

Our thorough inspection of the Line 21-22 sending-end relay performance illustrates how most transmission line protections are unlikely to see serious changes in their fault

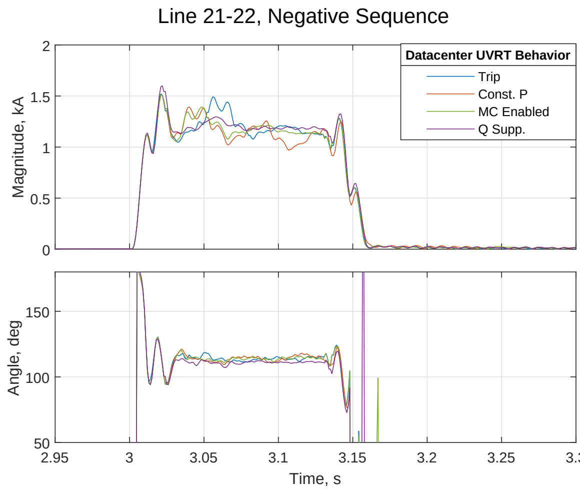

Fig. 10. Negative-sequence current on Line 21-22 in response to A-B fault on line 22-23.

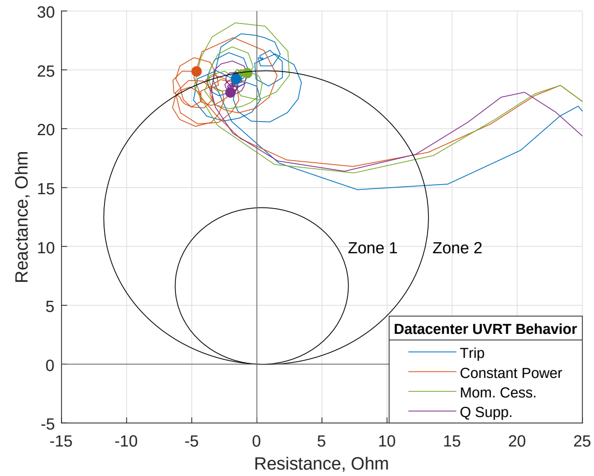

Fig. 12. A-B Impedance Trajectory on Line 21-22 response to A-B fault on line 22-23.

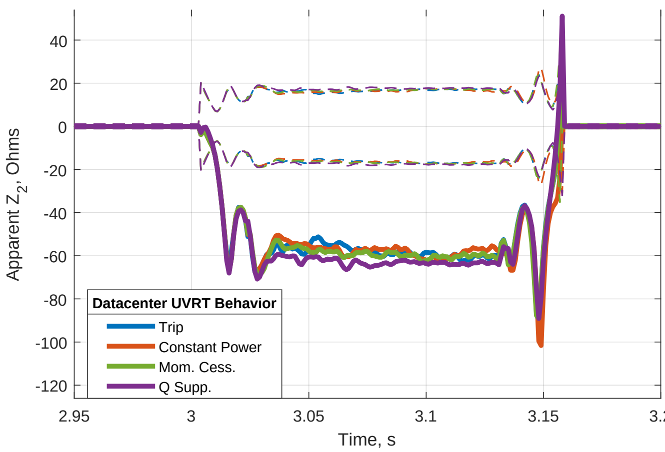

Fig. 11. Negative-sequence directional element on Line 21-22 response to A-B fault on line 22-23.

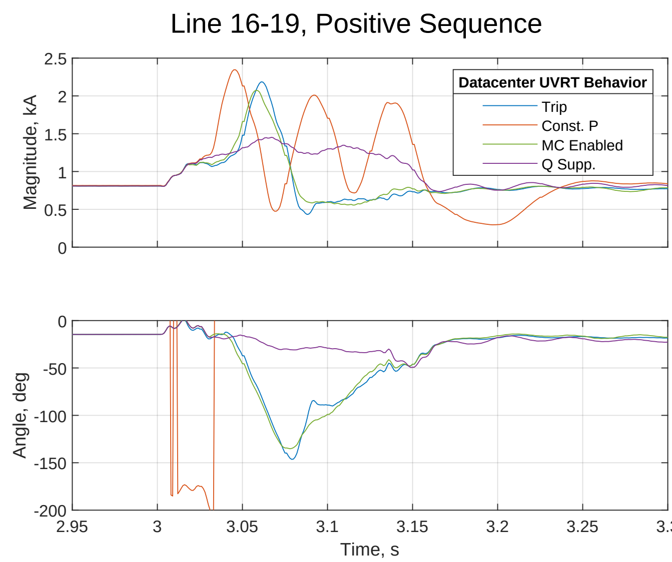

Fig. 13. Positive-sequence current on Line 16-19 in response to A-B fault on line 22-23.

currents as data center ride-through performance evolves. However, as we will discuss next, these findings do not apply to transmission lines that are solely supplied by IBGs. In the topology of the 39-bus test system, this criterion applies solely to line 16-19. As mentioned previously, replacing the bus 35 generator with an GFL IBG results in an implausibly fragile system. Further deployment of IBGs in this system will require integration of grid-forming IBGs, but exploring this is beyond the scope of this work.

Fig 13 and 14 illustrate the positive- and negative-sequence currents in line 16-19 for the same fault discussed previously. Unlike the fault currents seen on line 22-23, these vary significantly with the data center ride-through response.

The variations in positive-sequence current with data center ride-through (Fig. 13) illustrate that the data center's ride-through behavior also significantly affects the ability of the IBG plants at Bus 33 and 34 to remain stable during the fault. In cases where the data centers disconnect (Trip, MC Enabled), the IBGs temporarily lose synchronism (from roughly $t = 3.04$ to $t = 3.08$ s but are able to resynchronize. However, if the data centers remain connected and in constant power mode (Const. P), the IBGs are unable to resynchronize for the duration of the fault. This makes it more likely that the IBG plant will trip offline (in response to inverter-level protections which are not modeled here and vary by vendor and site). If the data centers remain connected and provide reactive power support, the IBGs do not lose synchronism during the fault. This result suggests that simply having data centers consume current during nearby faults may exacerbate IBG ride-through challenges. Unless the data centers can also contribute VAR support, MC is preferable (assuming that cessation ends and the load returns rapidly enough to avoid frequency regulation issues).

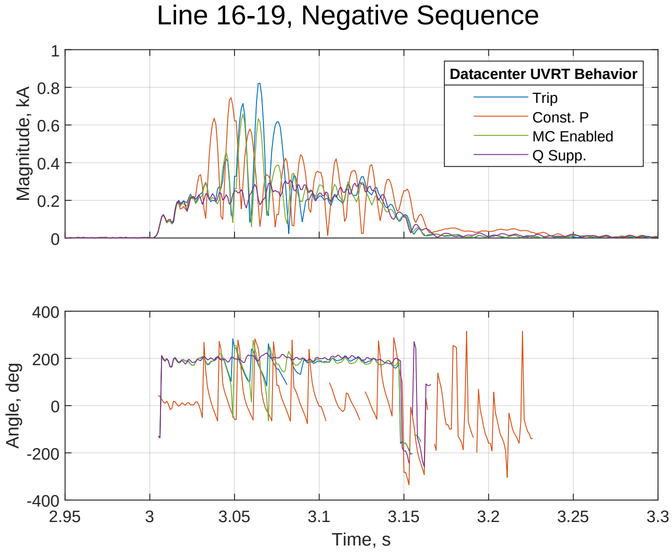

Fig. 14. Negative-sequence current on Line 16-19 in response to A-B fault on line 22-23.

The variations in negative-sequence current with data center ride-through (Fig. 14) illustrate how the IBG loss of synchronism (LOS) exacerbates the injection of abnormal negative-sequence currents. At time periods where the IBGs are out of synchronism, there are rapid oscillations in the negative-sequence current magnitude and angle where a directional logic and faulted phase identification will almost certainly malfunction. Observe that, even in the case where the IBGs maintain synchronism (Q Supp.), the IBGs contribute a non-negligible amount of negative-sequence fault current. The negative-equence current angle, while stable, is nearly 180°. This corresponds to a roughly resistive source impedance and is also unlikely to yield a useful directional indication. In other words, any elements based on negative-sequence current applied to Line 16-19 are likely to face issues regardless of the ride-through response of nearby data centers.

The significant negative-sequence current injection observed in Fig. 14 is noteworthy as, in more typical grid conditions, the GFL IBG control employed here injects very little negative-sequence current and thus the main concern is that the directional element will not pick up for in-zone faults. However, under these weak grid/high GFL penetration scenario, the GFL control is unable to fully suppress the negative-sequence current. This sort of malfunction has contributed to IBG-related protection misoperations in the past [25]. This has interesting implications for LOS protection practices for IBGs—recent NERC guidance has advocated for reducing the sensitivity of LOS protection for IBRs in order to maximize ride-through [26]. However, as shown in Fig. 14, having IBGs remain connected while out of synchronism may increase the likelihood of transmission line protections misoperating. This interplay between protection system and planning requirements should be further investigated. However, doing so is outside the scope of this work, and modeling of IBG response under LOS conditions likely requires a vendor-specific model.

Fig. 15 and 16 illustrate the response of the line 16-19 negative-sequence directional element to the A-B fault on line 22-23. Measurements are taken from the bus 16 end of the line, meaning that the fault is in the reverse direction. The response obtained when data centers provide reactive power support (Fig. 16) is plotted separately to ensure the trace is legible.

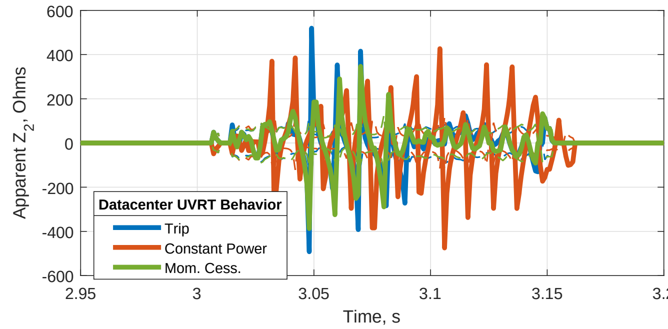

Fig. 15. Negative-sequence directional element on Line 16-19 response to A-B fault on line 22-23.

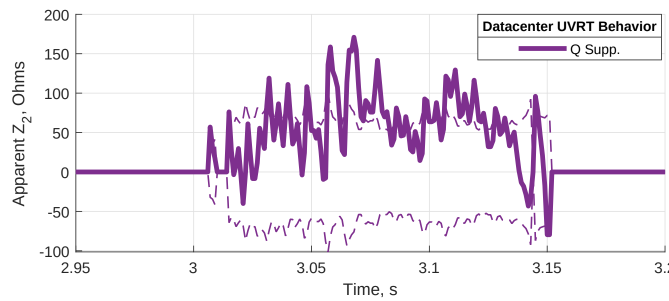

Fig. 16. Negative-sequence directional element on Line 16-19 response to A-B fault on line 22-23.

While the negative-sequence current magnitude is sufficient to enable the 32Q, an incorrect directional indication is clearly present for all four ride-through scenarios. Time periods where there are large oscillations in apparent impedance (e.g., up to roughly 400 Ω in Fig. 15) correspond to time periods where the IBG is out of synchronism. However, even in the scenario where no LOS occurs (Fig. 16), the operating quantity has the incorrect sign and its magnitude fluctuates unpredictably. This is attributed to the nearly resistive source impedance of the IBG (refer back to the negative-sequence current angle of 200° visible in Fig. 14). This illustrates that the IBG LOS issues associated with data center ride-through can also exacerbate issues associated with unintentional negative-sequence current injection.

Fig. 17 illustrates the apparent impedance trajectories for the A-B fault loop from the bus 19 terminal for various data center ride-through strategies. Unless reactive power support is provided, significant transient overreach can be observed, with the apparent impedance passing through Zone 2 for several samples. In the case where the data centers trip or

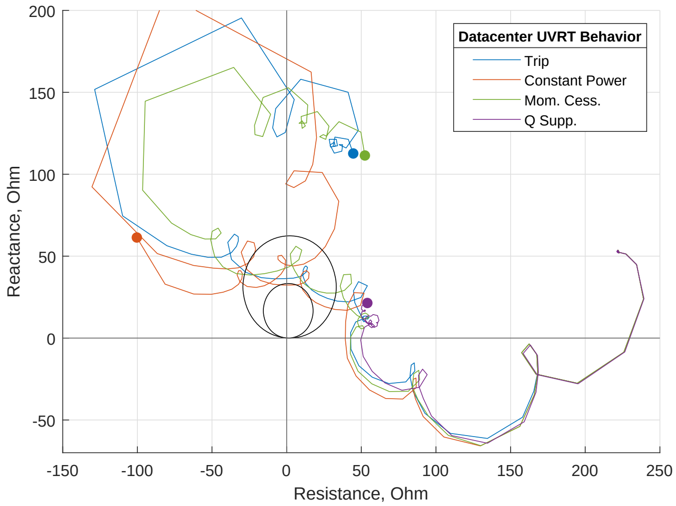

Fig. 17. A-B Impedance Trajectory on Line 16-19 response to A-B fault on line 22-23.

enter MC, the IBGs regain synchronism and the impedance measurement settles to a value well beyond the Zone 2 reach. In the case of current-limited constant power, the IBGs do not regain synchronism and so impedance trajectory continues in an unpredictable trajectory, passing through Zone 2 multiple times and very nearly entering Zone 1. With the data centers providing reactive power support, the IBGs remain synchronized and the transient overrreach is eliminated. This suggests that the dynamic reactive power capabilities offered by data centers could significantly reduce distance element security issues associated with high source impedance ratios in IBG-dominated portions of the grid.

V. Discussion

In this section, we discuss additional protection system considerations for data center ride-through that are not explicitly addressed in the field events or EMT studies

A. Short-Circuit Modeling of Data Centers

The short-circuit behavior of the data center is primarily determined by the control algorithms used in the AC/DC conversion stage of the power electronics. In the data center design we studied, this is the rectifier of the 3 PH double-conversion power supply. For a 3 PH double-conversion UPS, the positive- and negative-sequence fault current contribution can be approximated using short-circuit models previously developed for use with Type-IV wind turbines [27], such as voltage-controlled current source models. This is because both use a three phase voltage source converter with similar control strategy for their grid interface. However, there are several important nuances to bear in mind:

- The current limit should be based on the summation of power electronic device ratings, not the site demand. In constrast with IBG, which usually have a combined converter rating close to their peak production, UPS are usually oversized and redundant units are often kept on hot standby. Thus, a data center with 100 MVA of electronic load could feasibly have 150 MVA of UPS capacity connected, with each UPS being capable of consuming up to 1.1 pu current (on the UPS current base).
- Most UPS do not provide active power support but rather operate at unity power factor. Thus, the power factor angle will remain near 0 degrees even during a voltage sag.
- The UPS consumes active power, rather than supplying it. Thus, the active current, even during a fault will have the opposite sign than that of a Type-IV wind turbine.

In cases where the data center trips or enters MC, the pickup time delay for the data center trip or MC activation should be obtained. It is likely to be near typical fault clearing time (e.g., 10 to 100 ms), and the engineer must make an assumption as to whether or not the data center electronics have gone into MC/disconnected at the moment in time that the short-circuit calculation is performed.

The zero-sequence current contribution is determined by the power transformer impedance and winding connection used at the transmission bus. It is common for TSPs to require the utility-facing winding to be delta-connected to ensure minimal coupling between the utility and data centers' zero-sequence networks.

Some data centers do not use three-phase UPS, instead using single-phase AC/DC power supplies with batteries located on the DC side. In such cases, the negative-sequence current injected during a fault may be non-negligible, as only power supplies on the faulted phase(s) will experience a voltage sag. This requires further study.

B. Effects on Line Current Differential

The results discussed in Section IV suggest that, in most cases, the effects of the data center fault contributions pose little challenge for the perspective of line current differential protection (87L). Two possible exceptions are tapped lines and radial feeds. Fig. 19 illustrates fault scenarios which may cause issues for the 87L element if not accounted for.

In the case of a data center that is supplied via a transmission line tap, the concern is that the data center may supply sufficient fault current to cause the 87L element to operate for external faults. This concern can be evaluated by computing whether the maximum fault current supplied by the facility exceeds the minimum operate current threshold

$$I_{OP,T} = I_{lim} \bullet R \bullet I_T \quad (4)$$

where:

- $I_{OP,T}$ is the operate current produced by the tapped data center load for an external fault, given in amperes.
- I_{lim} is the current limit for the UPS, given in per-unit on the UPS's rated current base.
- R is the ratio of the connected UPS capacity to the facility capacity.
- I_T is the rated current of the facility, given in amperes.

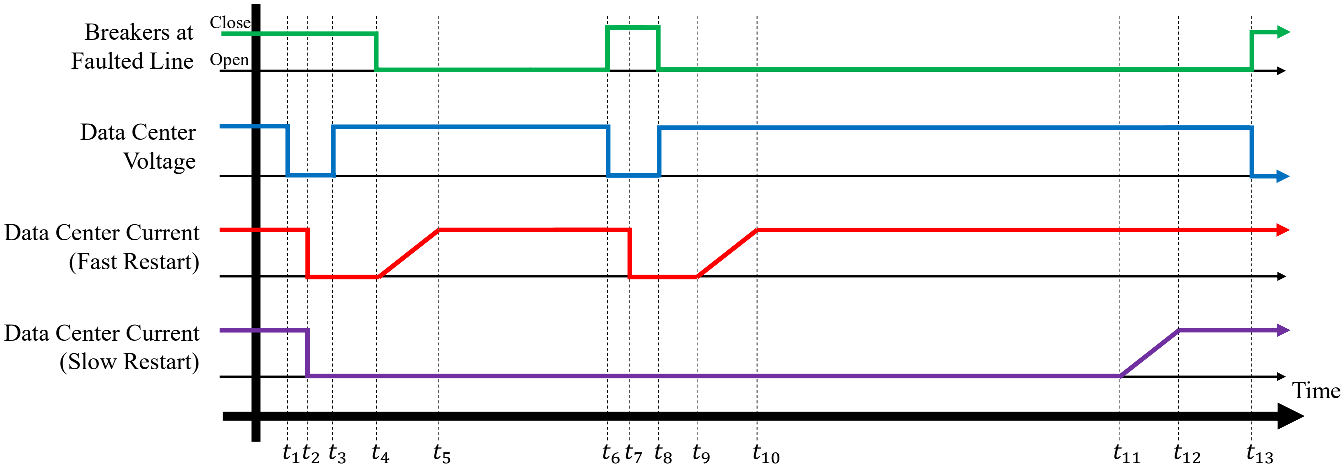

Fig. 18. Fast- and slow-restart approaches for coordinating data center restart with transmission line reclosing.

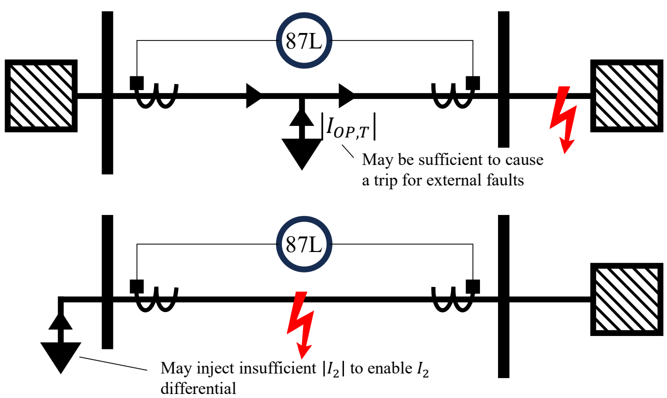

Fig. 19. Fault scenarios for consideration when applying line current differential near data center loads.

TABLE III
DESCRIPTIONS OF EVENTS IN RECLOSING SEQUENCE

Time Instant	Event
t_1	Fault occurs
t_2	Data center electronics enter MC
t_3	Fault is cleared
t_4	Fast-restart data center leaves MC and begins ramping
t_5	Ramping complete for fast-restart data center
t_6	First reclose attempt
t_7	Fast-restart data center re-enters MC
t_8	Fault is cleared
t_9	Fast-restart data center leaves MC and begins ramping
t_{10}	Fast restart data center completes ramping
t_{11}	Slow-restart data center leaves MC and begins ramping
t_{12}	Slow-restart data center completes ramping
t_{13}	Second reclose attempt

For example, let $I_{lim} = 1.2\ pu$, $R = 1.67\ pu$, $I_T = 250\ A$, and $I_T = 1000\ A$. In this case, the operate current required to trip the 87L element for an external fault should be at least 0.501 pu (i.e., 501 A primary). For a conservative approach to setting pickup and restraint values, this can be added to other sources of false operating current during external faults, such as current transformer error.

In the case where a data center is supplied via a radially fed transmission line tap, the concern is that any magnitude supervision based on negative-sequence current (e.g., for negative-sequence current differential) at the data center terminal will prevent operation for an internal fault. This is a simple misapplication issue and can be resolved by relying on the system-side terminal to provide any supervisory checks based on current magnitude.

C. Coordination with Reclosing

Reclosing practices for transmission lines vary widely by voltage level, region, and utility. In the context of data center ride-through, we are concerned ensuring compatibility of the reclosing sequence with data center's recovery from MC and short-term energy storage capacity.

For severe voltage sags (e.g., to below 0.5 pu), most power supplies will likely need to temporarily enter MC in order to protect themselves or their downstream load. Thus, any system fault that occurs in a region with many data centers is likely to cause at least some to enter MC. From an angular and frequency stability perspective, it is desirable for the load to rapidly exit MC and return to pre-fault levels. However, if the fault is re-introduced while many data centers are restarting, this may cause a more severe voltage transient and trip the data centers offline. Therefore, it is advantageous to coordinate the MC and reclose timing so as to reduce instances of reclosing at times when many large loads may be starting simultaneously.

Fig. 18 illustrates two simplified data center MC timings that could be used to accomplish coordination with the first and second reclose attempts. Table III describes the events occuring at each annotated time instant in Fig. 18, and Table IV describes how different time windows correspond to time delays in the reclosing scheme and MC control.

The critical difference between the fast and slow restart

TABLE IV
DESCRIPTIONS OF TIME WINDOWS IN RECLOSING SEQUENCE

Time Window	Event
$t_2 - t_1$, $t_7 - t_6$	MC pickup time delay
$t_3 - t_1$, $t_8 - t_6$	Fault clearing time
$t_4 - t_3$, $t_9 - t_8$	MC fast restart dropout time delay
$t_5 - t_4$, $t_{10} - t_9$, $t_{12} - t_{11}$	Post MC ramp time
$t_6 - t_3$	First reclose attempt time delay
$t_{11} - t_8$	MC slow restart time delay
$t_{13} - t_8$	Second reclose attempt time delay

sequences lies in whether or not the MC control is configured to restart the data center before the first reclose attempt is made. In the fast restart case, the MC dropout time (e.g., $t_4 - t_3$) and ramp up time (e.g., $t_5 - t_4$) must be shorter than the time delay before the first reclose attempt ($t_6 - t_3$). Assuming there is minimal fault-induced delayed voltage recovery (FIDVR), this approach will likely require the time delay for the first reclose attempt to be at least roughly 500 ms. However, if the first reclose attempt must be made significantly faster (e.g., in 100 ms), it will likely be necessary to adopt the slow restart approach, wherein the dropout time for the MC control ($t_{11} - t_8$) must be longer than the time delay of the first reclose attempt but shorter than the time delay of the second reclose attempt ($t_{13} - t_8$).

The degree to which the data center ride-through characteristics impact reclose timing will vary significantly based on the nature and severity of angular, frequency, and voltage stability constraints near the line in question. These will need to be evaluated as a part of planning studies that consider both the first shot of reclosing and data center ride-through performance. In scenarios where inertia is high and the data centers are located in a well-networked portion of the transmission system, there may be minimal risk associated with either allowing reclosing during data center restarts or employing the slow restart method. However, in areas where grid strength is low and/or voltage stability is an issue, it may be necessary to adjust the timings for MC controls and/or the first reclose attempt in order to ensure stability.

For reclose attempts beyond the first shot, the capacity of data center energy storage can be a concern. UPS systems designed to facilitate transitions to and from on-site generation are unlikely to be an issue as they are often sized to carry the load for potentially tens of minutes, making an cumulative outage time of even several seconds irrelevant. However, low capacity storage systems (e.g., several seconds' worth of energy) are becoming more popular as a means for achieving low voltage ride-through, load smoothing, and controlled shutdown of software processes. Large AI data centers, especially those developed and operated by vertically-integrated companies, tend to forego on-site backup generation and are adopting these short-term storage approaches. The ability of data centers to ride-through multiple reclose attempts should not be assumed [3]. While it may not be practical to consider reclosing sequences to lockout in planning studies, system planners should still be aware of their longest feasible reclosing sequences and collecting data on how interconnecting data centers will respond to these sequences in order to avoid unexpected large load losses.

VI. CONCLUSIONS

For the grid to maintain adequate frequency, voltage, and angular stability, it is necessary for large clusters of electronic loads to remain connected to the grid during faults and resume normal operation shortly thereafter. In doing so, these loads will take on one of a number of different fault response characteristics, many of which are similar to fault responses associated with inverter-based resources.

Table V summarizes the ride-through behaviors considered in the study, as well as the implications of each for system stability and protection system performance.

Observe that this summarizes a set of pros and cons that affect many different stakeholders (planners, operators, and protection engineers at both the data center and the transmission system side). In light of the power industry's growing experience with IBG integration over the last decade, it appears that many of the data center-related technical challenges are similar in their nature and avenues for technical solution.

Generally speaking, it is expected that large data centers will adjust their on-site protection settings to ensure compliance with utility ride-through curves (e.g., [28]), moving away from sensitive tripping behavior. Based on conversations with device manufacturers, MC will likely be the necessary response to deep voltage sags (e.g., below 0.6 pu) in order to ensure the load electronics remain stable and do not need to trip offline (e.g., in order to avoid damage from a transient overcurrent condition). For shallow voltage sags (e.g., 0.6 to 0.95), the data center electronics will likely operate in current-limited constant power mode (the typical response of a power electronic device). However, OEMs may choose to implement additional controls and temporarily operate in constant current mode during voltage sags.

While this initial study has resulted in a set of important design considerations, significant opportunities for future work remain. Extension of this work to include data centers based on single-phase power supplies (instead of three-phase UPS) is a near term priority. Efforts are also underway to benchmark models against field data and manufacturer-specific models. Longer term efforts could focus on near-future data center architectures such as those employing solid-state transformers.

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TABLE V
DRAWBACKS AND BENEFITS TO VARIOUS DATA CENTER RIDE THROUGH STRATEGIES

Ride-Through Strategy	Benefits	Drawbacks
Tripping	• Can be ignored for fault studies. • Load processes are protected.	• If systemic, can cause significant over-frequency conditions and widespread generator tripping on over-frequency ride-through protection. • Can cause both short-time and temporary over-voltage conditions, which may result in over-voltage ride-through tripping of nearby generation. • Can cause nearby heavily-loaded generation to lose synchronism, especially if the connection with the rest of the system is weak.
Constant Power Ride Through	• Improves frequency stability. • Simple to implement.	• Worsens voltage sags, hindering voltage recovery and potentially causing other resources to fail to ride through. • May introduce coordination challenges for site-level overcurrent protection. • May result in UPS instability and tripping for severe voltage sags.
Momentary Cessation	• Can ignore for fault studies. • Allows converters to remain stable (i.e., to avoid unnecessary tripping) even for severe voltage sags (e.g., below 0.5 pu).	• No voltage or frequency support until voltage recovers. • Ramping thresholds and rates must be coordinated with system voltage recovery and transmission line reclosing.
Reactive Power Support	• Improves ability of data center and other resources to ride through severe voltage sags. • Reduces transient overreach of transmission line protection by supporting voltage during faults. • Hastens postfault recovery of other loads on the system such as line-connected motors.	• Requires new feature development for many manufacturers and coordination with existing voltage controls. • May introduce coordination challenges for site-level overcurrent protection. • May result in UPS instability and tripping for severe voltage sags.

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