

Grid & AI load compatibility

System design requirements for AI load, grid code & fault ride- through

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Publication status: Version 1.0, published 28 September 2026. This document may be updated as technical standards, grid codes, connection requirements and industry practice develop. Users should confirm they are relying on the latest published version.

1 Introduction

This document is shared as a work in progress. The issues addressed are developing rapidly, as are the knowledge, tools, technologies and processes of System Operators, Regulators, equipment OEMs, data centre designers and operators.

We hope this document is helpful and informative but also recognise that no single organisation can address these challenges alone. Collaboration, knowledge sharing and collective learning across the industry will be essential if we are to respond effectively.

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1.1 A changing environment for data centres

Two new issues have recently surfaced for data centre and grid operators. The first is the rise of AI workloads with associated large and rapid variations in power draw. The second is that data centre electrical systems, acting to preserve power quality to the IT equipment, can unintentionally destabilise the grid to which they are connected when acting as a group.

This represents a reversal of the historic design relationship between data centres and the grid. Data centre electrical design has historically been organised around protecting the IT load from grid disturbance. The requirements discussed in this paper exist because the changes in character and scale of data centre loads now require the protection obligation to run in both directions: data centres must also act to preserve and protect the grids on which we depend.

1.2 AI Loads

Data centres have historically presented a stable and predictable demand profile to electricity networks. The aggregation of large numbers of independently operating servers, each varying in load according to their own workload, produced a smooth aggregate power draw at the grid connection point with modest ramp rates and minimal periodic variation. Electrical infrastructure, both within the data centre and on the grid, was designed around this characteristic and grid operators viewed data centres as large, well-behaved and predictable loads.

The rapid growth of AI has changed this character in a structurally significant way. AI training workloads synchronise computation, and therefore changes in power draw, across large numbers of processors simultaneously. Power draw variations are now large in magnitude, can be synchronised across many MW of compute, and occur at repetitive intervals capable of exciting electrical and mechanical oscillations in both data centre power systems and the connected grid. The result is a load profile that can cause instabilities, or failures in power grids and physically damage power generation equipment.

1.3 Grid stability & Fault Ride-Through

The increase in the total data centre MW load on power grids combined with the move toward transmission connections have exposed issues with data centre behaviour which were previously insignificant. Whilst there are many aspects to being a good participant in the power grid, Fault Ride-Through, a requirement which already applies to power stations, distribution networks and others, provides the clearest example.

The typical design and operation of a data centre, protecting the power quality to the IT equipment considers the grid as an external source, large enough to not be impacted by the data centre. When there is a disturbance to the power quality on the grid, most data centres will quickly move to battery power on some form of Uninterruptible Power Supply (UPS), in the case of a short disturbance, power quality will recover and the UPS will reconnect to draw power from the grid a few seconds or minutes later.

From the grid operator perspective this presents a serious issue. Whilst responding to a transient network fault and keeping power available, they experience a sudden and unplanned loss of load¹ from many data centres acting together, all responding to the same event. To keep the generation and load in balance on the network and avoid further events or damage, it may be necessary for the grid operator to emergency disconnect power generation capacity. A few seconds after stabilising the network from this second unplanned event, the data centres' UPS will typically re-attach to the grid, leaving a shortfall in generating capacity for the grid operator to respond to but with potentially greater difficulty sourcing additional supply capacity in time. This is clearly an undesirable interaction for both the grid and data centre operators.

1.4 Combined impact

These two issues meet in the data centre infrastructure design. The requirements of grid code and Fault Ride-Through propagate 'down' through the data centre to much of the equipment, whilst the impacts of the AI load variability propagate 'up' through the power infrastructure and generators to the grid connection.

This creates a structural change in system coupling. Meeting AI load variability and grid code compliance together requires that designers and operators approach the IT workload, energy storage, generation, protection systems, and grid connection as a more tightly coupled system. Tight coupling changes how events unfold: there is less time to react, and less margin between interacting systems. Previously 'safe' actions such as going to battery may no longer be available and pre-defined, programmed system responses take their place.

This tighter coupling and requirement for more complex analysis & behaviours across the entire system creates the potential for a small event to propagate across the wider system, either within the data centre or across the local grid. A detected event, such as Sub Synchronous Oscillation, can therefore cascade in ways earlier generations of data centre infrastructure did not experience, because those systems and controls were not required to be coupled tightly enough to respond to these issues. The requirements and design deliverables in this document should be read in that light: they exist to make the coupled system's behavior explicit, specified, and validated, rather than discovered in operation.

¹ For example, the [3 GW event in Virginia](#) reported by Dominion Energy

Grid operators across Europe and North America are responding with new and evolving connection requirements for large data centre loads, covering Fault Ride-Through, post-fault active power recovery, load ramp rates, step size limits, and allowable range for sub-synchronous oscillation. These requirements arrive at a moment when data centre design teams are simultaneously grappling with AI load variability requirements that originate from the IT side. Meeting both sets of requirements with a single coherent design, rather than solving each in isolation and discovering conflicts during commissioning, is the engineering challenge this document addresses.

1.5 Grid supporting services

With increasing scrutiny of the impact of data centres on the power grid, several grid operators and regulators are requiring data centres to provide additional grid supporting services as part of the conditions of connection. Whether these are designed and operated as part of the data centre or by a third party in support of the data centre, local compliance with these requirements will be necessary.

1.6 Objectives

The objective is to design data centre M&E infrastructure in such a way that it is capable of

- 1) Handling AI IT load variability
- 2) Meeting Grid connection requirement policies
- 3) Meeting Grid Fault Ride-Through requirements
- 4) Meeting local regulatory requirements such as demand response
- 5) Effectively constructing, commissioning & testing these new capabilities

1.7 Deliverables

The intent is to produce a base mechanical & electrical system design capable of meeting these varying & developing requirements without major design or equipment changes, whilst minimising additional base cost impacts. For example, UPS systems specified should be capable of meeting common European FRT requirements. The designs should allow for extensions of capability at incremental cost, such as additional energy storage or harmonic filters etc. where they are required under the selected combination of customer load shape, regional grid code, and local grid requirements.

The designer may be required to present evidence to the utility connection provider Transmission System Operator (TSO) or Distribution System Operator, (DSO or DNO), demonstrating that the data centre, once connected to the network, will meet the locally applicable requirements for power quality, ramp rate, step size, harmonic & sub-harmonic content etc. This may include data & models with the format and simulation tools specified by the connection provider.

Maintainability over time is a key consideration, as grid code is updated, deployed designs should be capable of adapting to reasonably forecast changes in tenant IT load profile variability and grid code without major plant replacement.

The designer will supply, in support of the system design conditions in section 4 and the required system capabilities in section 5;

- 1) A design for the data centre which meets these requirements

- 2) Specification of the IT power draw profile variability supported by the design
- 3) Additional commissioning requirements and pass/fail criteria as required to prove system capability and configuration
- 4) Additional equipment selection criteria as required by the design
- 5) Evidence as required by the local grid authorities that the design meets grid and local connection point requirements

1.8 Design impacts

Whilst these new requirements create some significant new work streams for the designer, as for many designs, once developed and piloted, much of the knowledge, data and design information will be portable and re-usable.

The primary impacts are to the breadth of co-operation across functions, particularly between data centre mechanical & electrical design teams and medium / high voltage power systems design teams with large connection experience to model & assess the overall system performance and create relevant submissions to the grid operator or regulator.

Early and effective definition of design responsibility and interfaces between different specialist teams will be key to successful outcomes. It is key to note that in addition to the increase in scope & complexity of the data centre design, the requirements in this document also create requirements for inter-disciplinary communication which did not previously exist. Design, equipment specification, review, modelling and commissioning approaches will all require review in the context of these changes.

1.9 Operational impacts & governance

These new requirements create shared obligations upon the data centre and IT operators to maintain compliance with both the physical plant capabilities at the data centre and the relevant grid code. The data centre operator is now accountable to the grid operator for a facility power draw profile which is partially outside of their control, influenced by the IT operator. It is possible, under grid constraints such as those on load variability, for an IT load to cause the data centre to violate grid code and be subject to penalties, including disconnection. Similarly, the data centre operator may be obligated to disconnect IT loads which are deemed to be causing disruption to the grid or impacting on-site generation assets, which would previously have been an SLA breach.

This accountability requires a defined, monitored and reported interface between the parties to ensure that the required load profile compliance, grid service participation (e.g. demand response) or response to infrastructure status signals operate correctly. This may be particularly challenging in the case of data centres which use row or rack level Battery Back Up in place of centralised energy storage such as UPS.

Establishing this interface, its technical specification, real-time monitoring architecture, standard and emergency operational procedures and response protocols is an activity that must begin alongside the mechanical & electrical design.

1.10 Contributors

Liam Newcombe, SVP Product, Energy Strategy & Innovation at GreenScale Data Centres, is the lead author of this document and led the development of its technical content, with review from the wider GreenScale Data Centres team.

We would also like to thank the industry partners, vendors and individual experts who generously contributed their time, knowledge and technical expertise. Their input has been invaluable in shaping this document.

Organisations

Vendors & partners

Kerry Haley and Dr. Ram Shenoy of [The RBR Group](#)

The RBR Group engineers data center delivery programmes so design, procurement, manufacturing, logistics and commissioning all perform as a coordinated system rather than a sequence of contracts.

Janne Paananen, Data Center Systems Architect at [Eaton](#), for contributing perspectives informed by Eaton's published paper on data centers as good grid citizens. For additional context, read [How data centers can become good grid citizens](#).

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2 Applicable specifications

The applicable specifications are still under development and inconsistent across the market. We are not currently aware of any DC industry, ISO or IEC type standards to define AI workload power draw variability patterns. On grid code, many TSOs and DSOs are also still developing specifications for required large load behaviour, with some organisations such as NERC and ENTSO-E bringing coordination. There are common aspects across operators, but also regional differences in response to varying local specific stresses and issues, with no common base specification yet available against which to design.

2.1 Traditional IT power draw

Traditionally the IT power draw in a data centre has been quite consistent & predictable. Whilst individual IT devices may ramp up and down in power by significant amounts, the distribution of applications and workloads across these devices has resulted in the aggregated kW load seen by the UPS, generator and grid connection points being relatively smooth with little or no periodic variation in frequency ranges which can cause instabilities, or large load steps due to IT equipment behavior.

2.2 AI power draw variability

The appearance of AI applications which synchronise workloads across large numbers of high-power racks has changed this profile. Instead of averaging out, the power draw variations are larger in magnitude at each rack, synchronised across many racks and occur with repetitive periods capable of exciting oscillations.

These combined large load steps, ramps and periodic behavior present electrical design challenges, to design for them it is necessary to specify them.

In the absence of industry-wide standards, IT power draw variation is currently expressed as some combination of ramp rates, step sizes (instantaneous changes), magnitudes of ramp or step, and the periods or frequencies at which these ramps or steps may occur.

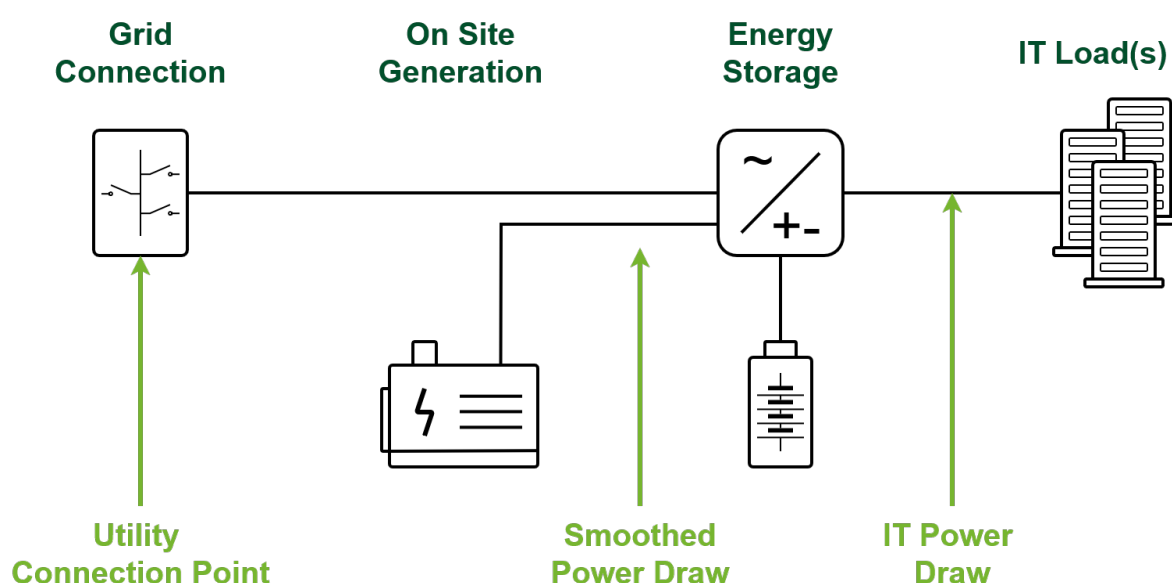


Figure 1 main power draw profiles

As shown in Figure 1, the impacts of this variability are expressed differently at different points in the infrastructure.

- 1) At the IT power distribution in the white space, power quality & stability to the IT load must be maintained. AI workloads present rapid fluctuations in IT power draw with single or repeated load ramps, or steps occurring in milliseconds, and at variable intervals. High peak loads, which exceed the nominal power ratings for short periods are also common.
- 2) The electrical design must be capable of handling this IT output load profile whilst presenting an acceptable load variability to upstream systems. This may utilise infrastructure energy storage such as BESS² or UPS, for IT platforms utilising in-row energy storage or in-rack Battery Back Up (BBU) systems, this may be performed at the IT load.
- 3) Where there is onsite power generation, whether as prime power, flex or backup, the combined, smoothed, power draw at each generator must stay within the operational envelope of the generation equipment. The ability to withstand load steps at load transfer is not a guarantee of resistance to repeated cyclic load variations.
- 4) At the Utility Connection Point the combined, smoothed, power draw profile must be within the constraints agreed with the grid operator.

Note that the level of smoothing required for generator and utility operation of the same data centre may differ for a number of reasons.

² Battery Energy Storage System

2.3 Example power draw profiles

To perform the design the allowable variations in power draw must be defined at several key points in the infrastructure, from the grid connection down to the IT load. This section provides example profiles for three points, the Grid Connection Point, Generator Connection Point and IT Load.

2.3.1 Grid Connection Point power draw profile

A major constraint on the design is that applied by the grid connection, as a condition of connection. From this, downstream requirements may be derived for data centre infrastructure and IT load profiles based on the grid (or onsite generation) limits.

This shall be determined in conjunction with the grid operator, as an outcome of analysis modelling by the HV designers, or as a direct specification of power oscillation magnitude & frequency from the grid operator (see 2.6.6 Grid load-induced forced oscillations below).

The example specification below is intended to provide a basis to commence design whilst the grid operator limits are determined, as agreement on these limits may require presentation of some level of design and analysis to the grid operator.

The combined Power Draw variability of the combined building or campus presented at the Grid Connection Point shall not exceed:

Item	Magnitude	Time
Randomly Occurring Step Size	10% rated capacity	N/A
Randomly Occurring Ramp Rate	Maximum ramp magnitude 25% of rated capacity At a rate of 1% rated capacity per second	N/A
Periodic Step Size	10% rated capacity	At any period between 10 and 100 seconds (frequency between 0.01Hz and 0.1Hz) ³
	2% rated capacity	At any sub-synchronous period below 10 seconds (frequency between 0.1Hz and 50Hz ⁴)
Periodic Ramp Rate	1% rated capacity per second Maximum ramp 10% of rated capacity	At any period less than 100 seconds (frequency above 0.01Hz)

Table 1 Example Grid Connection Point Power Draw Variability Specification

Note that some of these variations are described as singular randomly occurring event, whilst others are expressed as occurring with consistent period or frequency. This is significant when

³ Note that ENTSO-E defines that "The relevant TSO shall define the magnitude and accuracy of the allowed oscillations in the frequency range between 0.01Hz to 50Hz."

⁴ 60Hz in North America and other 60Hz grid regions

assessing the impact on systems susceptible to sub-synchronous oscillation such as generators and power grids.

2.3.2 Generator Connection Point power draw profile

Where there is onsite generation, prime power, flex or backup, the generation assets will have limits to the power draw variability they can withstand for continuous operation, whilst operating within emissions, power quality and warranty limits, see 2.5 below.

Note that the ability of rotating mechanical equipment to accept cyclic load variation varies significantly. Reciprocating engines and turbines exhibit quite different supportable operational conditions, initial specification data from sample vendors should be sought early in the design process.

This example specification below is intended to provide a basis to commence design whilst the generator technology & vendors are selected & limits are determined.

The combined Power Draw variability of the combined loads presented at the Generator Connection Point(s) shall not exceed:

Item	Magnitude	Time
Randomly Occurring Step Size	20% rated capacity	N/A
Randomly Occurring Ramp Rate	Maximum ramp magnitude 50% of rated capacity At a rate of 10% rated capacity per second	N/A
Periodic Load Variation (Ramp or Step)	30% rated capacity	At any period above 2 seconds (frequency below 0.5Hz)
	20% rated capacity	At period below 2 seconds (frequency between 0.5Hz and 50Hz ⁵)

Table 2 Example Generator Connection Point Power Draw Variability Specification

⁵ 60Hz in North America and other 60Hz grid regions

2.3.3 Example IT Power Draw Variability specification

A target IT power draw variability specification may be supplied by the IT operator as a design objective, alternatively it may be derived from the design infrastructure modelled capability. In either case, a resulting 'IT power draw variability envelope' must be defined within which the design will operate within data centre equipment and grid constraints. These requirements are the result of combining utility & generator constraints, plus the capability of any applied load smoothing and represent the outcome of the overall design.

The table below provides examples of how an IT Power Draw Profile may be specified by an IT operator for a training workload.

Item	Magnitude	Time
Linear Ramp Rate	10% rated capacity	Per second
	40% rated capacity	Per minute
Load Step Size	25% rated capacity	Instantaneous (<10ms)
Periodic Load Step Frequency	25% rated capacity	Instantaneous (<10ms) at 5, 4, 3, 2, 1Hz frequency or 1, 2, 3, 5, 10, 15, 30 Seconds & 1, 2, 5 Minutes repetition rate
Randomised Load Variations	25% rated capacity	Instantaneous (<10ms) At random intervals between 10 and 2,000 ms
Electrical Design Peak Power	120% rated capacity	Supportable for 20 ms, mean load per minute not to exceed rated design power

Table 3 Example IT Power Draw Variability Specification

2.4 Base IT power draw profile specification

There will generally be a commercial requirement to manage & optimise costs for the data centre system. A baseline performance profile should be developed to determine what IT load variability the data centre infrastructure can support, without any additional load smoothing capability. This supports cost comparison of different IT power draw profile requirements, or comparison of design options for load smoothing, such as in-rack or in-row systems vs. infrastructure solutions such as UPS or BESS.

The base specification provides a design baseline against which additions to support additional & specific IT Power Draw Variability requirements may be evaluated and costed. As stated in 1.7 Deliverables above, the objective is to deliver a design utilising major equipment capable of the required load variability management, whilst allowing for incremental equipment as required to meet greater IT Power Draw Profile variability or more stringent grid compliance criteria.

To capture the impact on system design, as described below in 4.2 Combination of IT power draw , Power Draw Profile variability is specified at both generator and grid connection point levels.

Figure 2 below shows a simplified set of power draw variability profiles across the data centre infrastructure. On the right, two IT load profiles are shown, these are connected via a UPS system with sufficient battery provisioned only for power outage protection, without load smoothing capability. These loads are then presented, un-smoothed to the on-site generators and combined at the Utility Connection Point.

Note that the power draw profile shown for the generator reflects the bottom of the two IT power draw profiles, this will depend upon the facility electrical design, but in this simplified example, there is assumed to be one LV generator per LV power block, thus each LV generator will be subject to one LV block power draw profile.

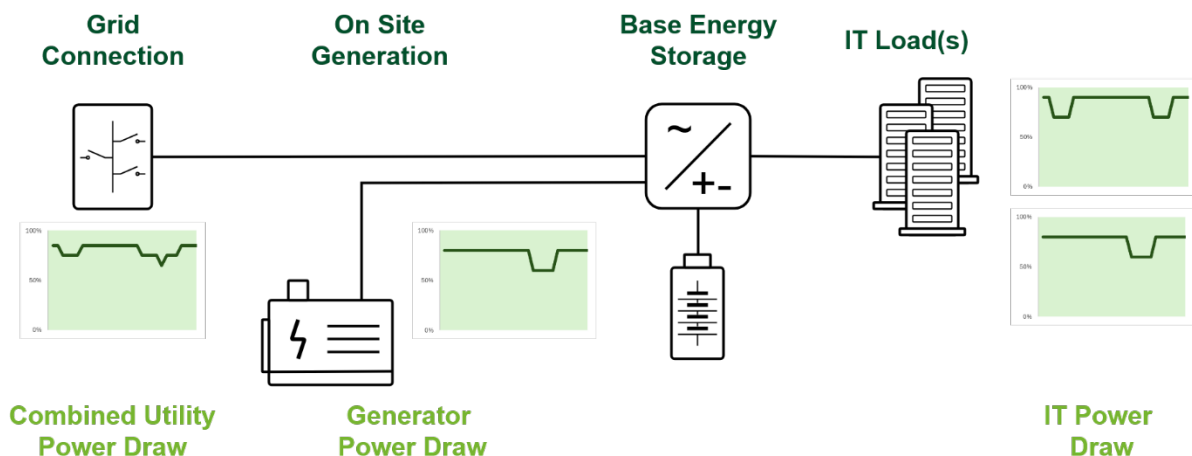


Figure 2 Base design IT profiles combined at Generator and Utility

As an example of an enhanced specification, Figure 3 shows the same data centre design, but with much larger batteries supplied to the UPS systems, rated and configured for load smoothing of the IT power draw profiles. This allows for the IT power draw profiles, as presented to the LV infrastructure, with much larger cyclic load steps & ramps whilst still presenting acceptable variability profiles to both the on-site generation and Utility Connection Point.

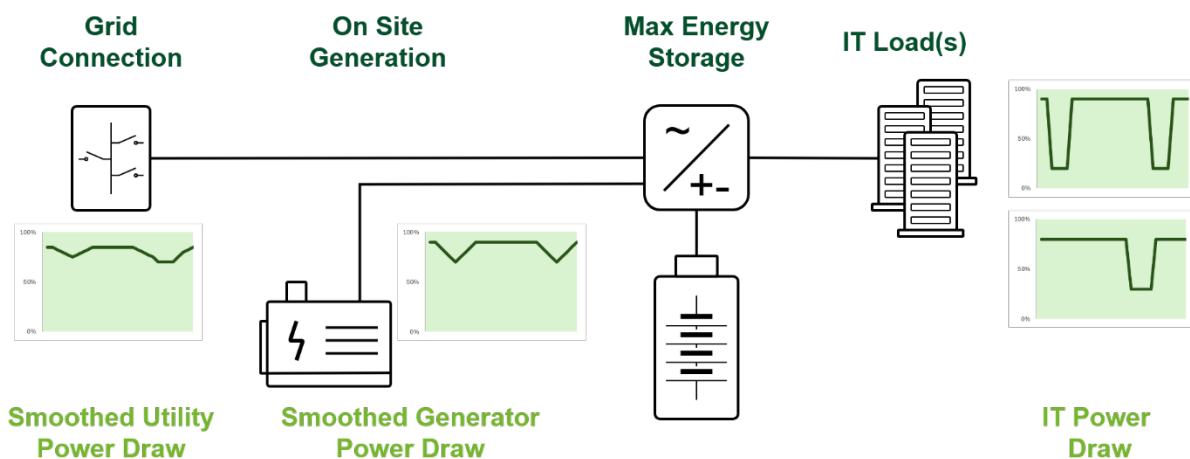


Figure 3 Max Storage design IT profiles combined at generator & utility

2.4.1 Base LV block power draw profile

In some cases, the desired IT power draw variability will be specified by the IT operator, as indicated in 2.3.3 above. Whether or not this is available at design time, the designer should detail the supported IT power draw variability as part of the specification. This provides the basis for agreement between data centre operations and IT operations on what IT power draw behavior is within specification and supported. The designer should take into account any load contribution from attached mechanical or other loads on the block separately.

The Power Draw variability of the combined IT loads presented to each LV Power Block during normal, non-fault operation shall not exceed:

Item	Capacity	Time
Randomly Occurring Step Size	25% rated capacity	N/A
Randomly Occurring Ramp Rate	10% per second 40% magnitude Between 10% and 100% load	N/A
Periodic Step Size	25% rated capacity	At any period less than 10 seconds (frequency above 0.1Hz)
Periodic Ramp Rate	5% per second 25% magnitude Between 10% and 100% load	At any period less than 100 seconds (frequency above 0.01Hz)
Peak Power	120% rated capacity	Supportable for 20 milliseconds, mean load not to exceed rated design power

Table 4 Example LV Block Power Draw Variability Specification

This specification is intended to allow LV generators to operate within voltage, frequency and emissions limits without requiring significant mitigation of load variability in the LV Block as per section 4.2.4.

2.5 Generator & turbine specifications

ISO 8528-X provides ratings for generator load step acceptance and ramp rates for infrequent load transitions to serve events where load transfers to and from generator. A class G2 or G3 generator is commonly specified, with the voltage and frequency stability selected based on the electrical design, and IT customer requirements. The design will specify, in addition to traditional Generator Specifications, the required acceptance of repeated & periodic load ramps & steps applied to the generator during normal operation under the selected IT Power Draw Profile variability.

2.5.1 Generator operation under AI load profiles

Generator & turbine specifications are typically evaluated in the context of infrequent load transfer events where load is ramped onto, or off a generator. Under these short transient conditions, the common specifications for the step response of the generator, including voltage and frequency deviations & settling times are well understood and generally available in standardised specifications such as the ISO 8528-X series.

As for the power grid, AI workload fluctuations within the data centre electrical infrastructure can cause power quality issues and damage equipment. Whether the site is operating in an islanded prime-power configuration, operating paralleled with the grid in the case of extending capacity or grid operator directed demand flex, or simply running on backup generation during an outage, the impact of the cyclic load variations must be considered.

The major issue is that the cyclic load variations present a different package design & control problem to the traditional generator. The cyclic variations in load present continuously varying torque to mechanical systems, with associated control actions to maintain voltage and frequency. These control actions may, in turn, impact the emissions performance of the generator package as it is no longer operating in a near steady state speed and load condition. In some cases, cyclic loads can excite additional resonances in the generator-load system creating large variations in power quality, destructively high torsional loads, or undesirable vibrations in the rotating machinery. Each of these can impact power quality, fuel efficiency, emissions performance and the operating lifetime of the generating equipment.

Generator and turbine manufacturers are developing analytical models, test regimes and methods of presenting the allowable operating envelope in terms of load condition, amplitude and frequency of cyclic load variation. These allow the designer to establish the acceptable load presentation to the generating equipment, or conversely, to specify the required generator cyclic load performance based upon the desired IT load and smoothing.

2.5.2 Generator operational envelope

The design will specify the requirements for the generator operational envelope, at the Generator Connection Point(s). This will consider both the operational envelope of the generators and the power quality requirements of the LV block and mechanical loads to ensure that the generator(s) operate within their defined envelope.

In addition to the normal environmental and load application step & ramp rate conditions, evaluation of the generator operational envelope shall consider

- Emissions performance of the generator under the applied load profiles
- Power quality including voltage, frequency, RoCoF and harmonics

- Equipment lifetime and maintenance impacts of applied load variability
- Sensitivity of the generator to applied load variability magnitudes at varying harmonic & subharmonic frequencies

2.5.3 Ramp rates & step sizes

The generators' response to applied ramp rates and step sizes is a major factor in determining the performance requirement for load smoothing. Whilst this is typically considered during a load-transfer from utility to generator condition, variable IT loads require that this is also evaluated as a continuous operating condition.

Where the combined load at the generator connection point is outside of the generator performance envelope, the energy storage infrastructure is required to modulate the power draw in such a way as to ensure that the generator operates within the defined operational envelope.

2.5.4 Generator performance envelope data

Data from the qualified generator vendors shall be obtained describing the acceptable levels of minimum and maximum load, load step sizes, ramp rates and load-induced oscillation which allow the generator to maintain the required voltage & frequency output to support critical & essential load and stay within its defined operational conditions.

This data may be supplied in the form of a generator package compatibility chart of alternating load peak to peak measurement against applied frequency.

2.6 Grid compliance

This document is primarily based on European grid codes, example frequencies and other data focus on European standards. In North America and other regions, the same issues exist, and similar TSO code changes are being developed, but around 60Hz rather than 50Hz systems.

For each project the currently applicable TSO & DSO codes and regulations will apply, however due to the current rate of change in grid codes and the retrospective application, designs should consider a common baseline set of requirements even for sites where requirements such as Fault Ride-Through are not yet in force.

2.6.1 General grid operator specifications

The currently in place, or proposed, grid code and connection conditions for the TSO & DSO supplying each site shall form the minimum specification for each specific Data Centre project.

ENTSO-E

As guidance on the target performance of designs and equipment the current ENTSO-E position on data centre load connection should be taken as a general target.

The current relevant ENTSO-E documents include:

[ENTSO-E position on the need for national connection requirements to ensure EU power system stability](#)

And

[Data centres and the power system: expected trends, challenges and opportunities](#)

2.6.2 Country specific grid operator specifications

The known published and under development country specific specifications are listed below:

Belgium

See https://www.elia.be/-/media/project/elia/elia-site/public-consultations/2025/20251210_public-consultation-on-additional-technical-requirements-for-grid-forming-battery/20251210_general_requirements_for_demand_ltcibl_requirements_en.pdf

Denmark

See [Energinet Technical Regulation 3.4.3](#)

Finland

See Fingrid [KJV2026 New requirements for demand connections](#)

The [linked presentation](#) is an excellent overview of the Fingrid FRT and AI load requirements, the rationale behind them, how the limits are expressed and what data is expected to be submitted for approval.

France

See [RTE technical reference document article 8.3.6](#)

Germany

See [Maturity process for grid connections to the transmission grid](#)

Republic of Ireland

For sites in the Republic of Ireland the EirGrid data centre connection code applies;

[MPID 345 Fault Ride-Through, Rate of Change of Frequency and Post Fault Active Power Recovery for Demand Facilities](#)

In addition, the Commission for Regulation of Utilities [Large Energy Users Connection Policy](#) applies.

Northern Ireland

As for the Republic of Ireland, SONI has also submitted MPID 345 to the NI Utility Regulator for approval, this draft should be considered applicable to any design for Northern Ireland.

Norway

The current Statnett documents include;

The [2025 NVE National Guidelines for functional requirements in the power system](#) and the [Consultation document for updating the NVE](#)

Canada

Alberta (AESO)

See <https://www.aeso.ca/assets/Uploads/grid/Guide-to-AESO-Connection-Requirements-for-Transmission-Connected-Data-Centres.pdf>

United States

Texas (ERCOT)

See <https://www.ercot.com/mktrules/issues/NOGRR282>

2.6.3 Grid voltage & frequency conditions

The table below provides a base set of voltage and frequency conditions which we believe to be consistent with the core of ENTSO-E planned large load code modifications and forms a minimum design basis⁶.

Item	Capacity	Time
Voltage	90% to 111.8%	Continuous
Frequency	47 to 47.5 Hz	20 seconds
	47.5 to 48.5 Hz	90 minutes
	48.5 to 49 Hz	90 minutes
	49 to 51 Hz	Unlimited
	51 to 51.5 Hz	90 minutes
	51.5 to 52 Hz	60 minutes
Rate of Change of Frequency	±4.0 Hz/s	over a period of 0.25s
	±2.0 Hz/s	over a period of 0.5 s
	±1.5 Hz/s	over a period of 1 s
	±1.25 Hz/s	over a period of 2 s

Table 5 Common Grid Voltage & Frequency Conditions

Note that voltage specifications depend upon TSO & region, for reference the table provided in Annex II of [ACER NC RfG DC Recommendation Annex 2](#) should be used until a local TSO specific value is available.

In all cases the currently applicable requirements shall be verified with the connecting DSO or TSO. For example, the NVF 2025 standard for Norway currently requires loads to stay connected from 45Hz to 57Hz.

⁶ Note this is Europe specific, North America, Western Japan and other regions will base AC frequency around 60Hz nominal.

2.6.4 Grid Fault Ride-Through and Active Power Recovery

Fault Ride-Through (FRT) and Active Power Recovery (PF-APR) specifications are evolving rapidly, however there are broad similarities, with the major differences being

- 1) The voltage-time profile of the 'ride-through' fault
- 2) The Post Fault Active Power Recovery time
- 3) Active Power Recovery percentage

The data centre mechanical and electrical systems shall be designed such that they are able to meet the following requirements:

Item	Recovery Target	Note
Active Power Recovery Time	Between 500 and 5,000 milliseconds	Typically, 500 to 2,000 ms
Active Power Recovery Fraction	Between 80% and 100%	As a fraction of the pre-fault load at the utility connection point

Table 6 Common Active Power Recovery Targets

The majority of FRT and PF-APR is likely to be achieved in the IT and mechanical UPS systems, with the major OEM vendors updating products & firmware to implement these requirements. To fully validate the Post Fault Active Power Recovery fraction however, it will be necessary to determine the behaviour of house and non-UPS protected mechanical loads such as chillers. Again, where sites utilise in row or in rack BBU systems, the design requirements for FRT and PF-APR may transfer to these systems if no centralised UPS is present.

Note that these non-UPS protected loads may show substantial variation with external ambient temperature, with heating loads high during cold conditions, whilst compressor & fan loads will be higher during hot conditions. There may be a requirement to engage with the grid operator to determine whether the recovery target stress conditions occur during winter or summer to establish the required modelling scenarios. Evaluation at part load is also recommended as the power fraction contribution of 'house' and other loads such as pre-heat or frost protection can be substantially larger at part IT load.

Some example voltage-time curves are shown below:

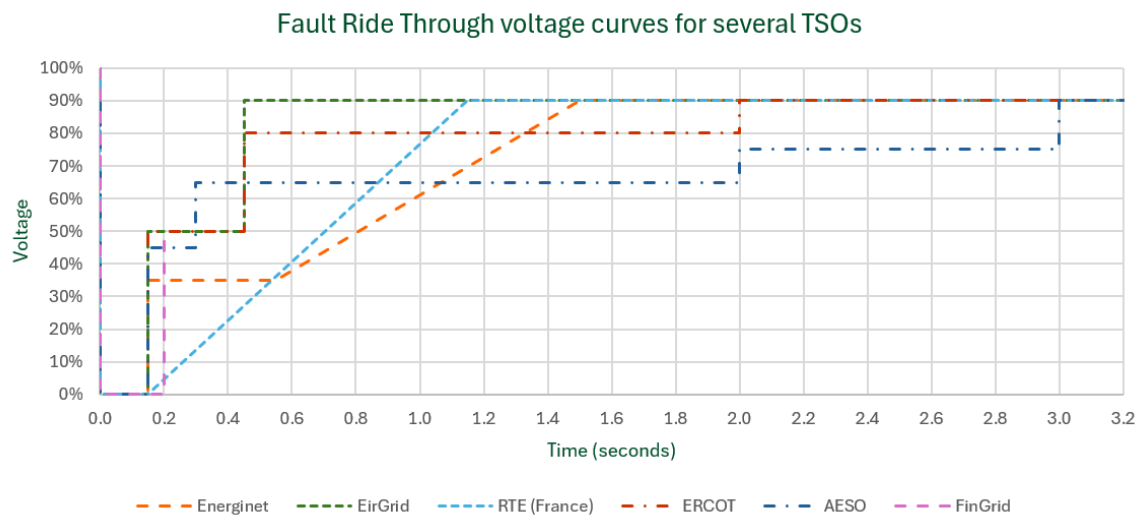


Figure 4 EirGrid comparison chart of several TSO FRT voltage time curves

TSO	Post Fault Active Power Recovery Time
SONI, EirGrid	500 ms
ERCOT	1,000 ms
AESO (Alberta)	1,000 ms
Fingrid	500 ms

Table 7 Comparison of TSO Active Power Recovery times

In all cases the currently applicable requirements shall be verified with the connecting DSO or TSO.

2.6.5 Grid step size & ramp rate constraints

At the grid connection point for the Data Centre load there will be a set of constraints on the load step size and load ramp rate(s) which are acceptable to the TSO or DSO. This may be a combination of utility specifications in the connection agreement, known characteristics of the local grid connection point, and thresholds determined during modelling & analysis of the data centre and grid system.

At a minimum the step size and load ramp rate maximums at which the grid connection point stays within the TSO / DSO specified operating voltage ranges should be calculated.

The TSO / DSO or appropriate expert will also be consulted to determine the sensitivity of the grid connection point to voltage or current harmonic content and sub-synchronous oscillation.

2.6.6 Grid load-induced forced oscillations

Forced Oscillations, also known as Sub-Synchronous Oscillation (SSO), are recognised as presenting a stability issue to micro, distribution and transmission grids. The impact of these load oscillations depends upon a variable set of factors including the network at the

connection point and the nearby active generation & load assets. This is expected to require connection-point specific analysis.

The ENTSO-E position paper in 2.6.1 describes the TSO action as:

“The relevant TSO shall define the magnitude and accuracy of the allowed oscillations in the frequency range between 0.01 Hz to 50 Hz (rotating reference frame). Within the 0.01 Hz to 50 Hz range, the relevant TSO may define more than one frequency range and relative allowed oscillations.”

In all cases the currently applicable requirements shall be verified with the connecting DSO or TSO.

Specification of Flicker or SSO Limits

Note that some TSO specifications use language of the form *“Some facilities exhibit cyclic dynamic demand, for example AI Data Centres. Demand facilities shall operate stably with the power system. Voltage and frequency oscillations shall not be amplified and shall instead be damped”*.

This presents a problem for the designer as it does not present a clear and measurable set of design requirements, further the current & future behavior of the power grid outside the data centre facility may be complex, dynamically variable with generation and load scenarios, and not realistically known at design time.

In place of this some TSOs provide more quantitative goals (see the Fingrid presentation in 2.6.2 above) with data of the form;

Frequency Range (Hz)	Peak magnitude of power oscillation in % of rated demand capacity		Window length of spectral analysis (seconds)
	%	Must remain below (MW)	
0.01 to 0.025	20	40	300
...			
0.1 to 0.2	10	20	40
...			
18 to 45	3	6	0.5

The objective for the designer is to obtain a defined, measurable and achievable definition of the SSO targets for the Grid Connection Point which allows for a data centre to be designed with confidence that the target can be met once in operation.

3 Design process

This section provides some guidance on how the design process may be updated to incorporate these new requirements.

3.1 Establish baseline & additional power draw variability

To establish a baseline, the design should initially be validated for a traditional non-variant IT load and then apply the target and 'worst case' IT load variability to establish;

- 1) Cost and design baseline under the local grid code constraints
- 2) Additional requirements for planned workload (e.g. energy storage for load smoothing & SSO control at both generator and grid)
- 3) Additional requirements for 'worst case' workload, what is the worst set of IT power draw variations the design can accommodate without substantial changes to design or equipment? This represents the upper bound to which the data centre may reasonably be upgraded during its operational life as IT equipment changes.

3.2 Designs with IT coupled energy storage or without central UPS

This document generally discusses AC LV distribution systems with central UPS, however there are other design patterns such as in row or in-rack Battery Back Up (rack BBU) and emerging DC power distribution systems which place energy storage at other points in the power distribution system.

3.2.1 IT coupled BBU storage in place of central UPS

In the absence of central UPS systems, the IT coupled BBU systems may be required to perform key functions otherwise provided by the UPS including

- 1) Voltage, Frequency and RoCoF Ride-Through
- 2) Harmonic & power factor control
- 3) Fault Ride-Through and Post Fault Active Power Recovery
- 4) Load smoothing including step size & ramp rate control
- 5) Sub-Synchronous Oscillation mitigation

This may require real time communication and orchestration of multiple BBU units by the IT platform operator, in addition to requirements to respond to infrastructure status or alarm signals.

For example,

- The BBU may be required to operate on a different load step-in rate after power loss when the data centre is operating on Generator than when performing Active Power Recovery after a ride-through fault
- The BBU may be required to operate a different step & ramp control profile when SSO is detected within the data centre infrastructure or at the grid connection point

These requirements may result in a transfer of responsibility from M&E infrastructure operator to IT operator to ensure the design stays within allowable conditions for LV systems, generators and grid compliance.

3.2.2 DC power systems

It is recognised that LV power distribution design is rapidly changing to incorporate DC power distribution, particularly in the case of the high-density AI loads.

For the currently proposed designs the principles of workload variability and grid code evaluation are similar, once the presence of additional power conversion stages and energy storage stages are considered. This [presentation by Schneider Electric](#) at GTC provides a useful overview.

Potential changes

- 1) The traditional AC LV Transformer and UPS may be replaced with a specialised DC power distribution block such as a Transformer Rectifier Unit or Solid-State Transformer.
- 2) DC distribution systems are more likely to have multi-layer energy storage including
 - a. Directly adjacent to the compute (a 'sidecar' rack such as OCP Mount Diablo)
 - b. LV block level UPS, TRU or SST
 - c. Centralised UPS or BESS connected at MV

3.3 Design process suggestion

The flowchart below provides an outline of the additional design process flows that should be considered to establish the performance of the data centre design.

This breaks down the evaluation into two parallel flows

- On the left, evaluation from the IT load variability outward assessing the impacts on the data centre infrastructure and grid connection
- On the right, evaluation from the Grid Code inward, assessing the impacts of these new constraints on the data centre design & operation

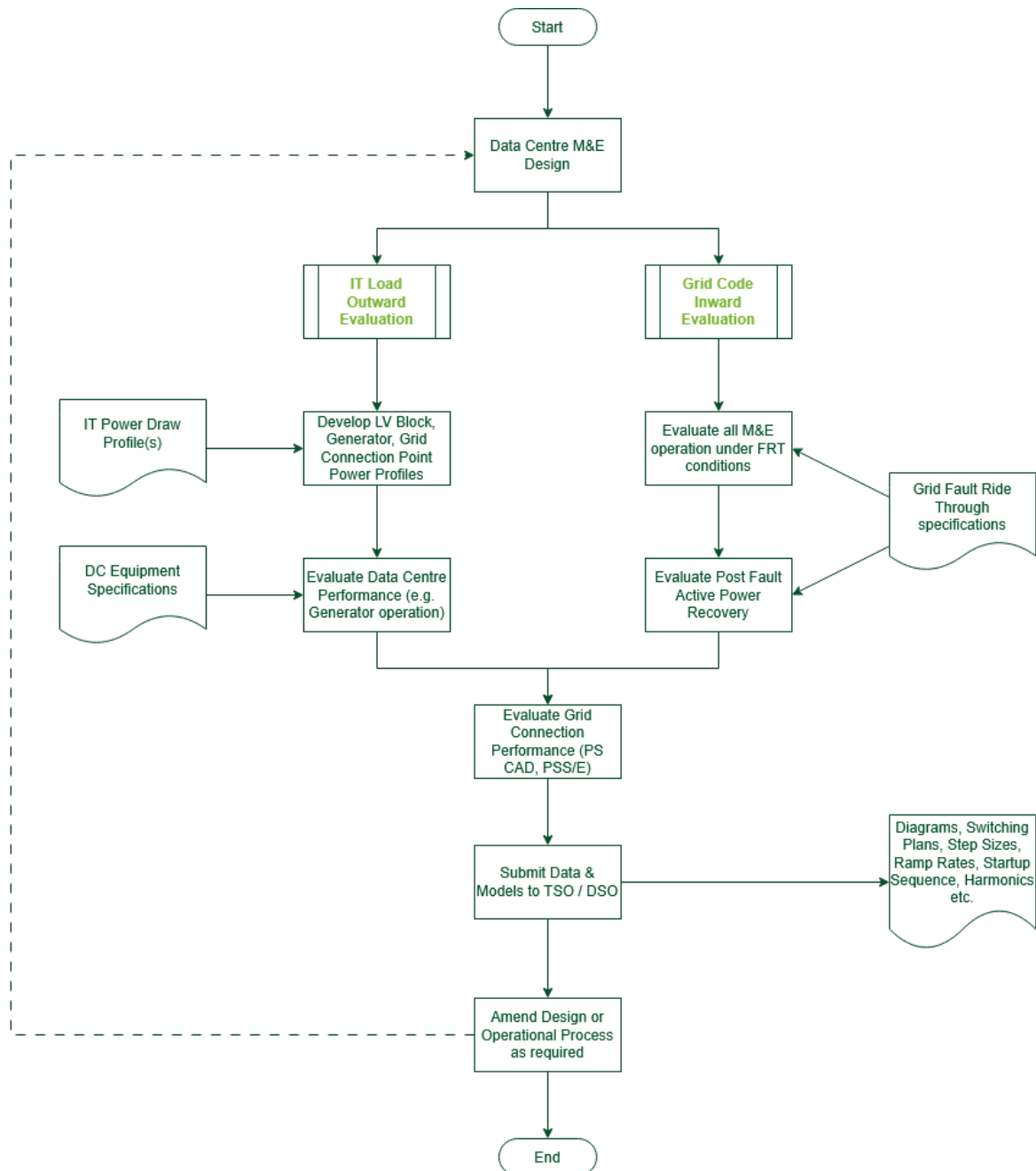


Figure 5 Indicative additional design process flow

3.3.1 IT load outward

Evaluate the impacts of IT load variability on the data centre infrastructure, onsite generation, and grid connection point. Specifically address step sizes, ramp rates and periodic load variations.

- 1) Evaluate the impact of random or infrequent steps & ramps
- 2) Evaluate the impact of periodic steps & ramps which may give rise to sub-synchronous oscillation at either the data centre power generation system or grid point of connection

3.3.2 Grid code inward

Evaluate the impact of grid code compliance on the data centre infrastructure, including.

- 1) All Mechanical & Electrical plant operating across defined frequency and voltage ranges
 - a. Consider voltage ranges and resulting current ratings for equipment
 - b. Consider which devices should be protected by UPS or other systems capable of correcting voltage or frequency deviations without disconnecting from grid power
- 2) Post Fault Active Power Recovery
 - a. Consider the behavior of the UPS systems
 - b. Consider the behavior of the non-UPS protected loads
 - c. Map the proportion of data centre pre-fault load which will return within the required APR timeframe, evaluate this for multiple IT load points and external ambient temperatures
 - d. As required by TSO, evaluate the grid connection point voltage, current and reactive power profile during fault and APR
- 3) Power quality, harmonics & power factor
 - a. Evaluate the contribution of the data centre load to power quality at the grid connection point
 - b. Evaluate the power quality impact of the data centre load at the grid connection point, this may require collaboration with the DSO or TSO
- 4) Develop a utility load profile statement from design and operational processes
 - a. Evaluate start up sequences, generator transfer sequences, maintenance sequences
 - b. For each load event evaluate step size, inrush current, voltage impact
- 5) Evaluate the impact of any additional grid code or connection requirements such as
 - a. Dispatchable or auto-generation requirements
 - b. Voltage or frequency support services

4 Design requirements

4.1 Overall requirements

The data centre shall be designed such that it is able to meet the following design requirements

- 1) Specific IT power draw variation as defined in section 2.1 above
- 2) Utility voltage & frequency long & short-term deviations as defined in the local grid code and section 2.6 above
- 3) Utility Fault Ride-Through and Post Fault Active Power Recovery as defined in section 2.6.4 above
- 4) Local Grid connection point code and regulatory requirements including voltage, ramp rate, load step, harmonic & power quality constraints as determined from local grid code and power system analysis as in section 2.6.6 above
- 5) Utility demand flexibility, auto-dispatchable generation, voltage control, reactive power control, phase jump and Frequency / RoCoF control standards where applicable

4.2 Combination of IT power draw profiles

Load variability specifications will be evaluated at a single LV block, LV Group and entire campus levels. It will be common for multiple IT load profiles to exist within a site, in which case these shall be modelled and combined appropriately at LV block, Generator and Utility level for system assessment.

Figure 6 provides a simplified data centre electrical layout, identifying the named load evaluation points, note that whilst only a single LV block is shown, multiple LV blocks combine at the MV Switchgear.

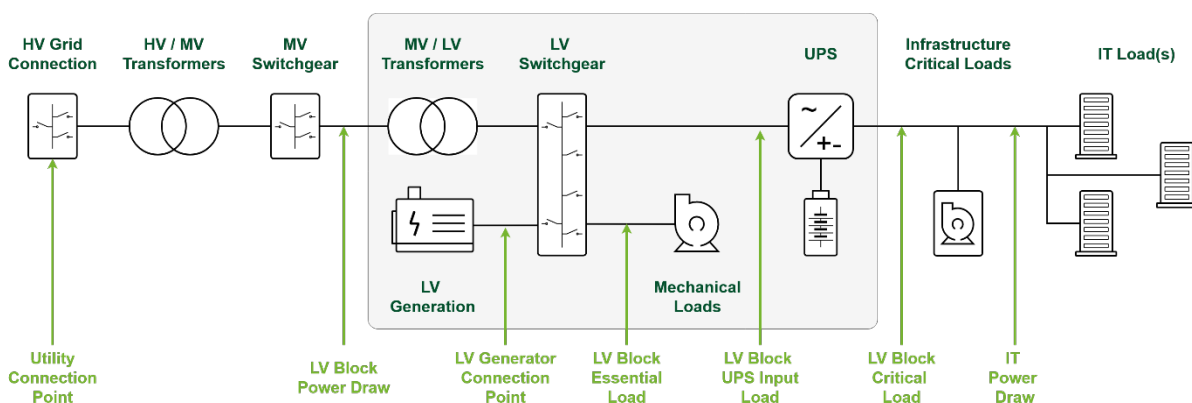


Figure 6 Named Load Points - LV Generation

4.2.1 LV Block

Load profiles shall be evaluated at the LV block outputs, typically the LV Block Critical Load and LV block Essential Load outputs. These loads shall be combined, including any transfer function for the UPS, to determine the LV Block Power Draw.

Load profile evaluation allows for the smoothing demand on the energy storage systems (e.g. UPS) to be determined against the required overall LV Block Power Draw profile.

The LV Block Critical Load may include

- 1) One or more IT load profiles which combine to an overall LV Block IT Power Draw profile.
 - a. For example, a block may have 1,700kW of GPU load which can vary from 10% to 100% load and 300kW of network and storage load which is modelled as constant. This would combine to give a load variability range of 470kW to 2,000kW.
 - b. The 'worst case' IT installation shall be considered for the LV block design, to allow the evaluation of the 'worst case' IT power draw profile the design is able to support.
- 2) Any Infrastructure Critical Power Draw, such as CRAH, CDUs or other equipment supported by the LV block UPS output

The combined total load at the LV Block may include

- 1) The LV Block UPS Input Load, presenting the combined Critical Loads with the UPS transfer function applied to represent any load smoothing.
- 2) The LV Block Essential Load incorporating
 - a. Any CRAH, CDU, Pumps etc. supported by an additional mechanical UPS within the LV block
 - b. Chiller, house loads, generator pre-heats etc. supplied directly by the LV block

4.2.2 Exceptional, random and periodic variability

When combining IT Power Draw Variability, it may be necessary for the designer to establish whether the profiles combine in such a way as to produce

- 1) Infrequent, exceptional events such as a substation trip, which the TSO or DSO will accept outside normal limits as an unplanned event
- 2) Randomly occurring collisions between load variability profiles, producing infrequent, non-periodic larger Step Sizes or Ramps which are evaluated against step & ramp limits but are not considered to create a risk of Sub Synchronous Oscillations
- 3) Regular, periodic events resulting from one or more synchronised or periodic workloads, capable of creating or exciting Sub Synchronous Oscillations

This evaluation may impact the sizing of required energy storage as the requirement to control step & ramp variability can be different for random and periodic variations.

4.2.3 IT Load correlation & combination

To correctly assess the impact of IT power draw variability on the design it is necessary to determine how the IT loads combine, not only at the LV Block level but further up the power distribution chain at MV and HV points.

Figure 7 shows a simplified example of a data centre, with three LV groups feeding IT loads. An LV group being a set of LV Blocks which feed a set of racks in a redundant configuration. In this case two groups of 4 to make 3 distributed redundant racks for high density AI loads and one group of traditional 2N powered racks for lower density loads.

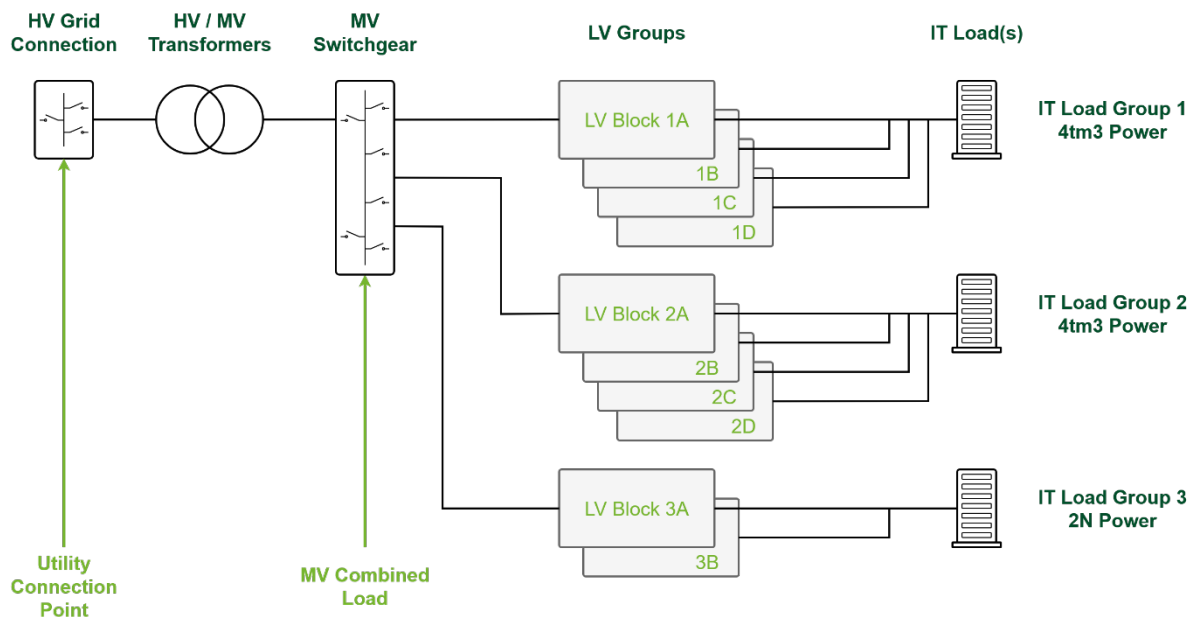


Figure 7 IT Load Combination

The LV distribution design will specify groups of IT racks & rows which are powered from multiple LV Blocks in an LV Group. The loads in these racks combine across the LV Group to present a common IT Power Draw profile for each LV Block in the group. These LV Group Power Draws then sum at the MV Combined Load to give an overall power draw profile for any shared MV generation and the Utility Connection Point.

The IT Load groups may be low or high variability and either correlated or uncorrelated in load profile.

- 1) An uncorrelated set of low variability workloads, for example, multiple Cloud and AI Inference workloads running across IT Load Groups 1, 2 & 3 will tend to average out when combined at the MV Combined Load.
- 2) A correlated workload, for example, an AI training load running as a single, synchronised workload across all racks in IT Load Groups 1 & 2, will present variability larger than MV Combined Load and thus may require more significant step & ramp mitigation
- 3) Multiple uncorrelated AI training workloads with large load steps may produce smaller load steps on average, but will periodically coincide, thus the system must be capable of riding through an evaluated reasonable 'collision' step size, but energy storage may be sized for this charge / discharge transaction to occur infrequently from a lifetime perspective

4.2.4 Generator connection point

In the case of an LV generator directly coupled to a single LV block, the demand profile for each generator is that of the attached LV block. Generators will be specified to meet the associated LV block profile.

Alternatively, the generators may be grouped, with their load profile combining multiple LV blocks and potentially other loads such as MV chillers.

Figure 8 provides a simplified electrical layout, showing a common MV Generator Connection Point, only a single LV block is shown for simplicity.

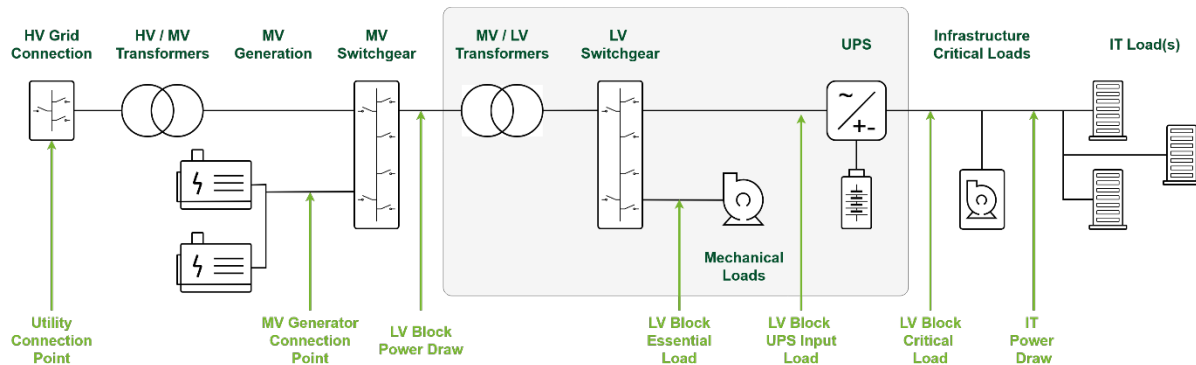


Figure 8 Named Load Points - MV Generation

4.2.5 Utility connection point

As shown in the figures above, the Utility Connection Point (PCC) will experience the combined load of the entire data centre, including IT, mechanical and house loads. In more complex designs this connection point may also have renewable energy sources, large-scale BESS or other assets connected which should also be evaluated as part of the system model.

5 Required system capabilities & design deliverables

The system design shall provide the following capabilities

5.1 Specification of design grid code & regulatory requirements

Statement of the applicable grid standards, codes, connection policies and local regulatory requirements applicable to the data centre and any accompanying energy generation or storage as a grid connected asset. Including

- 1) All applicable grid codes, requirements, standards, connection policies and processes, including applicable Demand Connection Codes, specific Large Load policies applicable to Data Centres.
- 2) All applicable local regulatory requirements, standards, connection policies and processes, including applicable Large Load connection policies applicable to Data Centres.
- 3) Reasonable expectations of requirements, standards, policies & processes which may change by the time of energisation, including any applicable published draft codes or regulatory instruments.

From these sources the design will state the required operating conditions and capabilities for the Data Centre including

- 4) Required operating voltage, frequency, RoCoF, phase jump and other power quality long & short-term deviations
- 5) Fault Ride-Through and Post Fault Active Power Recovery requirements
- 6) Any grid support service requirements such as demand flexibility, auto-dispatchable generation, voltage control, reactive power control, frequency & RoCoF

From the applicable specifications, power systems analysis, and liaison with the local authorities, DSO or TSO as necessary the design will specify

- 7) Local grid connection point design constraints including voltage, ramp rate, load step, harmonic & power quality

5.2 Specification of allowable IT power draw profiles

Definition of the IT power draw variability profiles against which the design is validated. Provide a clear statement of required or prohibited behaviours of the IT load within the data centre. This is to specify for the IT equipment operator how to avoid outages, loss of warranty or SLA for the data centre, or risk of disconnection by the grid operator for violation of grid code.

The specifications should include

- 1) Allowable IT power draw variation, random & periodic, within specification for the data centre infrastructure
- 2) Allowable IT power draw variation, random & periodic, within specification at the Grid Connection Point at the time of design

Where the design requires IT Coupled BBU storage, such as where there is no central IT UPS system;

- 3) Required local and distributed behavior of IT coupled storage to control individual, LV block and grid level IT power draw profile
- 4) Required response of IT coupled storage to infrastructure status signaling and alarms such as 'on generator' or 'SSO detected'

5.3 Operational management of IT power draw profiles

The monitoring and reporting design shall

- 1) Include instrumentation to record, report and alarm on the status of the IT power draw profiles against the defined allowable IT power draw envelope

Standard and Emergency Operating Procedures, including where necessary, programmed actions in SCADA or other control systems shall be defined to

- 2) Identify and respond to events restricting IT load variability, such as an LV block being forced into UPS bypass and losing load smoothing capability
- 3) Identify and respond to events where IT load variability exceeds the defined envelope, to protect the data centre equipment or maintain grid code compliance

5.4 Monitoring & reporting at the utility connection point

Incorporate equipment to monitor & report at the utility connection point

- 1) Power quality
- 2) Harmonics
- 3) Ramp Rates & Step Size
- 4) Sub harmonic oscillation (flicker)

5.5 Monitoring & reporting at the LV blocks and generator connection point

Incorporate equipment to monitor & report at the LV string connection point, and generator connection points

- 1) Power quality
- 2) Harmonics
- 3) Ramp Rates & Step Size
- 4) Sub harmonic oscillation (flicker)

5.6 Equipment specifications

Include in equipment specifications used for selection & procurement

- 1) Additional requirements arising from load variability, Fault Ride-Through, Active Power Recovery, flexible demand etc.
- 2) Required equipment specification data, textual, graphic or model components for tools such as PS CAD or PSS/E to support evaluation of the equipment and combined system
- 3) Clear specifications for voltage, frequency and RoCoF, within which each item of critical or essential equipment is required to operate, including motors, controllers etc.
- 4) Clear specifications for power quality and harmonic content for each item of critical or essential equipment where required to provide the overall data centre validation study, note that harmonic content data supplied for modelling must include specific harmonic data, simple THD or TDD values are insufficient.

For onsite power generation packages such as generator, turbine or fuel cell

- 5) The supplier shall describe the allowable operating envelope of the package, including acceptable levels of minimum & maximum load, load step sizes, ramp rates, allowable load oscillation magnitudes & frequencies and achieved performance under these conditions, power quality, voltage & frequency stability, fuel efficiency and emissions.
- 6) The supplier shall describe the applicable maintenance and warranty conditions under the design load profile, covering the full package, engine, aftertreatment, alternator, fuel system & controls. This shall include, maintenance schedules, minor and major overhauls, spare & service parts schedules, required monitoring and inspection equipment, processes and schedules.

5.7 Load validation studies

Provide studies to validate the operation of the electrical system under the design conditions, specified IT load profiles, on utility and generator power. Studies shall

- 1) Consider
 - a. Ongoing IT power draw variations based on the IT load profile(s)
 - b. Expected load transfers to or from generator
 - c. Any other Behind the Meter energy sources such as Solar or Wind
- 2) Be delivered to the local regulatory and TSO / DSO requirements, including appropriate selection of software tools such as PS CAD or PSS/E
- 3) Evaluate the Utility Connection Point Load Ramp Rates & Step Size, considering the data centre and local utility infrastructure as required by the grid operator
- 4) Evaluate the Utility Connection Point power quality including harmonics and sub-harmonic contributions from the Data Centre
- 5) Evaluate generator connection point load ramp rates & step sizes
- 6) Evaluate generator connection point harmonics & sub-harmonic contributions
- 7) Evaluate generator power quality, voltage and frequency stability under the applied conditions

5.8 Fault Ride-Through design

The entire data centre electrical & mechanical system shall be designed to be compliant with the applicable grid operator Fault Ride-Through and Post Fault Active Power Recovery specifications, including

- 1) Operation of all mechanical and electrical plant at design capacity, without deration of supported IT load, across the full range and duration of voltage and frequency conditions specified by the grid operator
- 2) Operation without disturbance to critical load or critical cooling conditions through the defined 'Ride-Through' fault conditions and Post Fault Active Power Recovery ramp
- 3) Sizing and configuration of all equipment, including electrical distribution and protection systems, to operate at increased current draw during periods of reduced utility input voltage as specified by the grid operator
- 4) Study or studies to demonstrate the Post Fault Active Power Recovery behavior of the load at the grid connection point, sufficient to meet grid operator requirements
- 5) Studies to confirm the RoCoF and phase jump behavior of the system under the TSO specified limits
- 6) Specify whether operating in prolonged voltage or frequency anomalies results in any change to warranty or SLA conditions such as due to reduced fault current supply of UPS systems when performing voltage boost / cut or frequency correction

5.9 Load flexibility & grid services

Provide the capability, to

- 1) Manually dispatch local generation assets to provide load flex to the utility
- 2) If specified – Auto Dispatch local generation at the request of the local utility
- 3) If specified - provide demand flexibility through energy storage or generation without impacting IT loads
- 4) If specified – provide grid support services such as reactive power control, frequency support or dynamic load adjustment

Note that the generator performance specification, fault current ratings and other elements of the electrical design should also be validated for these non-traditional use cases.

5.10 LV Block capabilities

Incorporate the capability at the LV blocks to

- 1) Serve IT equipment step sizes, ramp rates, power quality & sub harmonic oscillation whilst maintaining an input power profile such that load variation levels, rates and frequencies are permissible at the Generator Connection Point and Utility Connection Point (the design may also choose to meet generator and grid connection point requirements through load smoothing in another location)
- 2) Contain energy storage sufficient to meet load management criteria 5.9-1 above in addition to design specified autonomy at EoL, this includes both capacity of energy storage and expected charge/discharge cycle lifetime
- 3) Provide physical space, either within the LV pod or for adjacent energy storage pod(s) sufficient to expand from a 'base' energy storage specification meeting the base requirement in 5.9-1 to the full power draw variability achievable by the design
- 4) Meet attached IT load power quality specifications under the applied IT power draw variability profile(s)
- 5) Function correctly with a generator as defined in section 5.7 above, unless otherwise specified
- 6) Ensure that IT equipment power supply meets the tenant power quality specifications, including voltage, frequency, harmonic content and RoCoF under the full range of applied utility and generator power input conditions, including utility voltage & frequency conditions, phase jumps and FRT events, or is protected by the electrical design resulting in a smaller required operating condition range

5.11 Mechanical equipment

Ensure that mechanical equipment, including subcomponents such as control panels, VSDs etc. whether powered by LV or MV systems

- 1) Is maintained within rated operational voltage range, frequency range and RoCoF, such that it operates to design capacity without interruption. Note that this includes generator voltage & frequency variations, whether induced by load transfer or IT load variation.
- 2) Is rated to operate for the full range and duration of voltage and frequency conditions specified by the grid operator whilst meeting design capacity and reliability requirements.

5.12 Energy storage

Incorporate electrical energy storage at the DC converters, UPS, TRU, SST or additional BESS, sufficient to support the design conditions, specifying for each element of energy storage

- 1) Type, location and roles, e.g. "UPS battery to support load step size, ramp rate, voltage and frequency control"
- 2) Rationale for selection of this energy storage type and system location, e.g. LV block UPS vs. MV connected BESS
- 3) Maximum charge and discharge power ratings as constrained by the system design, e.g.
 - a. Discharge at 100% of UPS capacity
 - b. Charge at 40% of UPS capacity (battery charge rate limit) plus IT load up to 120% UPS capacity total
- 4) Design lifetime for the energy storage to a specified minimum capacity, under the operating profile indicated by the IT load specification. The capacity degradation at EoL shall also be stated, e.g. 70% capacity at EoL.
- 5) State of Charge measures applied to the energy storage EoL capacity due to the required roles, including
 - a. Capacity assigned and maximum SoC for load step and ramp rate control, for example 20% of capacity at $\leq 80\%$ SoC
 - b. Capacity assigned and min / max SoC for RoCoF control on either utility or generator supply
 - c. Capacity assigned and minimum SoC for load support during an input power failure, e.g. 50% of capacity at $\geq 10\%$ SoC
- 6) A calculation to show the impact on energy storage lifetime of operating with or without the load step & ramp rate control required by the IT load profile
- 7) Whether a different load smoothing profile is required for utility & generator operation modes and if so, how the building control system will implement this

Note that for UPS (TRU or SST) systems, most of this information is likely to be available from the vendor's analysis tools.

5.13 Generator Connection Point(s)

Incorporate the capability to, at the generator connection points (if included)

- 1) Ensure that the generators operate within their design specifications, including both one-off and repeated ramp rates and step sizes
- 2) Ensure that the load presented to the generators does not include load steps, load ramp rates or sub-synchronous oscillations sufficient to disturb operation of the generators or output power quality including voltage, frequency and RoCoF
- 3) Ensure that the load presented to the generators does not cause the generators to operate outside defined acceptable emissions limits other than at startup or shutdown

5.14 HV Systems & Utility Connection Point

Incorporate the capability to, at the utility connection point

- 1) Ensure that the load presented to the utility does not include sub-synchronous oscillations exceeding limits specified by the utility or analysis
- 2) Ensure that the load presented to the utility does not exceed ramp rate or step size limits determined by the utility or analysis
- 3) Ensure that the load and electrical characteristics presented to the utility connection point are compliant with the utility specifications for harmonic behavior
- 4) Interoperate as required by the TSO or DSO with the utility connection provider's requirements for signaling, control and data interchange for switchgear, power flow & protection systems.

At the HV & MV systems,

- 5) Design, equipment specification, Control and SOO of HV/MV systems to support Data Centre & LV systems, e.g. HV or MV transformer Auto Tap Changer control to manage long duration voltage deviations
- 6) Design, equipment specification, Control and SOO of power quality equipment such as power factor correction, STATCOM etc. as required to meet the grid requirements at the point of connection

5.15 SSO Discrimination & mitigation capability

Incorporate the capability within the power metering systems to identify

- 1) Whether a detected SSO event originates within the data centre infrastructure or externally on the grid
- 2) Which parts of the DC infrastructure are a forcing part of the SSO event, e.g. by time correlating power profiles on LV blocks to the detected SSO profile at the grid or generator connection points

Incorporate the capability within the electrical systems to take corrective action when required to maintain grid or data centre power generation system stability, such as when sub-synchronous oscillations are detected. This may be

- 3) Breaker tripping from
 - a. Central SCADA controls
 - b. A tenant provided Controller (such as an RTAC, SICAM etc.)
- 4) Active oscillation damping by energy storage systems

The implementation of any tripping capabilities shall implement grid limits including step size, ramp rate and reactive power during a trip event as required by the grid provider.

6 Configuration, testing & commissioning

The addition of system capabilities to withstand AI loads and comply with grid connection constraints presents new requirements in configuration, operation, commissioning and testing.

It is recognised that some tests, such as variations in utility supply voltage and frequency at building design load are not practically achievable on site, however, this does not remove the need to validate these capabilities and configurations. Where integrated system level tests are not practical, unit level, Software in the Loop and Hardware in the Loop tests should be applied as required to validate capability and configuration.

6.1 Device & controls configuration

The design shall document additional device & controls configuration intent & requirements, whether this be operating modes, thresholds, alarm states, inter-unit communications, set points etc.

Examples of this may include

- 1) UPS system configurations for
 - a. Input voltage & frequency ride-through
 - b. Post Fault Active Power Recovery
 - c. LV load step or ramp rate mitigation, on utility or generator feed
 - d. Battery State of Charge management
- 2) Mechanical plant configurations for
 - a. Input voltage and frequency allowable ranges
 - b. Restart timing after short-break power outages

6.2 Factory testing

Some of the new equipment capabilities & configurations will be best suited for factory testing. In some cases, it will be appropriate for this to be a first of a kind only test, in others the tests will apply to all units.

Examples of this may include

- 1) Mechanical plant voltage & frequency range tolerance under design load conditions
- 2) LV block
 - a. IT load ramp rate & step size mitigation
 - b. Input voltage, frequency range & RoCoF tolerance
 - c. Post Fault Active Power Recovery
 - d. Correct discrimination between a ride-through APR fault on utility and appropriate power recovery on generator or a longer utility break
 - e. Load testing under the design IT load variability specification, including one-off and periodic ramp rates & step sizes as well as peak power ratings.

HV & MV validation; the risk of protection or control misconfiguration is most cost effectively mitigated before site installation. Protection and control design will prefer configurations which use an electronic description of the system such as Substation configuration language or a digital twin to derive deployed configurations. Factory acceptance of HV & MV protection systems should include Software-in-the-Loop testing of the protection and control systems to be deployed, using simulation environments as necessary to test each protection or control specification. Where Hardware-in-the-Loop capability is available, it should be applied to validate the as-configured behavior on the final hardware and firmware.

6.3 Commissioning & system testing

Commissioning & system testing present a key opportunity to validate and prove new capabilities and configuration as equipment is integrated on site.

Examples of this may include

- 1) Testing under ramping & stepping LV load conditions, using suitable load banks as described in 6.3.1 to prove
 - a. Transfer to generator from utility power under a non-static load
 - b. On generator voltage & frequency stability
 - c. Generator emissions under variable load conditions
 - d. Sub harmonic and ramp rate performance at the grid connection point
 - e. IT power quality and supply stability under short duration peak loads (>100% nominal rated)
- 2) Harmonic and power factor compliance at the generator and grid connection points
- 3) Communication between generator controls and energy storage such as UPS, where load smoothing modes vary between utility & generator operation
- 4) Metering, communication, discrimination, monitoring & alarming for utility ride-through PF-APR, generator operation and non-ride-through utility events
- 5) Testing of monitoring, reporting & alarming for power quality, harmonics, sub-harmonics, ramp rates & step size

Testing & Commissioning of MV & HV systems

There may be complex protection & switching configurations necessary to meet requirements including FRT, step size, reactive power, harmonic & sub-harmonic control. Further, much of this configuration will not be possible to test on-load at the site as suitable test conditions are not feasible, utility voltage and frequency are not variable on demand.

This generates a substantial risk of misconfiguration resulting in incorrect operation, damage to equipment, loss of IT load or failure to comply with grid code.

The testing & commissioning plan should directly address and mitigate this risk. This may include;

- 1) Dynamic (EMT) simulations of the integrated power system identifying transient conditions
- 2) Software simulation & validation of protection relay and SCADA configurations as an integrated system, considering transient conditions
- 3) Software-in-the-Loop testing of the protection relay and SCADA programming configurations to be deployed.
- 4) Hardware-in-the-Loop testing of the system or as subsystems with the remainder simulated, either at the factory or onsite

6.3.1 Specification and approval of commissioning test equipment

The addition of dynamically variable IT loads and variable voltage & frequency conditions present new requirements for commissioning test equipment. These new requirements shall be identified sufficiently for the OEM during factory testing or the commissioning contractor on site to meet the test criteria.

This may include

- 1) Load banks capable of generating realistic variable IT load patterns for on-site testing, including peak load demands > 100% rated, and ramps & steps as defined in the IT load specifications. For useful testing across multiple LV blocks these load banks may require central or synchronised controls to usefully represent a synchronised AI load connected across multiple (e.g. 4) LV blocks.
- 2) Variable voltage & frequency sources for factory testing of LV blocks and mechanical equipment
- 3) Hardware in the Loop equipment for MV/HV systems.

6.4 Sequence of Operations

Additional design conditions & Sequence of Operations instruction will be required, including

- 1) Allowable operational ranges for voltage, frequency, RoCoF, harmonic content etc. at instrumented points
- 2) Allowable operational ranges for ramp rate, step size and sub-harmonic content at instrumented points
- 3) MV switching sequences for planned events including load startup, maintenance and evaluated fault conditions such as utility feed failure which comply with utility constraints such as load step size
- 4) Allowable UPS or BESS battery State of Charge and State of Health conditions under planned operational modes
- 5) Sequences for demand flex operations, automatic or manual, where incorporated in the design

7 Definitions

For information, some of the terms used in this document are defined here

7.1.1 BESS

Battery Energy Storage System. A dedicated energy storage system, typically with storage depths measured in hours, connected to the facility LV or MV systems. A BESS typically provides features supporting grid services such as automatic Voltage, Frequency and RoCoF control, but may also be used to protect onsite generation assets or manage power quality where onsite renewable assets contribute to the power system.

7.1.2 Fault Ride-Through

A requirement from the Transmission System Operator (TSO) for the demand facility (data centre) to stay connected and drawing power from the Utility connection point during a short voltage fault condition such as those generated by transient events on the transmission network. This is typically defined by a voltage against time curve which defines the voltage / time profile considered to be within the 'ride-through' conditions. This requirement exists to prevent data centres destabilising utility grids through synchronised rapid disconnection of large volumes of load.

7.1.3 Frequency ranges

One or more minimum to maximum AC frequency ranges over which the equipment is expected to stay connected and operate normally for a defined period. This is a common specification for the Utility connection point but also applies to equipment within the data centre, such as chillers, UPS etc.

7.1.4 Generator Connection Point

The point(s) within the power infrastructure where each generator group connects to supply power. This may be a single generator connected to a single LV block at an LV (400V) generator panel or a group of generators connecting at an MV Generator Connection Point.

7.1.5 Hardware-in-the-Loop

A testing approach which provides a combination of a software simulation environment and hardware which is connected to the controllers under test. The controllers under test are deployed with their production software & configuration and connected to the HIL hardware. The simulation and HIL hardware environment supplies simulated input conditions, e.g. voltage and current waveforms to the controllers under test to allow evaluation of as-configured performance.

For example, a simulation of an MV & HV power network might be used, along with HIL hardware for one set of protection relays to evaluate the performance of that subsystem, whilst still in the context of the full HV & MV network. This allows for testing the as-configured rather than as-designed behaviours, including system transient responses.

7.1.6 Harmonics

Variations in voltage or current from a simple linear sine wave at the base AC frequency. These present above the base AC frequency of the power supply or phase shifted from the

base supply. Commonly produced by the actions of non-linear loads, motors or power generators and generally occurring on some integer multiple of the AC base frequency.

7.1.7 Sub-harmonics

Variations in voltage or current occurring below the base AC frequency. These may be related to the base AC frequency, or in the case of variable IT power draw profiles, entirely unrelated to the AC frequency. Commonly produced by variable IT loads, PWM drives and power factor correction equipment.

7.1.8 IT Electrical design power & peak

With AI workloads exhibiting synchronised peak power draw behavior across multiple servers, racks & rows, peak power draw events now appear at the row and LV string level. The electrical design specification will include both a continuous Electrical Design Power (likely equivalent to TDP) and a short-term peak rating to allow for these synchronised peaks.

7.1.9 IT Power draw

The power drawn by the tenant IT equipment in the white space. This includes all rack loads fed by the white space power distribution equipment either directly feeding a tenant rack or via a power conversion, sidecar, or row level power distribution system. This may consist of a mix of network, storage, general purpose compute, and specialist compute such as GPU / XPU racks.

7.1.10 IT Power draw variability

The periodic variation in power draw from tenant IT equipment, once installed and operating normally. This does not refer to any 'ramp rate' due to IT load installation or decommissioning.

Where energy storage such as battery or super-capacitor is embedded within the IT racks or supporting LV power conversion racks in the white space, the IT power draw is taken to mean the LV power draw profile applied to the white space power distribution as connected to the landlord systems, e.g. row busway end feeds or service corridor distribution panels. Specifically, any shaping of the IT equipment power draw due to the local storage downstream of the landlord's power distribution is considered to be the applied IT power draw to the LV infrastructure.

7.1.11 IT Power draw profile

For traditional data centre IT loads the observed power draw at the LV distribution is effectively constant, with small sub-hourly variations, major changes in power draw are generally correlated with IT equipment installation schedules.

Some AI loads exhibit rapid and large variations in power draw in the range of microseconds to minutes. These variations are represented as a 'power draw profile' indicating the magnitude, ramp rate and intervals of these variations to allow evaluation of the power systems of the data centre.

The power draw profile is typically described in terms of the variations which are expected to occur on a load, e.g. 50% of capacity steps occurring at 2 second intervals. Each load will be represented by a number of these variability specifications to capture the key behaviours.

7.1.12 Infrastructure critical power draw

Power drawn by equipment such as CDUs in the white or grey space fed power from the same critical power distribution as the tenant IT equipment. This may be tenant owned equipment within rack rows or landlord owned equipment.

7.1.13 Infrastructure essential power draw

The power draw of any load-supporting systems, such as CRAH, Chiller etc. This may be supplied by LV Blocks or directly from MV systems for devices such as large chillers.

7.1.14 Load smoothing

Actions taken by power infrastructure to reduce the magnitude or rate of power draw changes from downstream equipment as experienced by upstream equipment. For example, a UPS system may charge & discharge batteries in response to IT load steps to reduce the rate-of-change in power draw experienced by upstream generators or at the utility connection point.

7.1.15 LV Block

A set of equipment providing Low Voltage power within the landlord's infrastructure. Low voltage is defined as below 1,500V AC or DC.

The LV block typically receives MV power and converts this to LV power to feed loads, commonly incorporating UPS to provide protected power to Tenant IT load & infrastructure critical power loads. An LV block may be dedicated to IT & critical loads, dedicated to house & essential loads or provide a mix of critical and essential power depending upon the design.

Equipment within a traditional AC LV block commonly includes an MV Ring Main Unit, an MV to LV transformer, switchgear, UPS and battery systems and output distribution switchgear to connect loads.

LV blocks may deliver AC or DC power to the loads and may present either as a traditional 400V AC system, with or without UPS, or as a combined Transformer Rectifier Unit (TRU) or Solid-State Transformer (SST) module for DC power delivery.

7.1.16 LV Block critical load

The combined load on a single LV block from attached Critical loads such as IT Power Draw and any Infrastructure Critical Power Draw from loads such as CDU, Pumps, Fan Walls etc.

7.1.17 LV Block essential load

The combined load on a single LV block from attached Essential loads such as chiller, pumps, generator preheats etc.

7.1.18 LV Block power draw

The input power draw of an LV block, including IT power draw, infrastructure critical power draw and any infrastructure essential power draw.

7.1.19 LV Block UPS input load

The input power draw of an LV block UPS system, resulting from the LV Block Critical Load plus any UPS losses and UPS Load Smoothing activity.

7.1.20 LV group

A set of LV Blocks which feed a set of racks in a redundant configuration and are therefore presented with a common Power Draw Profile. e.g. a set of 4 LV blocks in 4 to make 3 distributed redundant or a set of 5+Catcher in block redundant configuration.

7.1.21 Post Fault Active Power Recovery

A requirement from the Transmission System Operator for the demand facility to return to a certain percentage of the pre-fault power draw within a specified time. This requirement ensures that a sufficient portion of the pre-fault network load is restored quickly enough after the fault to avoid exacerbating the fault on the network. It is recognised that the data centre cannot continue to draw full load during a near-zero volt fault condition as the required currents would be undesirable.

This is typically defined as a percentage, typically 80% to 95% of the pre-fault power draw within a number of milliseconds, typically 500 to 2,000 ms, of the utility connection point voltage returning to a specified fraction of nominal, typically 0.9 per unit (90%).

7.1.22 Ramp rate

The rate of change in power draw during a change in load, where the transition is slow enough to be considered a (linear) ramp, expressed in terms of

- MW change in power flow per unit time, seconds or minutes, e.g. 1MW per minute
- A percentage of the rated load at the point in question, such as 1% per second of the UPS rated capacity at the UPS input or 1% per second of the MIC at the utility connection point

As for step size, ramp rate may refer to singular events or a continuous behavior caused by the IT power draw profile.

7.1.23 Rate of Change of Frequency

The Rate of Change of Frequency (RoCoF) is a further frequency specification which describes the maximum rate at which AC frequency may change. This is generally defined as a number of Hertz (Hz) per second or millisecond, over a rolling period, defined in seconds or milliseconds and within a given Frequency Range.

7.1.24 Software-in-the-Loop

A testing approach which provides a simulation environment in which to run the software & configurations to be tested. For example, simulation of an MV & HV power network along with a simulation environment running the actual software and configuration to be deployed on protection relays and other SCADA systems. This allows for testing the as-configured rather than as-designed behaviours, including system transient responses.

7.1.25 Solid State Transformer (SST)

A primarily semiconductor-based voltage converter unit which may perform the role of MV to LV transformers, UPS systems, BESS systems, AC to DC converters and generator integration.

7.1.26 State of Charge

State of Charge (SoC), the fraction of 'full' charge for an energy storage unit, typically a battery. This specification is relevant to operating modes, charge & discharge rates for the battery as these vary with SoC as well as preserving the charge or discharge headroom on the battery to allow for UPS load protection or ramp up / ramp down rate control actions.

7.1.27 Step size

The magnitude of a power draw change, sufficiently short to be considered a 'step', expressed in terms of

- MW change in power flow, for example a maximum step size defined by the TSO or DSO at the utility connection point
- A percentage of the rated load of the device in question, for example a 1,000kW step applied to a 2,000kW UPS would be a 50% load step

These may be singular events, such as during a load transfer or repeated events caused by the IT power draw profile.

7.1.28 Transformer Rectifier Unit (TRU)

A combined MV to LV transformer and AC to DC rectifier system, commonly with attached battery storage, performing a function similar to a traditional LV Block and Transformer pair. Converts MV AC power to LV DC power for DC distribution to IT equipment.

7.1.29 UPS Battery total capacity

The total energy storage capacity of the battery on each UPS system, measured in kWh at the defined End of Life battery state of health.

7.1.30 UPS Battery capacity at EOL

The available discharge capacity of the battery on each UPS system, measured in minutes at the design kW load at defined End of Life state of health.

This measure is defined as the remainder after allowing for State of Charge, Ramp Rate Control, minimum charge level and any other constraints or considerations required by the design, to specify the minutes of discharge rating at the design load from the minimum SoC after load smoothing and other activities.

7.1.31 Utility Connection Point

The common point(s) within the power infrastructure where the utility power feed connects to supply power. This is typically at medium or high voltage at the site substation.

This is also referred to as the Point of Common Coupling (PCC).

7.1.32 Voltage ranges

One or more minimum to maximum voltage ranges over which the equipment is expected to stay connected and operate normally for a defined period. This is a common specification for the Utility connection point but also applies to equipment within the data centre, such as chillers, UPS etc.

