GLOBAL PST CONSORTIUM

System Needs and Services for Systems with High IBR Penetration

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October 8th, 2021

This document has been produced by the Services Group within the IBR Research Team of the Global Power Systems Transformation Consortium (G-PST). It is designed to underpin, inform and shape the Research Agenda of the G-PST and is also deemed to be a contribution in its own right to our collective knowledge and insight into the transformation of power systems.

Table of Contents

List of Figures

1 Introduction

Power systems that are fulfilling their primary objective of reliably meeting demand at least-cost can be thought of as adequately providing a range of "services" to meet a set of "needs". The way in which needs and services are defined will have many common features across different power systems but there will be differences in the details, volumes and types of providers of services arising from the physical, regulatory and policy differences of each system (Figure 1). While power systems around the world have natural physical differences and a wide variation in regulatory, governance and ownership structures, most are now evolving toward much less use of fossil-fueled generation, which will require an evolution in needs and services.[1]

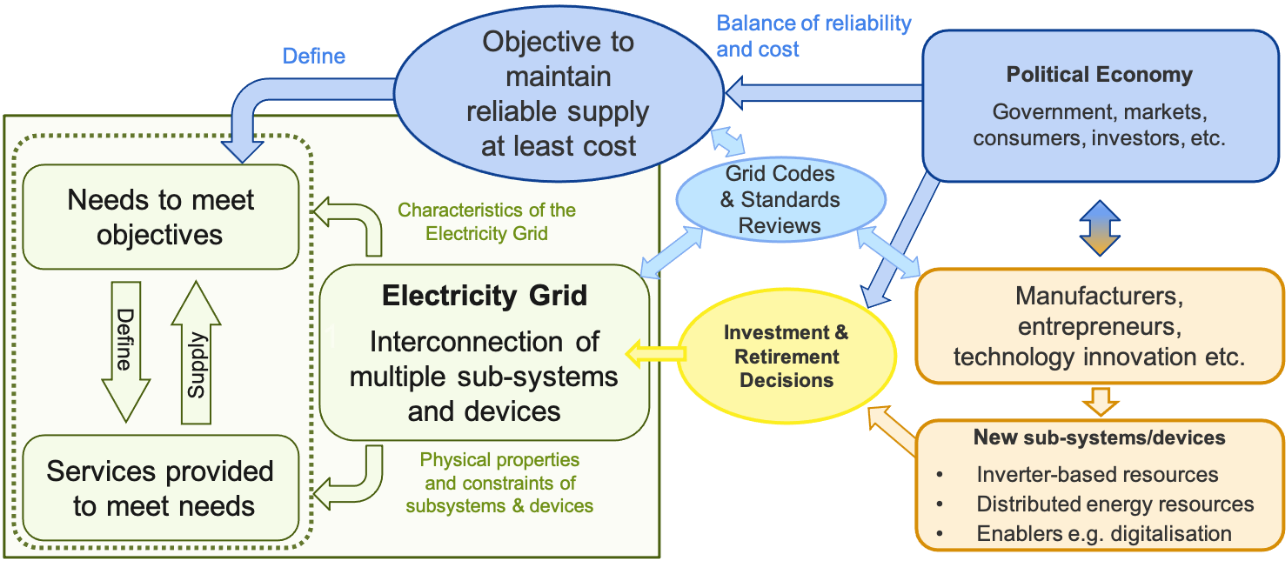


Figure 1: Schematic diagram of system needs and services with recognition of physical properties of grid, technology innovation and the regulatory and policy context.

In a power system with a highly developed competitive market, the delineation of needs and services is clear because the market structures and associated grid codes and standards have been designed specifically to provide the services to meet the needs in open competition. As a power system undergoes large changes, the challenge is to ensure that this remains true while the underlying system transitions with consequent changes in definitions of needs and services and the suppliers of services. It is imperative to manage these changes in a way that continues to meet the primary objective.

Managing this change is the focus of this document in the context of a power system that is changing with an increased penetration of IBR, such as wind [1], solar [2], battery energy storage and some types of demand-side response. The emphasis is on the IBRs and not the resources behind them, that is, the focus does not include the variability of wind and solar or dispatch of storage.

Within the G-PST there is a Resource Adequacy Research Team, recently formed, that is addressing all these issues and we will refer to that discussion when variability of resource and IBR characteristics interact. A holistic approach that combines the adequacy and IBR characteristics to meet the primary objective by balancing needs and services is at the core of the G-PST research approach, i.e., making it all work together. Given the emphasis in this document on IBRs, two key needs associated with resource adequacy, energy and capacity, are not dealt with directly here but will be discussed in-depth in a forthcoming Resource Adequacy Research Team paper. However, at several points within this document, energy and capacity needs will be referenced for completeness.

[1] The IBR research team observed that currently there is already substantial focus on evolution of services but that much less attention is paid to evolution of the needs.

Synchronous machines (SMs) appear to us today as standard equipment with consistent properties and only a small number of variations in how governors, automatic voltage regulators and power system stabilisers can be configured. However, in the decades following their first introduction in 1891 they underwent many changes of configuration, innovation and refinement until converging on common formats. IBR are being refined also and show some signs of convergence of properties but not to the extent achieved by SM.

We also note that zero-carbon power systems in some territories may include a considerable fraction of SM in hydro, geothermal, CCS and nuclear plants and the types and quantities of system needs and system services will vary from system to system. There will be marked differences between systems dominated by SMs, systems with a mixture of SMs and IBRs and systems dominated by IBRs. Beyond this, systems differ in terms of degree of interconnectedness, separation of load centres from generation centres, length of lines/cables and size of the largest continency relative to system load.

With increasing penetration of IBRs, there are endless possibilities of how we could change the power system, e.g., we could change the frequency of operation and/or allow it to become more variable (while of course respecting the operational limits of transformer and load equipment). The intention of this document is to help guide the next series of changes in evolution of needs and services rather than invent a radically different future, although some foresight of very different futures may emerge. We take this stance because, for example, changing the frequency of the system and the range of frequency will have so many legacy issues with existing equipment that it is almost certainly not viable in the medium term and the path beyond the medium term could take many different directions [3]. However, the issue of protection and a move away from high fault currents for detection may need to begin soon because of the length of time it would take to effect a system-wide change. In the long-run, deep changes are possible and we could consider widespread adoption of DC over AC. We have chosen to have a medium-term focus where the gird system is still centred on AC operating with relative narrow allowed ranges of frequency and voltage magnitude. Thus, various ways in which the system might change are deemed plausible, some too radical to be plausible in the foreseeable future and some will need further research to determine if the changes bring sufficient benefit to overcome the cost. In other words, we are adopting a pragmatic approach to what is seen as a realistic change.

In considering how a grid should evolve as it becomes dominated by IBR, it is useful to think about this as a two-sided (needs & services) compatibility issue. It is about making IBR fit to work in our grid and making our grid fit to accommodate IBR. How much of each we do should be determined by what achieves minimum system cost, as illustrated in Figure 2. As an example, making IBR supply short-term overload or fault current (a service) exactly like SMs is expensive. We should be looking at whether there is a lower cost solution by adjusting our grids somewhat to operate at lower fault currents (a need) of IBR (plus fault current from other sources), but not to the point where grid costs become excessive. In particular, requiring IBR to fit today's grid with minimal adaptation of the grid means that IBR have to be drop-in replacements for SM, the most extreme view of a virtual synchronous machine (VSM), will most likely add a large cost burden to IBR and not yield the lowest system cost. While it may not be possible to construct an exact version of the cost-curve like the one in Figure 2, we should have in mind the principle of balancing the cost burden.

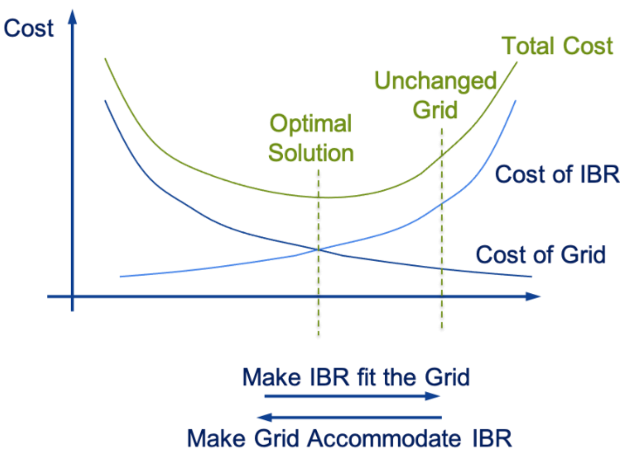


Figure 2: Total System Cost of a Grid with IBR.

This document describes the evolving needs and services to maintain a reliable and stable of a power system with a high penetration of IBRs that have displaced SMs as a consequence of the shift from fossil-fuel to variable renewables. Most of the services to meet these needs will be familiar from traditional systems built around SMs since the objective of secure provision of an AC voltage within defined limits of frequency and voltage is core to any power system. The emphasis on systems with high penetration of IBRs leads us to unbundle the services into smaller pieces of the jigsaw in recognition of the fact that in a SM these might be delivered as a package because of the physical characteristics of the machine, whereas for an inverter they might be delivered separately through choices made in the control configuration or subtle differences in the way physical limits apply. It is noted that an IBR, to a much greater extent than an SM, is defined by its control configuration much more than its physical characteristics and limits. Also, IBR may themselves create the need for a service and/or increase or decrease the needs of other services. All this makes for a highly complex environment where the definition and organisation of the needs and services is critical to finding good solutions.

In trying to separate needs into several finely graded sub-types, to facilitate the provision of services to meet these needs, we recognise that some of these needs may be coupled with each other. Multiple needs might arise from a coupled or common cause. For example, a large loss of infeed may cause a frequency disturbance, an angle disturbance and a voltage disturbance giving rise to three potential instability types and three needs. If we define services in terms of mitigation of the potential instability, we may have several services for the same root-cause problem. As a second example, the need for more energy supply in one part of the grid can lead to an increase in the need for reactive power to maintain voltage.

Services to meet needs may also be coupled. For example, if there is a need for an inertia-type service, a synchronous condenser might be provided which may then be able to deliver services to meet other needs in voltage regulation and protection. There can also be competition or conflict between providing services. For example, a wind turbine can produce frequency regulation, but for up-regulation (a service) it needs to operate below maximum power point and therefore provides less energy (another service). The provisions of one service at the expense of another needs to be considered at the system level and at the device level in terms of the economics.

These couplings between various needs and various services are important to understand as they impact the quantity of service required, the combination of resources needed in a region and the economic value of combinations of services. That said, if the coupling is weak or the quantities of needs are small or the costs of the services are low then it may be acceptable to ignore the coupling for practical purposes (in planning and possibly in operations also) and treat each need as being met by a set of services independently of other needs and services.[2]

The traditional system has had strong coupling between services. For instance, the various types of reserve and response services from fossil-fuelled plants interact with each other through the availability of short-term energy and power capacity in the machine and through their combined action to regulate frequency. Some services arise from inherent features of SM and those services came at a low cost with provision of inertia and fault current being good examples. For an IBR, some coupling or competition can arise through the physical limits of the equipment but almost all of its behaviours are formed by its control system and need to be explicitly designed. Coupling needs to be considered in the design of the control system: where is coupling helpful or unhelpful and how can the design accommodate that.

The balance between needs and services is behind any market design and as a market equilibrium requires a financial long-term equilibrium there are some complex challenges ahead to ensure the core objective is maintained throughout in the transition. For example, if energy prices drop as more and more zero marginal cost renewables are integrated then it is widely accepted that the other services will increase in relative value in order to maintain financial equilibrium for the investors. Therefore, a fundamental understanding of how the balance of needs and services is managed in the transition is critical and this framework is being

[2] In circumstances where the coupling between services can be dealt with only by considering the dominant service and ignoring the others there will be some inaccuracy with either over investment or call-off of the dominant service where helpful coupling is ignored or under investment or call-off where unhelpful coupling is ignored. Further investigation of each case will be needed.

developed to inform this process of change. Combined with other activities within the G-PST, e.g., the RA Research Team, a holistic framework is being developed to guide the Research Agenda of the G-PST and to assist the industry more broadly in managing the pressing and important transition in electricity systems.

2 Types of System Need & Service

Eight types of system need, illustrated in Figure 3, have been identified which combine to deliver the primary objective under all credible circumstances. The first column cover aspects of stability and power quality. The second column cover aspects of security of supply and resilience blending into quality of service to customers. Of these eight needs, the need for energy has dominated investment decisions for generation and other resources, with capacity also important (promoted in many jurisdictions through capacity markets or other mechanisms). Energy and capacity typically dominate investment decisions because of their relative high costs and these are the focus of the Resource Adequacy Research Team as described above. There are new initiatives by some SOs to tender for new services and so services to meet all 8 needs may play a role in driving investment decisions. It is generally recognised that in high-IBR, high-VRE futures the relative importance of these needs will shift away from energy and towards capacity and the other needs [4].

Six of these types of needs are discussed in detail and broken down into specific sub-types of needs in the following sections. (Energy and Capacity needs will be dealt with by the Resource Adequacy Research Team and are not discussed in further detail here.) Because of the overlap, coupling and lack of one-to-one correspondence between needs and services, there is not a unique definition (cardinality and one-to-one correspondence) of the sub-types of need nor services that might meet those needs. There may be other definitions of types and sub-types of need that are more practical for a particular system. Most importantly however, the broad types and specific sub-types of need must cover the whole space (i.e., all credible circumstances, as discussed above) and be as independent of each other as possible.

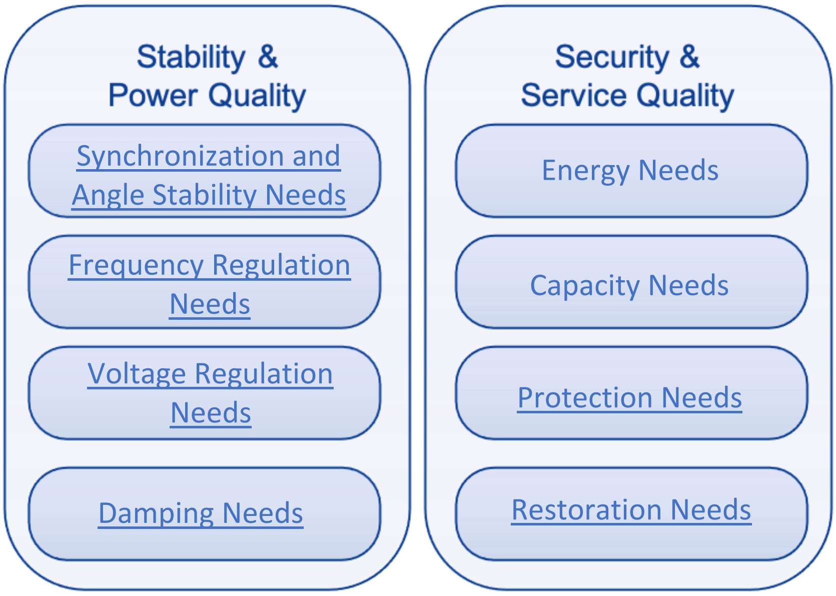


Figure 3: Broad types of power system needs. Excluding energy and capacity needs, each need here is discussed in detail below and the respective sections are linked in the Figure.

The discussion above covered the needs of the power system; this is somewhat different than a discussion of services that can be provided by various types of equipment to meet these needs. For example, there is a lot of debate around an inertial energy service but that does not appear as a distinct item in our discussion because inertial energy is not a fundamental power system need but rather a reflection of a feature of SMs that has had a fundamental role in regulating frequency as we know it today. Inertial response capability is a potential service that can contribute to meeting the frequency regulation need, but there are other non-inertial response services, such as fast frequency response (either enforced through explicit control or due to static non-mechanical IBR characteristics), that can also meet the frequency regulation need and therefore directly compete with the inertial response service.

It has been remarked that the control system of IBRs can be augmented in a flexible way to add various services. However, there are physical limits of the plant that will restrict what can be achieved. Some of these are direct features of the inverter (such as current limits and synchronisation mechanism) but others relate to the energy source on the DC side of the inverter and so depend on whether that source is a variable renewable energy plant, a battery, an HVDC link, or indeed no source at all as in a STACOM. The various limits are illustrated in Figure 4.

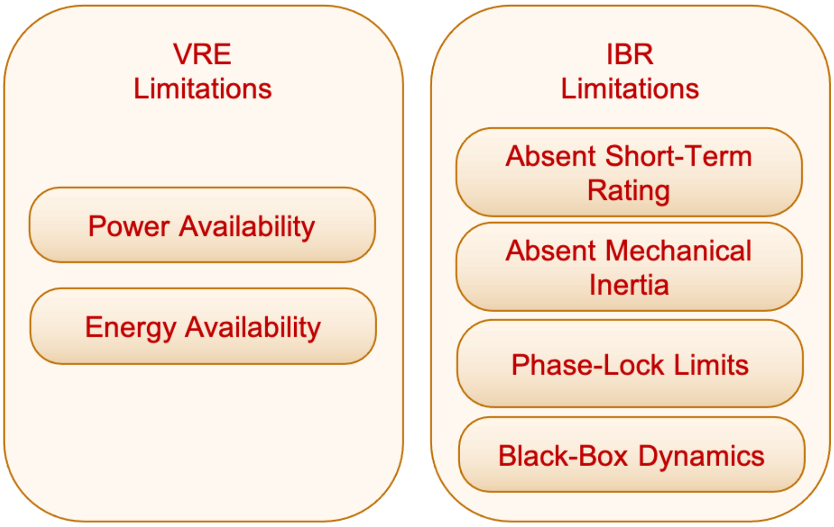


Figure 4: Limits impacting IBR ability to provide services, arising from the inverter itself or its connection to a VRE energy source.

With IBRs replacing SMs, some needs will remain largely unchanged; some will experience quantity changes and some new needs may emerge. It is non-trivial and is the subject of research to discern the details of changes in needs and/or emergence of new needs that allow system operators to continue to minimise cost of their operations as the physical system changes. The source of the services to meet these needs will change from SMs to IBRs (assuming a benefit of doing this, see Figure 2) and other technologies. Because of the differences in SMs and IBRs it is worth revisiting the needs/services definitions to ensure that the needs can be met i.e., there is no point in having a service that IBRs cannot produce if there is another service and/or combination of services that IBR can produce that will meet the same need.

In the descriptions that follow, the main focus is on a discussion of needs in a high-IBR system but blended in with that is a discussion of the ability of IBRs to provide services to meet those needs. In a future iteration of this document, we hope to achieve a cleaner separation of needs and services and a mapping between needs and services and between needs and resources, such as illustrated in Figure 5 and Figure 6.

Figure 6 illustrates a particular inverter-based resource, a windfarm and a battery in this case, that has the potential to meet some but not necessarily all needs. The solid lines indicate the IBR resource is expected to be able to provide a service that can help meet the need within its own physical limitations. The dashed lines indicate that this resource may not be well placed to meet the need. The green boxes indicate that there is a specific limitation that must be observed in meeting the need. The holistic challenge is to ensure, when combined, all the IBRs plus any remaining SMs resources and any other control resources are collectively able to meet the needs to maintain reliability and to do so in a least cost manner.

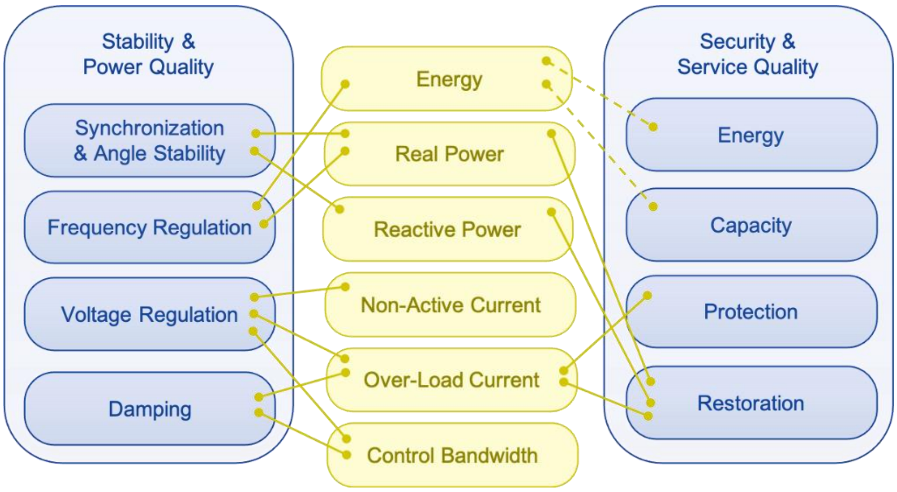


Figure 5: Illustration of a mapping between types of need and the characteristics of IBR (centre) that would be required to provide a service for that need.

Real power here is assumed to be over a short period of time while energy here is taken to mean real power sustained over a relatively long period such that it is energy not power that becomes the potentially limiting factor. Energy and capacity are not dealt in this document and will be handled separately by the Resource Adequacy Research Team. They are included for completeness.

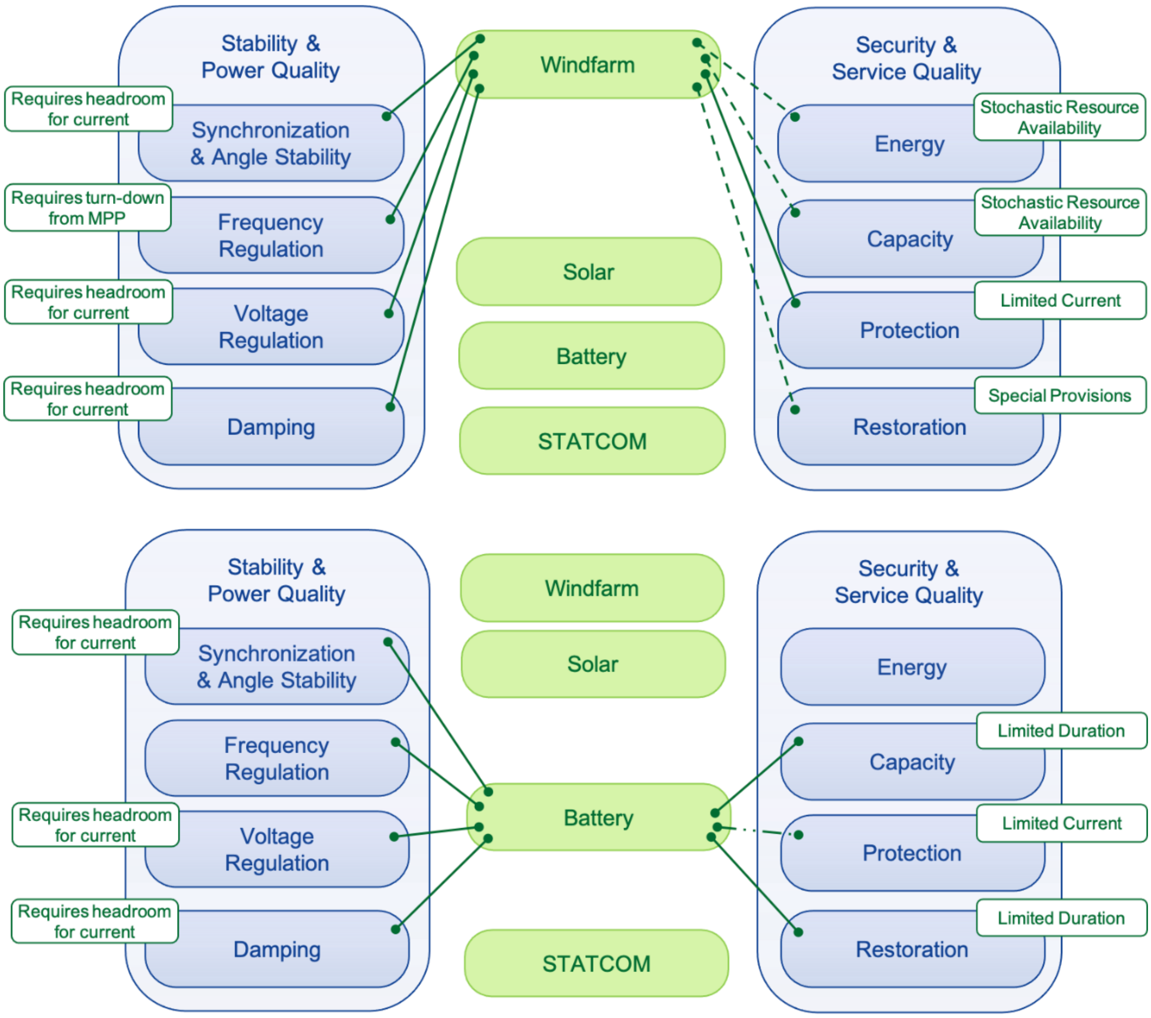


Figure 6: Illustration of a mapping between of the needs and the IBR resources (windfarm and battery in this illustration) able to provide a service for that need.

Energy and capacity are not dealt with in detail in this document and will be handled in a separate work from the Resource Adequacy Research Team. They are included for completeness.

In the sections that follow, each broad type of needs (Figure 3) are broken down into specific needs. There is often significant overlap between the characteristics of the various specific needs and a blending of various services or indeed one service that can be provided to meet the need. This is not surprizing since, by definition, we want services to meet the needs. In some places the terms needs and services are used interchangeably without contradiction, e.g. if the specific need is large, increasing, decreasing so also are the services to meet the need and vice versa. Cleaner and more precisely delineated descriptions will be sought in future iterations of this document. However, it is unlikely that this blending will be entirely eliminated from all the needs and a complex interrelation of needs and services will remain.

Some of the needs described below would more often appear as a composite need. For instance, a need could be defined for "grid strength". This is a composite of need for a low impedance voltage source and includes the needs for good voltage regulation, mitigation of harmonic distortion, synchronization stability of PLL and sourcing of fault current [5]. Because an inverter would need specific controls or physical features to address these different aspects of grid strength, they are kept separate here.

Some needs can be seen from a system point of view and a resource point of view and are a joint need or an issue of compatibility. For instance, the need for mitigation of PLL instability is somewhat an issue of ensuring PLLs (and other associated control loops) maintain stability in the face of a certain amount of grid impedance and partly an issue of ensuing a sufficiently low grid impedance to allow PLLs to synchronize. This is an issue of setting compatibility level and would have a cost-curve rather like that of Figure 2 in which a grid impedance needs to be determined that minimizes the sum of burdens on the grid and PLL characteristics. In the sections that follow there are several other examples of where a cost balance will need to be found.

3 Synchronization and Angle Stability Needs

Return to *Types of System Need & Service*

Today's power systems are fundamentally synchronous power systems and based on the SM. This synchronism is the "glue" that enables SMs to act together to maintain the integrity of the power system.

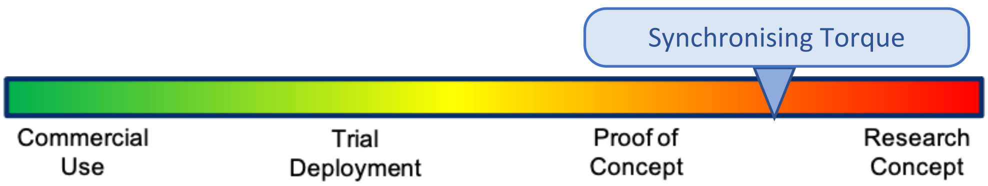
Need Type	Reason for Need
Synchronizing Torque	Need to keep SM and IBR synchronised. Loss of synchronisation from angle instability can arise in low synchronising torque cases. Sometimes also called synchronising power.
Phase-locked loop (PLL) Stability Support	Need to keep IBR with PLL synchronised. Recognises instability arising from high impedance (low strength) at connection point.
First-Swing Mitigation	Need to maintain synchronisation during large voltage disturbance.
Phase-Jump Mitigation	Need to maintain synchronisation following abrupt change of voltage angle from loss-of-infeed or loss of line.

Our ambition has been to define all needs in a technology neutral fashion but in discussing synchronisation it has been hard to do that because there are two types of synchronisation: (i) an angle-frequency-power feedback loop as found in SM and grid-forming IBR that use frequency droop, and (ii) angle-voltage feedback within a phase-locked loop (PLL) as used in grid-following IBR. The first of these is a familiar need for synchronising torque but one which needs re-examination for GFM-IBR.[3] The second need, for PLL compatibility, has grown over the last two decades. There is research underway to establish a framework in which the two synchronisation methods can be consider together under a single, technology-neutral heading of Synchronisation Strength or Synchronisation Power but that is not yet available [6] [7] [8].

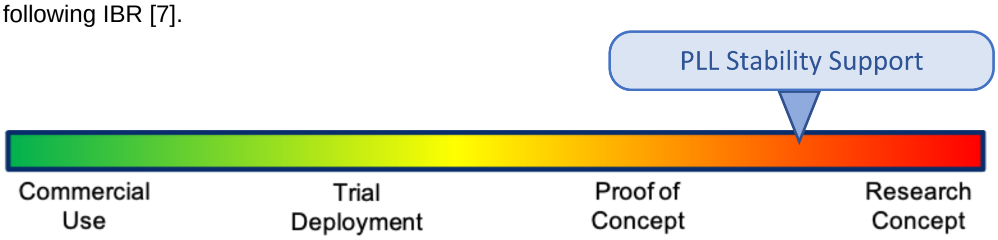
The need for synchronisation is an issue of compatibility between SM/IBR and the grid. The grid should be able to synchronise a well-designed IBR and an IBR should be able to synchronise to a well-designed grid. The issue is defining a compatibility level and then a synchronisation "standard" for grids and a synchronisation "standard" for IBR design such that the worst IBR that is still compliant with the standard is able to synchronise to the worst grid location that is still complaint with the standard. This is the pattern set in the emissions and susceptibility sides of standards in electromagnetic compatibility, EMC. With a standard for the grid established, there may be a need to procure services to make the grid compliant with the standard. It is not obvious that this was the path taken in traditional SM-based grids but there is a common "understanding" of the needs that SM have for synchronising torque and that the grid should maintain a low impedance connection to other SM to provide this.

[3] A GFM-IBR may also use a PLL in some subsystems but not normally for primary synchronisation.

3.1 Synchronizing Torque

Need	Synchronisation and Angle – Synchronising Torque
Importance / Consequence if unmet	In technology neutral terms, the need is to support synchronisation of SM and GFM-IBR. That would be commonly interpreted as synchronising torque. Existing fleet of rotating machines are coupled to each other through the swing equations that relate acceleration of machine rotors to exchange of power through the network driven by angle differences between machine rotors (and hence electro-motive force (EMF). The flow of power that tends to close angle difference and maintain synchronism is known as the synchronising power. The power creates a torque to do this is often expressed as a synchronising torque. When the magnitude of this torque reduces, such as when two synchronous machines are connected to each other via a long transmission line, their ability to exert a positive stabilizing influence on each other reduces. A low availability of synchronizing torque can result in larger swings between machines resulting in larger fluctuations in voltage and power transfer and ultimately instability and system collapse. Grid-forming inverters synchronising through a governor-like frequency droop have a broadly similar need for synchronising power or torque.
Influence on Relevance or Scale of Need	Number of machines in service, impedance of transmission paths between machines and the angle spread across the network (influenced by impedance and magnitude of power transfer) all affect the relevance of the issue.
Expected Volume of Service to meet Need	Qualification of the volume is from consideration of swing equation and is a combination of both network and machine/IBR settings. The quantification is locational and system dependent.
Physical Limits on Availability	Ability to provide synchronising torque is partly a function of control and physical parameters of the IBR or SM. In a SM there is a stability limit set by swing past 90°. An IBR has similar limits, perhaps more amenable to modification through control design but also subject to strict current limits that affect high instantaneous power transfers.
Overlap with other needs	Synchronising torque arising from a swing equation is related to damping torque and inertia from the same equation. In synchronous machines these are closely related through physical properties, but in an IBR they can be made less dependent through control parameter choices.
Supporting Tools & Analysis Techniques	Small signal stability evaluation (either Eigen values [9] or impedance diagrams [10] [11]), improved and robust positive sequence models [12] [13], EMT analysis.
Market, Mandatory or Inherent Need	This is an inherent need as it operates in a time frame that is too small for market operations. Further, since it is a need that will maintain system stability, it has to be inherent.
Redundant, legacy, enduring or new need	This is a legacy need that may in time become redundant. It is a need for rotating machines rather than power converters. But the synchronization loops of converters may show similar dynamics and have similar needs even though the converters have more control flexibilities [6] [7] [14] [15]. This needs more insight and research.
Readiness for IBR Supply	In principle, IBRs with an appropriate energy source can provide a service that meets this need [16]. In practice that has not been established as a service nor received significant attention in the research community. Some stability studies have shown how inverters (HVDC stations etc) can aid first-swing stability [17]. 
Return to Synchronization and Angle Stability Needs or Types of System Need & Service	

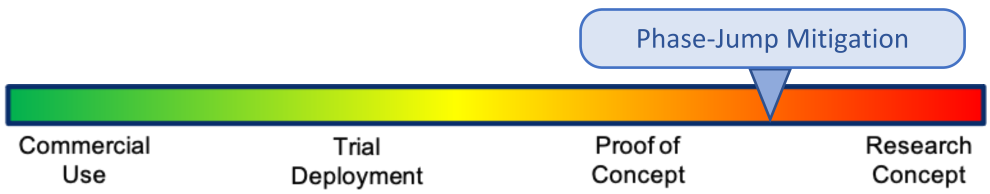
3.2 Phase-locked loop (PLL) Stability Support

Need	Synchronisation and Angle – PLL Stability Support
Importance / Consequence if unmet	Interactions occur between the PLL of grid-following IBR and voltage variations arising from high grid impedance and this leads to instability. There is a need to ensure grid conditions (notably high system strength or low grid impedance) are sufficient that a well-designed PLL remains synchronised (remains phase-locked).
Influence on Relevance or Scale of Need	This is a system level issue and the need to maintain a low grid impedance is influenced by how PLL have been designed and tuned. Manufacturers have various different methods of ensuring robustness and some may use adaptive methods to respond to grid conditions. While system characteristics such as high impedance have been shown to play a role in the stability profile of PLL, other aspects such as adequate voltage regulation, load characteristics, and unbalance also have an impact. Further, as the percentage of IBR increases, the operating point of the network prior to disturbance can also play a role so the need is system and location specific.
Expected Volume of Service to meet Need	Quantification of volume of service is not straightforward here as factors such as design/configuration of PLL, design/configuration of additional control loops within IBR can also play a crucial role in determining stability. One approach may be to define standard PLL and ensure sufficient mitigation (such as sufficiently low grid impedance) to ensure stability. OEM can design to the PLL standard or ensure their PLL is stable under the same conditions. Services to lower effective gird impedance might be similar to voltage regulation services that reduce the variation of voltage for a variation in current flow. As such, grid-forming IBR (which may itself contain a PLL) could provide PLL instability mitigation to grid-following IBR.
Physical Limits on Availability	Grid-forming IBR delivering a support service, such a lowering the grid impedance in the local area, would be subject to IBRs current limit on any additional reactive power.
Overlap with other needs	The PLL stability is related to the grid impedance (I.e., grid strength) and voltage phase tracking (voltage stability).
Supporting Tools & Analysis Techniques	Small-signal stability evaluation (either Eigen values [9] or impedance diagrams [10]), trajectory sensitivity analysis [18] [15], improved and robust positive sequence models [12] [13], EMT analysis.
Market, Mandatory or Inherent Need	Can be related to voltage support services and provide in a related market. Possible also to mandate a maximum allowed output impedance of a grid-forming IBR but a market still needed to call up grid-forming IBR in sufficient voltages and various locations.
Redundant, legacy, enduring or new need	This need appears in grid locations with existing IBRs (such as wind farms, PV farms, etc) and is expected to appear more frequently and commonly with the increasing penetration level of IBRs into power systems [19] [14].
Readiness for IBR Supply	Problem is widely recognised and solutions through proper tuning of the PLL or only connecting to low impedance (stiff) grids is understood [19] [20] [21]. Little attention yet on whether Grid-forming IBR can deliver voltage stiffness to assist synchronisation of grid-following IBR [7]. 
Return to Synchronization and Angle Stability Needs or Types of System Need & Service	

3.3 First-Swing Mitigation

Need	Synchronisation and Angle – First-Swing Mitigation
Importance / Consequence if unmet	SMs may suffer from loss of synchronisation due to large disturbance and system collapse that causes a swing that exceeds the equilibrium limit. IBRs (both grid-forming and grid-following) can face similar problems and lose synchronism.
Influence on Relevance or Scale of Need	The key factors include: the damping torque and inertia of SMs, and virtual damping torque and virtual inertia (explicit or implicit) of IBR. This is a system issue where characteristics of resources and of the grid are both important. Other factors include the pre-fault conditions of apparatuses and the parameters of transmission lines. Excitors and prime movers of rotating machines may also participate if a longer time period and multi-swing stability are the issue. Similarly, the slow tertiary and secondary control in a hierarchical control structure of IBRs may influence over longer periods. It is unclear to what extent GFL-IBR are prone to long-lasting loss of synchronism from a single large disturbance. The generic need to provide first-swing stability for all resources may in fact be a set of differing needs for different technologies: SM, GFL-IBR and GFM-IBR. A technology neutral set of detail definitions may not be possible.
Expected Volume of Service to meet Need	The volume of need is locational and system dependent and has to be assessed through detailed study of the system.
Physical Limits on Availability	For SMs, the values of damping and inertia have physical limits. For IBRs, the values of virtual damping and virtual inertia (explicit or implicit) have greater flexibility but are still subject to the physical limits of the IBR or its energy source. The values of damping and inertia contribution for IBR will be chosen to respect physical limits of IBR and the capability of the grid to accommodate the service.
Overlap with other needs	Maintaining synchronism during a large disturbance will occur alongside a need to regulate frequency and voltage and many common technical requirements and services may be present.
Supporting Tools & Analysis Techniques	Swing equations [3], power angle equation [3], equal area criterion [3], Lyapunov stability analysis [22] [23], phase portrait analysis [22] [23], power flow analysis tools [3], etc.
Market, Mandatory or Inherent Need	To be decided after further investigation.
Redundant, legacy, enduring or new need	This need is somewhat different for SMs, GFL-IBRs, and GFM-IBRs and may be met differently as a result [7] [14]. There will be a legacy need for SM and a new need for IBR [15] but the proportions of the two will change in future and the services procured to meet the need may change.
Readiness for IBR Supply	In principle IBRs can provide services to meet this need but no trials are known. 
Return to Synchronization and Angle Stability Needs or Types of System Need & Service	

3.4 Phase-Jump Mitigation

Need	Synchronisation and Angle – Phase-Jump Mitigation
Importance / Consequence if unmet	Loss of synchronisation from abrupt change of phase angle from loss-of-infeed or loss of line.
Influence on relevance or scale	The line impedances and the power flow of lines play a key role in the difference between pre-fault and fault operation conditions that give rise to phase-jumps. Sensitivity or immunity of IBR and other equipment to phase-jumps needs to be considered, for example, will there be a definition in grid codes of the worst phase-jump that IBR and SM must ride-through and beyond that loss of synchronism is expected? Are there measures that a system operator can take to mitigate this, such as by ensuring that voltage magnitudes remain high during the event and does that establish a need?
Expected Volume	It is not simple to evaluate the required volume. Many regions have started implementing phase-jump thresholds that have to be met (such as 30° extreme limit). However, it should be coordinated with protection thresholds such as the maximum phase difference across which breakers would be allowed to close lines.
Physical Limits on Availability	Ability of IBR to either withstand a phase-jump or to provide voltage recovery to mitigate effects on other IBR depends on headroom for additional current flow within the current rating.
Coaction or Competition for Service	The phase-jump is related to the transient stability (first swing and multi swing stability). The phase jump may lead to extra pressures on the IBR control. For example, the sudden change of the output power of an IBR makes the regulation of its dc-link voltage challenging, which is also related to the dc-link control bandwidth and the capacitance of the dc-link.
Supporting Tools & Analysis Techniques	Swing equations [3], power flow analysis tools [3], Lyapunov stability analysis [22] [23], phase portrait [22] [23].
Market, Mandatory or Inherent Service	Some measures to alleviate risk might be procured in a market in regions known to be vulnerable but some mandatory provision through gird design or grid codes is indicated. Open question on how to spread the burden between immunising equipment to the risk or reducing the risk at system level.
Legacy, enduring or new need	This would probably be an enduring need since, in their different ways, IBR and SM both need this. That said, the need might relax thanks to the control flexibility of the synchronization of IBRs [6] [7] [14].
Readiness for IBR Supply	Very early stage of investigation. 
Return to Synchronization and Angle Stability Needs or Types of System Need & Service	

4 Frequency Regulation Needs

Return to *Types of System Need & Service*

Power systems have been designed around the principle that frequency is directly related to supply-demand balance and this balance is a fundamental need. Regulating the frequency accomplishes supply-demand balance over the near term. If supply-demand balance could be maintained without using frequency regulation as a surrogate, then this need could be reduced or replaced. Beyond that, the increased use of DC in generation, transmission, distribution and end-use may reduce the central role of regulating frequency. Further, it has been necessary to keep frequency within a narrow band where generation and demand equipment operate safely. The use of inverters and other modern interfaces to an AC system means that large frequency ranges might be tolerated in future. Notwithstanding these thoughts on the long-term view of whether tight frequency regulation will be needed, there is a clear need in the medium term, say 10-15 years, to continue to regulate AC frequency within relative narrow limits around a nominal value.

At present a variety of services are used to manage frequency after a major contingence occurs. The exact arrangements and the terminology vary from one operator to another, but Figure 7 illustrates one example taken from [24]. In the table below we have used generic descriptions of needs which could be mapped to the present day services of most operators.

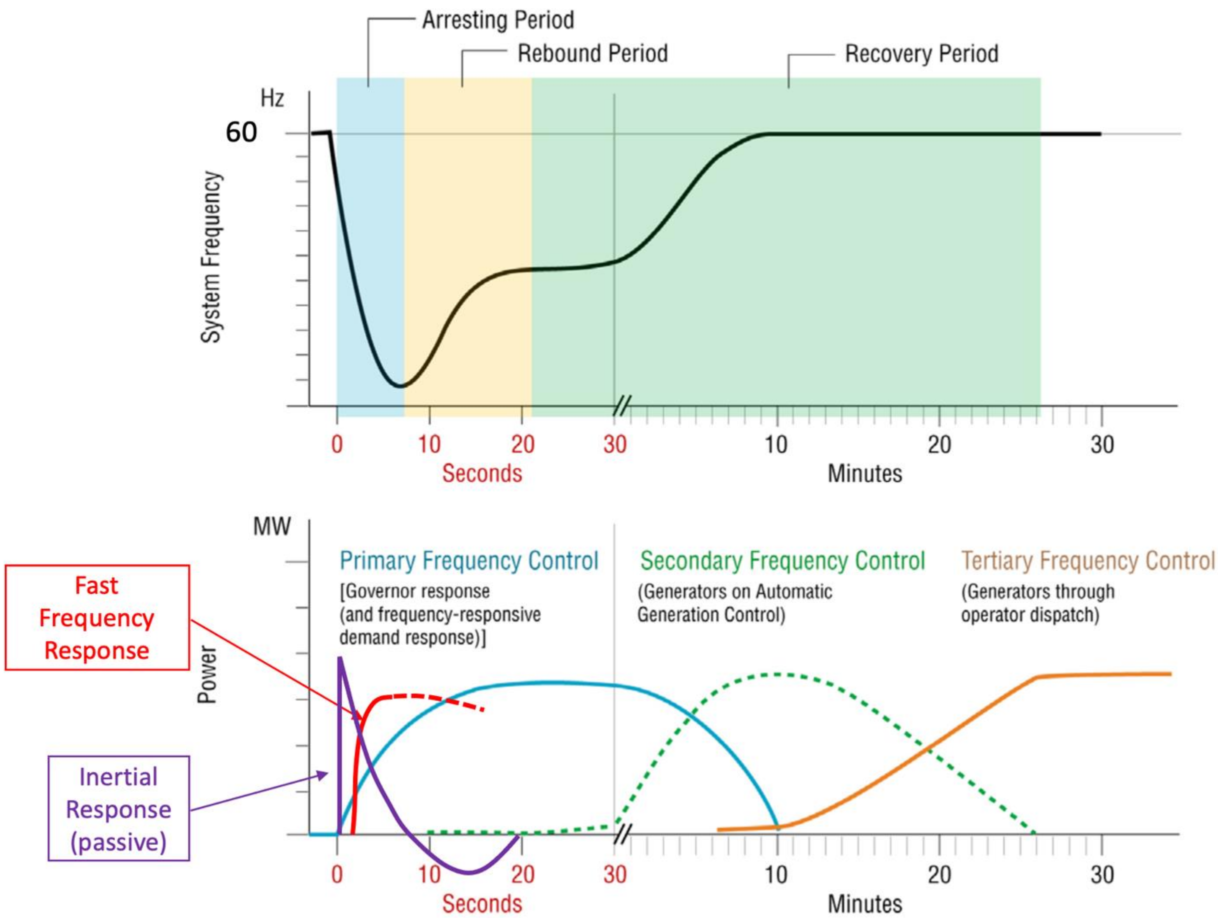


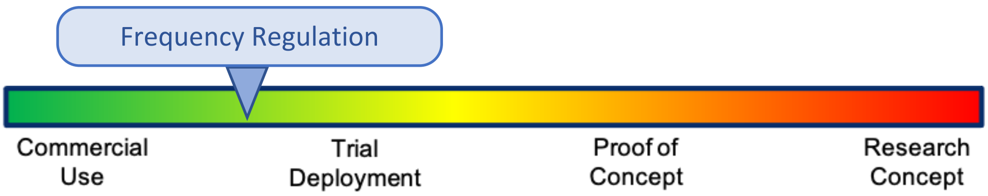
Figure 7: Example of services deployed following contingency such as a loss of infeed.

Note that terminology varies from one region to another and from on SO to another, but the principle that a range of services on different timescales are deployed in response to contingency and to re-position the system so it is able to withstand a second contingency. The range of services allows several types of resource to contribute a service.

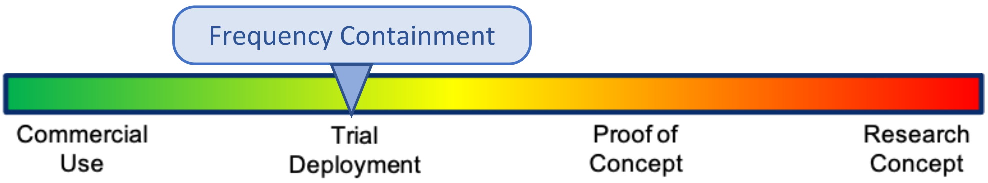
The questions that will arise for an IBR-dominated grid is whether services to meet needs should be redefined because of the changes in the dynamics of frequency in an IBR-dominated grid and because of the different capabilities of IBR to provide services. As an example, National Grid ESO is presently updating its service definitions in this area [25].

Need Type	Reason for Need
Regulation	Power fluctuations of VRE or load causing drift of frequency need to be mitigated
Containment of Frequency within Limits	Loss of load/infeed causing large increase/decrease of frequency to the outside limits defined and causing equipment malfunction or loss of service
Limitation of RoCoF	Loss of load/infeed causing rapid change of frequency and protection malfunction or unwanted triggering of protection.
Settling of Frequency	Following a major event, immediate containment of frequency to settle (or stabilise) the frequency.
Recovery of Frequency	Reserve services to restore frequency following large disturbance.

4.1 Regulation

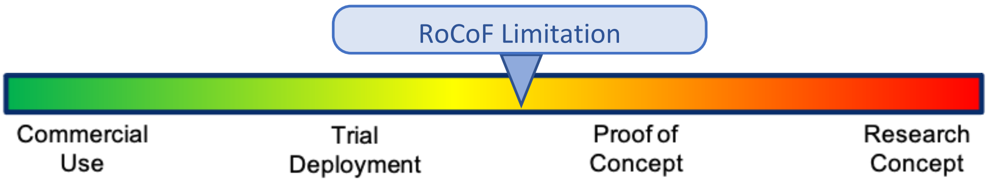
Need	Frequency Regulation - Regulation
Importance / Consequence if unmet	Small power fluctuations of VRE, changes in dispatch points of other generation or variation of load causes drift of frequency that needs to be mitigated. This is a familiar topic in power systems and markets exist for provisions of frequency response services at several timescales (primary, secondary, tertiary etc.).
Influence on Relevance or Scale of Need	Many changes underway with growing VRE share but arguably less variability from offshore wind than onshore. New demand from EV charging possibly adding variation but allowing more DSR to shape demand.
Expected Volume of Service to meet Need	The need is relatively small, on the order of a few precent of the demand for a large system, but the fraction increases for smaller systems. This is a need for which services are procured to guard against problems but not often called-up to their full extent. The volume of need depends on the dynamics of the system (such as inertia) and on the speed with which the service is delivered with early action avoiding larger action later.
Physical Limits on Availability	Delivery of a service for frequency regulation requires up and down variation of power. Down-regulation is often straightforward but for IBR up-regulation has little or no short-term overload to exploit so headroom is needed within the continuous rating. Further, VRE operating to maximise power yield cannot up regulate so service can only be provided by part loading to operate at a lower power (with consequent loss of revenue in energy market) and the volume of service will depend on the available VRE in given conditions and the degree of uncertainty around that.
Overlap with other needs	This need is closely related to frequency settling and containment, and services should be procured with all three of these needs in mind.
Supporting Tools & Analysis Techniques	Planning/forecasting tools of capacity/generation/load are established [3] [26]. Power flow analysis tools (which have to consider the power-frequency characteristics of apparatuses) may need refinement.
Market, Mandatory or Inherent Need	Market provision is well-established in some jurisdictions and is likely to persist. Competitive procurement by other means is also popular.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	IBR shown to be cable of providing service but rarely participate in VRE format due to economic trade-offs in providing energy. Battery IBR feature in short-duration frequency regulation services. 
Return to Frequency Regulation Needs or Types of System Need & Service	

4.2 Containment of Frequency within Limits

Need	Frequency Regulation – Containment within Limits
Importance / Consequence if unmet	A large loss of infeed (or loss of large load centre) causing rapid fall (or rise) of frequency beyond the limits for normal operation of the power system. Very large excursions might cause the nadir (or zenith) outside limits and malfunction of equipment, tripping of generators or loads.
Influence on Relevance or Scale of Need	Reduction of system inertia and/or increase in size of largest contingency giving rise to higher RoCoF makes it likely that nadir/zenith will be lower/higher and be reached more quickly. Rising size of HVDC links and infeed from multi-terminal HVDC networks risks higher loss of infeed risk and therefore requires higher volume of service.
Expected Volume of Service to meet Need	Trade-off likely between RoCoF-based ($P_{Service} \propto df/dt$) and frequency-deviation-based ($P_{Service} \propto f - f_{nom}$) services. Volume also affected by size of expected loss of infeed.
Physical Limits on Availability	IBR and SM are similar in that to provide a frequency containment service, there must be up- and down-regulation power available from the prime mover. Wind/Solar can only up-regulate (act to increase frequency) if they are running part-loaded. A wind turbine may provide a short-term inertia-like service that does not require capacity reservation by using the inertia of the blades (this has to be an active choice since the blades are asynchronous) but the turbine might face some payback effect in the following period if the maximum power point (MPP) has to be regained. Demand-side can act to decrease consumption (c.f. increase generation) and in some cases (thermal loads or EV charging) could increase consumption (c.f. reduce generation).
Overlap with other needs	Similar discussion as under noted under RoCoF need. A service such as Fast Frequency Response may mitigate this but still likely that larger volumes of power increase/decrease triggered by frequency (not RoCoF) will be needed to contain frequency deviation within limits.
Supporting Tools & Analysis Techniques	Tools for analysing loss of infeed are well-established in terms of swing-equation dynamics (at least for an SM system) [3] and has been included in an approximate fashion in dispatch/scheduling models [27] [28] [29]. EMT or phasor simulation can also be useful for confirmation of details.
Market, Mandatory or Inherent Need	Already procured as a service with the service being defined in a technology neutral fashion (simply defining volumes of power, response time and sustain period) that allows IBR to compete.
Redundant, legacy, enduring or new need	Need to contain frequency within prescribed limits is enduring but those limits might relax in a future system.
Readiness for IBR Supply	
Return to Frequency Regulation Needs or Types of System Need & Service	

4.3 Limitation of RoCoF

Need	Frequency Regulation – Limitation of RoCoF
Importance / Consequence if unmet	This issue has a lot in common with containment of frequency within limits with similar causes, solutions and analysis tools. A large loss of infeed (or loss of large load centre) in low inertia conditions causing high negative (or positive) rate-of-change of frequency. This can be a problem in its own right for some loss-of-mains protection with low RoCoF thresholds (actively being replaced in some territories), may cause trips of SM and malfunction of relays under-frequency load-shedding (various names, e.g., UFLS or LFDD). Further, a high RoCoF goes on to influence the nadir (or zenith) of the frequency excursion. All this can lead to system collapse. It appears that the need to limit RoCoF arises from the design of various items of network and network-connected equipment and is not an inherent need. As RoCoF-based loss-of-mains protection is retuned, this need may reduce.
Influence on Relevance or Scale of Need	Reduction of system inertia gives rise to higher RoCoF. Rising size of HVDC links and infeed from multi-terminal HVDC networks risks higher loss of infeed risk and therefore requires a higher volume of service to mitigate. Increasing size of loss of infeed may be experienced in some areas through, for example, common mode of failure (voltage-induced frequency events, or simultaneous loss of high amount of distributed generation), which would require higher volumes of service to address.
Expected Volume of Service to meet Need	Trade-off likely between RoCoF-based ($P_{Service} \propto df/dt$) and frequency-deviation-based ($P_{Service} \propto f - f_{nom}$) services in tackling frequency containment in Section 4.2 but trade-off also applies to limiting RoCoF since very fast deployment of frequency containment will lower RoCoF. Volume also affected by size of expected loss of infeed.
Physical Limits on Availability	A SM would have an Inertia Constant H (expressing power proportional to acceleration) and a Damping Coefficient D (expressing power proportional to velocity). Some grid-forming IBR provide an equivalent inertial energy and damping (H and D) because of their configuration of frequency droop; others may add these features as additional services. Service is often characterised as part of virtual synchronous machine (VSM) but could be a separately considered service [16] [30]. The ability of an IBR to provide inertial energy is limited by free power capacity and the extent that additional energy is available on demand. Some IBR may have very limited ability to provide inertial energy or other RoCoF services but some may be able to outperform a SM. Batteries would suit this service well. Small amounts of energy storage elsewhere in DC links of IBR and DC links for HVDC might play some limited role. Comments on regulation need are also relevant here. A wind turbine may provide a short-term inertia-like service that does not require capacity reservation by using the inertia of the blades (this has to be an active choice since the blades are asynchronous) but the turbine might face some payback effect in the following period if the MPP has to be regained. Demand-side can act to decrease consumption (c.f. increase generation) and in some cases (thermal loads or EV charging) could increase consumption (c.f. reduce generation). Fast explicit measurement of RoCoF that is also accurate is difficult because of instrumentation and sampling noise during the differentiation operations and this can limit performance [31]. Determination of RoCoF indirectly without differentiation is preferred.
Overlap with other needs	Providing RoCoF service may also mitigate frequency nadir/zenith and co-act with services for frequency containment. RoCoF service provision is in trade-off with energy and other services if headroom is needed (e.g., solar PV that is running at full power would need over-sized inverter). Provision of an inertia response modifies the swing equation of the system and brings with it a need to consider damping of the swing (sub-synchronous damping as considered in Section 6).
Supporting Tools & Analysis Techniques	Analysis of the system dynamics are required, traditionally through the "swing" equation of a composite system or at individual machine level [3]. Concept of total system inertia (TSI) [16], used by ENTSOE, combining physical and synthetic inertia is important.
Market, Mandatory or Inherent Need	Inherent service for SM. For IBR, independent market procurement possible but path forward but final outcome unclear at present.
Redundant, legacy, enduring or new need	If RoCoF sensitive protection is retired, then this need may become redundant.

Readiness for IBR Supply	Some SOs trialling VSM [30] in demonstration projects but unlikely this can be mandated as a configuration of all IBR because of physical limitations and possibility of various other IBR control architectures that can equally provide same service. 
Return to Frequency Regulation Needs or Types of System Need & Service	

4.4 Settling of Frequency

Need	Frequency Regulation - Settling
Importance / Consequence if unmet	Following frequency containment there may still be a supply-demand mismatch leading to continuing frequency changes and the next priority is to settle or stabilised the frequency at some value, not necessarily the nominal 50 or 60 Hz but as a prelude to returning to nominal
Influence on Relevance or Scale of Need	The size of the supply-demand imbalance will determine the magnitude of additional power needed (positive or negative) to restore balance and settle the frequency. This will in turn depend on the loss of load or infeed and any service such as fast frequency response or frequency containment already deployed. It is noted that if the frequency settles but away from its nominal value a balance between supply and demand has been achieved but some further corrective action would be need to return to nominal.
Expected Volume of Service to meet Need	Broadly similar to existing primary frequency response.
Physical Limits on Availability	Additional sustained power flow is needed requiring both an energy source and capacity in the inverter.
Overlap with other needs	Distinctions between types of frequency response and reserve (fast, primary, secondary etc.) are less clear cut than once was the case and this trend is likely to continue with a range of services of different speed, magnitude and duration that co-act to meet frequency regulation in terms of containment, settling, recovery and regulation. This need sits between containment and recovery and the three needs should be met in a harmonised fashion.
Supporting Tools & Analysis Techniques	Very similar to existing calculations of primary frequency response.
Market, Mandatory or Inherent Need	To be determined after further investigation.
Redundant, legacy, enduring or new need	In a system without strict frequency limitations set by legacy equipment, this may become less important but for the immediate future (as assumed here in G-PST), some limits to deviation around nominal frequency will remain.
Readiness for IBR Supply	
Return to Frequency Regulation Needs or Types of System Need & Service	

4.5 Recovery of Frequency

Need	Frequency Regulation - Recovery
Importance / Consequence if unmet	Following a large frequency disturbance, for which containment and settling have already occurred, there is a need to recover the system frequency to a value close to nominal (50 or 60 Hz) in order that the system is well-positioned should another event occur. Failure to do so runs the risk that even a relatively small loss of load or infeed could now cause a frequency excursion outside of limits. Further, some legacy equipment may require an accurate grid frequency for time-keeping.
Influence on Relevance or Scale of Need	To cause a change in frequency requires a temporary change to the supply-demand balance and then a return to balance. In traditional terms this changes the kinetic energy of the system and hence changes the frequency. Traditional systems use a variety of services to meet this need (with terminology varying by SO and evolving to be technology neutral). The scale of future services versus those of the traditional system will change as the underlying system dynamics change also.
Expected Volume of Service to meet Need	Broadly similar to secondary frequency response of today but subject to changes in the dynamics of the system, notably systems becoming faster-responding as inertia reduces.
Physical Limits on Availability	Since this service is energy (or at least power for a period), it requires an energy resource such as a battery, a generator able to up-regulate or a demand side resource able to reduce power.
Overlap with other needs	This need is closely related to frequency settling and containment, and services should be procured with all three needs in mind
Supporting Tools & Analysis Techniques	Very similar to existing calculations of secondary frequency reserve but with due account of changes in system dynamics as with physical inertia reduces and virtual inertia emerges [16]. A 100% IBR system may however warrant a reassessment of how frequency restoration need is met along with the operation paradigm that is followed [32] [33].
Market, Mandatory or Inherent Need	Presently procured in markets and likely to continue.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	
Return to Frequency Regulation Needs or Types of System Need & Service	

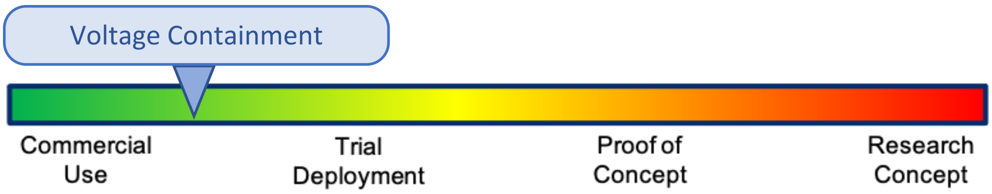
5 Voltage Regulation Needs

Return to *Types of System Need & Service*

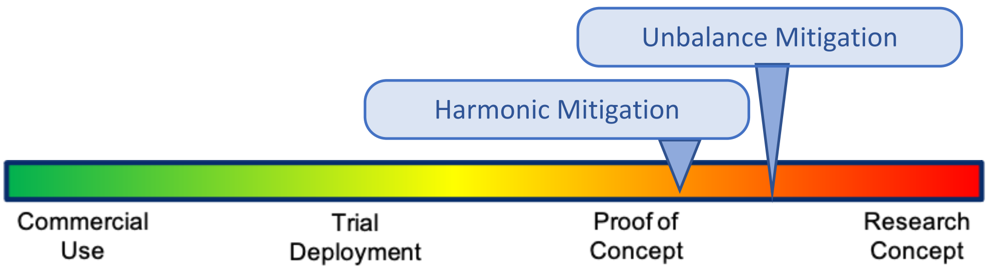
In contrast to frequency regulation which is a system wide need, voltage regulation is localised and also has multiple levels from very high at the transmission level to very low where the residential/domestic consumer is served. Nonetheless power system equipment and loads are all designed around certain voltages and hence voltage needs to be regulated to ensure proper operation of the power system and the connected loads. The voltage profile itself should be without harmonics and be held sufficiently far from the point of voltage collapse (the nose of the voltage against power curve) that risk of collapse from a disturbance is small.

Need Type	Reason for Need
Containment within Voltage Limits	Heavy line loading and/or absence of reactive power sources leads to voltage excursions outside limits.
Mitigation of Unbalance and Harmonics	Absence of mitigation (such as low impedance paths to shunt harmonics and unbalance) leads to poor voltage quality.
Voltage Collapse Mitigation	Sudden and large increase in line loading or grid impedance due to loss of line causing non-linear behaviour and collapse of voltage beyond bifurcation point.
Low-Voltage Ride-Through	Inability to ride-through leads to tripping of generation and consequent frequency regulation problems.

5.1 Containment within Voltage Limits

Need	Voltage Regulation – Containment within Limits
Importance / Consequence if unmet	System operators work to maintain a small range of acceptable voltage magnitudes to ensure final customers are supplied with safe and acceptable voltage. Further, to transfer real power/energy across a network requires a forcing voltage. Under-provision results in load pockets being formed with low voltage and this can result in stall of motor loads, and saturation of transformer tap changers. An extreme low voltage can progress to a voltage collapse, avoidance of which is covered as a separate need (Section 5.3). Over voltage must also be avoided because equipment can be damaged through insulation failure, etc.
Influence on Relevance or Scale of Need	Impedance and X/R ratio of transfer paths, location of capacitor banks/STATCOMS and other reactive power compensation devices, presence/location of FACTS devices, radiality of network, characteristics of the load.
Expected Volume of Service to meet Need	Volume will vary based on magnitude of active power transfers required and characteristics of the loads and generation present (including power factor and constant impedance(Z)-current(I)-power(P), ZIP mixture). Trade-off exists between transformer tap-changers and voltage regulation services such as reactive power injection. Tap-changers are cost-effective but relatively slow and with a cycle-life limit that restricts their use.
Physical Limits on Availability	Current limits of IBRs, operation mode of IBRs (two quadrant vs four quadrant), location of devices as voltage is a local issue.
Overlap with other needs	From IBRs, reactive power service delivery can compete with delivery of active power due to current limitation of the inverter. Coupling can exist between slow IBR voltage regulation and transformer tap changer action.
Supporting Tools & Analysis Techniques	Phasor based power flow [3], long term dynamic simulations (or Quasi-Static Dynamic Simulation) with only slow time constants represented along with current limits [34]. Evaluation of maximum transfer capability and PV/QV curves [3].
Market, Mandatory or Inherent Need	Many jurisdictions already have mandatory provision but with limits based on power factor.
Redundant, legacy, enduring or new need	This is a legacy need, but it will continue to be an enduring need. The quantity and location of provision may increase over time.
Readiness for IBR Supply	Voltage regulation services from IBR have been widely demonstrated and appear in some grid codes. 
Return to Voltage Regulation Needs or Types of System Need & Service	

5.2 Mitigation of Unbalance and Harmonics

Need	Voltage Regulation – Unbalance and Harmonic Mitigation
Importance / Consequence if unmet	Distortion of voltage waveforms can have adverse effects on customer equipment and network equipment leading to malfunction or damage. High-order harmonics may penetrate electronic equipment causing false signals. Low-order harmonics or negative- and zero-sequence unbalance can cause additional heating in transformers or vibration in motors.
Influence on Relevance or Scale of Need	At present this need is governed by power quality standards, connection standards and product standards in which compatibility levels are set. Compatibility levels seek to balance cost between immunising victims and constraining culprits in a shared electrical environment. A difficulty in power systems is that synchronous machines provided low impedance paths to shunt harmonic and unbalanced current so that their impact on network voltage was mitigated. Only occasionally did a network owner need to take additional measure to lower harmonic or imbalance impedance through parallel supply or larger transformers. The question is how this need for mitigation will be provide in a high-IBR system.
Expected Volume of Service to meet Need	To be confirmed after further consideration.
Physical Limits on Availability	IBR can be controlled to present a low impedance to particular distortion currents or across a broad range. This must fit within the current limit of the inverter. A small amount of energy is absorbed in the process which can be re-exported at fundamental frequency.
Overlap with other needs	Some overlap with general measures to provide a low-impedance voltage-source system.
Supporting Tools & Analysis Techniques	EMT simulation, harmonic and unbalanced load flows [35], [36] [37] [38].
Market, Mandatory or Inherent Need	Combinations of mandatory or market solutions possible. Mandatory standards on consumer equipment on emissions of harmonics and unbalance could be partnered with mandatory standards on mitigation provision by generation including IBR.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	
Return to Voltage Regulation Needs or Types of System Need & Service	

5.3 Voltage Collapse Mitigation

Need	Voltage Regulation – Voltage Collapse Mitigation
Importance / Consequence if unmet	Avoiding high loading conditions that trigger voltage collapse limits power transfer in lines and mitigation of the risk makes better use of assets. Mitigation could be through voltage support services which reduce the effective impedance of the supply. If a collapse occurs and recovery is not possible then service to customers is lost. Failure to recover could be because of increase constant-power load over constant-impedance loads or through limited current capability of resources. A low-voltage event that exceeds the depth and duration defined for low-voltage ride-through (LVRT) could cause disconnection of resources that makes recovery more difficult. It is possible that in high IBR grids with active loads, even short disturbance might trigger a voltage collapse.
Influence on Relevance or Scale of Need	Very important to consider characteristics of load (especially looking at proliferation of power electronic load replacing conventional induction motor load characteristics), impedance and X/R ratio of transfer paths, network topology, position/location of critical loads. Inability of IBR to provide short-term over-current to return from voltage collapse makes prevention more important. Collapse is likely to be much deeper voltage drops if IBR current is limited.
Expected Volume of Service to meet Need	Location and system dependent and in particular dependent on grid impedance and location of various resources such as DER.
Physical Limits on Availability	Current limits of IBRs, location of delivery of voltage service is local issue.
Overlap with other needs	From IBRs and DERs, due to current limit nature, voltage support can compete with frequency support in the short term after a disturbance. Although adequate voltage level is required in order to have efficient transfer of active power (which may imply that reactive support should necessarily have priority over active power), this is not a given across all networks as X/R ratio can play a role along with load characteristics.
Supporting Tools & Analysis Techniques	EMT based tools to understand fault recovery characteristics of power electronic equipment and to understand single phase induction motor stall. Positive sequence tools to understand locational delivery of service and maximum transfer capability in addition to fault recovery and motor stall behaviour [39]. Analytical methods are available to evaluate volume of load at risk and volume DER at risk [40] [41]. However, all tools must use models that properly account for inverters entering current limit (ceasing to be voltage sources) and GFL inverters with additional reactive power regulation also reaching their current limit [42]. In other words, simple voltage source and impedance models will not accurately present voltage collapse in presence of IBR.
Market, Mandatory or Inherent Need	Can be difficult to prescribe this service as a market need. Power system may be better served by having mandatory provision or inherent feature as it provides a greater good of helping keeping the system intact in short term after disturbance.
Redundant, legacy, enduring or new need	This is an enduring need. The quantity and location of provision may increase over time because of the strict current limit of IBR [43] [39].
Readiness for IBR Supply	
Return to Voltage Regulation Needs or Types of System Need & Service	

5.4 Low-Voltage Ride-Through

Need	Voltage Regulation – LVRT
Importance / Consequence if unmet	In the event of a short-circuit fault and subsequent low voltages on the system it is important resources do not trip off due to low voltage before the fault is cleared by the protection system. This is so a full range of resource is available to operate the post-fault system. In other words, LVRT ensures that other needs can be met post-fault and without this, cascading failure could occur. Described in this way, one might conclude that this a requirement placed on IBR by the grid such that the IBR can continue to service other needs. However, there are two sides to LVRT and a compatibility level to be defined: resources should have an LVRT capability and grids should ensure that low-voltage events do not exceed the depth or duration defined for LVRT. Thus there is a need for the system to mitigate the depth and duration of any low-voltage event so that LVRT is possible by suitably designed resources. The issues came to prominence with wind-turbines and PV arrays that had not been required to have LVRT or where the type, duration and number of successive events had not been adequately anticipated leading to large loss of generation infeed as a consequence of a system fault that cleared normally. There were several examples around world including in South Australia in 2016. The issue is important for large grid scale installations and small distributed installation. In the US, NERC has issued several reports on the issue [44] [45] [46].
Influence on Relevance or Scale of Need	LVRT is now widely recognised and part of connection standards for resources above a certain size. A very large majority of resources providing energy or services must be able to ride-through low-voltage events. Attention also needs to be paid to LVRT of several events in quick succession perhaps caused by action of re-closers or intermittent faults.
Expected Volume of Service to meet Need	All "necessary" equipment must be able to ride through and this must be assessed in a detailed study.
Physical Limits on Availability	IBRs with power sources on the DC-link that cannot be quickly controlled may have physical limits on the number of faults that can be rode-through in a certain period of time but, where that can be manged, IBR can ride through repeated events arguably better than synchronous machines. This limitation arises from the need to absorb, normally in a resistive dump, the power that is not exported to the grid. In principle, battery IBR can ride through repeated and long low-voltage events.
Overlap with other needs	During LVRT, an IBR may not be able to deliver other services although it is common to require IBR to deliver reactive current during LVRT to aid voltage recovery and protection system operation [42]. There is a need to consider reactive current injection from LVRT in discussion of protection needs. LVRT is part of the consideration of voltage collapse in that if LVRT is not ensured then recovery from a low voltage event may not be possible because resources to achieve that have tripped and a voltage collapse ensues.
Supporting Tools & Analysis Techniques	Dynamic simulations that accurately represent the IBRs and their connected devices. EMT-type tools and Phasor simulation tools can be used with appropriate models. As the diversity and number of IBRs increases, the computational effort of representing individual IBR becomes more difficult and accurate composite or aggregate models will be needed [47] [48].
Market, Mandatory or Inherent Need	Mandatory – typically via a grid code.
Redundant, legacy, enduring or new need	Enduring as cascade failure will impact on the ability of the power system to meet its primary objective.
Readiness for IBR Supply	
Return to Voltage Regulation Needs or Types of System Need & Service	

6 Damping Needs

Return to *Types of System Need & Service*

Power grids naturally have oscillation modes ranging from less than one hertz to thousands of hertz. These oscillation modes are introduced by the reactive components of lines/cables and the connected apparatus of sources and loads. Some of these modes are poorly damped and can become unstable (negatively damped) if the system changes. A system operator is required to ensure that these modes are adequately damped and robust against changes in operating point of the power grid.

Need Type	Reason for Need
Damping of Sub-Synchronous Modes	Poorly damped local or inter-area mode cause instability
Damping of Super-Synchronous Modes	Control interactions between IBRs in high frequency range cause instability

6.1 Damping of Sub-Synchronous Modes

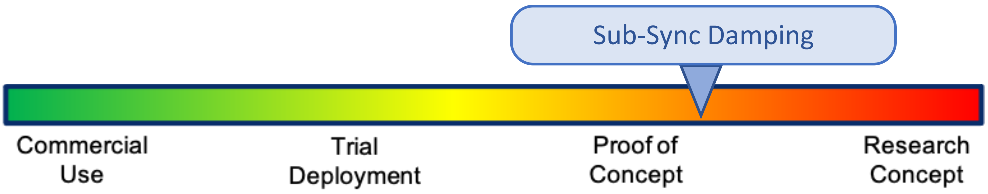
In a traditional SM-based system, two main sub-synchronous modes are present: sub-synchronous resonance and electromechanical (local and inter-area) oscillations. The sub-synchronous resonance (SSR) appears when adverse interactions appear between a series-compensated electrical system and a turbine generator mechanical system. Mitigation of the sub-synchronous resonance is presently usually provided by Thyristor-Controlled Series Capacitors (TCSC).

Electromechanical oscillations between rotors, or groups of rotors, are an inherent feature of a SM-based power system. While higher frequency (around 1 Hz) local modes between individual generators in an area are usually well-damped, low-frequency (0.1-0.5 Hz) inter-area modes are usually poorly damped. Damping is then typically enhanced by Power System Stabilizers (PSS) which provide an ancillary stabilizing loop in Automatic Voltage Regulators (AVR).

Those effects may vanish in systems when wind/solar satisfies 100% of demand but are important during the transition. Also, many zero-emission systems will still have some SM connected due to nuclear and hydro generation. Hence the need for damping may be diminished in the future but not disappear completely.

Grid-forming IBR can also participate in SSR but with somewhat different characteristics to SM. IBR may cause new frequencies and new types of sub-synchronous modes may appear due to interaction between various power electronics controllers. This is a phenomenon that has been observed in pockets of various networks.

Need	Damping of Sub-Synchronous Modes
Importance / Consequence if unmet	Sub-synchronous resonance (SSR) may lead to SM shaft fatigue or ultimately SM shaft damage. Inter-area and local area modes can cause oscillations of flows in lines (which may lead to tripping), excessive torques in remaining SM which cause mechanical damage and potential tripping of IBR from excessive current. In extreme cases, when damping is negative, unstable oscillations will cause widespread tripping and possible system splitting.
Influence on Relevance or Scale of Need	Inter-area modes are present when well-connected groups of generation sources are connected by relatively weak transmission links.
Expected Volume of Service to meet Need	Provision of damping to mitigate sub-synchronous resonance depends on the number of series-compensated lines. Provision of damping to mitigate inter-area modes depends on the characteristics of a given power system and the location of SM (if any) and IBR. Geographically dispersed systems with many SM will generally require more damping. Volume of need in an IBR dominated system is not clear at this stage; this would depend on the features of GFM and GFL IBR present and is not sufficiently researched.
Physical Limits on Availability	Damping of inter-area swings is usually provided by PSS. Hence, any remaining SM (including synchronous condensers) may have to be fitted with PSS. Damping of both SSR and inter-area swings could also be provided by FACTS controllers which suggests that it could also be provided by IBR. PSS may need new and faster characteristics as the modes of the systems evolve.
Overlap with other needs	Poor damping of local and inter-area modes is usually caused by a strongly-acting Automatic Voltage Regulators (AVR) on SM so there is coupling with voltage regulation needs in Section 5. This could change as the number of IBRs increases as strong active voltage control would not have to interact with slow moving mechanical modes.
Supporting Tools & Analysis Techniques	Small-signal stability evaluation (either eigenvalues [9] or impedance diagrams [10] [11] [49] [50]); EMT analysis. Eigenvalue analysis is a widely-used tool for the analysis of damping. Impedance scans are also used to ascertain risk of sub-synchronous modes along with assessing benefit of mitigation options.
Market, Mandatory or Inherent Need	Damping is considered a specialised technical need that does not affect economic performance of the agents and is usually subject to mandatory procurement. Provision of damping services from IBRs may however require either additional active power, energy

	storage or increased IBR ratings to accommodate reactive current delivery along with requisite level of active current. Further work required to clarify this position.
Redundant, legacy, enduring or new need	Damping of sub-synchronous resonance and local and inter-area modes is traditionally associated with SM [3] and will remain in a system with nuclear and hydro generation but may fade out in 100% IBR systems. However, 100% IBR systems may well have to guard against the emergence of new modes in the sub-synchronous region. In the meantime, as more and more synchronous machines are replaced by wind/solar, damping needs will evolve and may require retuning of some existing providers of damping such as TCSS and PSS. Additionally, sub-synchronous control interactions might arise between different power electronic components [7]. These new forms of sub-synchronous modes may require additional and innovative damping solutions.
Readiness for IBR Supply	Power Oscillation Damping from FACTS controllers is already known [3] [51] [52]. Extension to general IBR is needed. 
Return to [Damping Needs](#) or [Types of System Need & Service](#)	

6.2 Damping of Super-Synchronous Modes

Need	Damping of Super-Synchronous Modes
Importance / Consequence if unmet	IBRs normally control their output voltages and/or current through control-loops with relatively high bandwidths, for example from tens of hertz to hundreds of hertz or a few kilo hertz. Oscillation modes caused by these fast control loops could lead to high-frequency and super-synchronous oscillations through unplanned interactions between IBR in close electrical connection, as has been seen between HVDC converter stations and wind turbine generators. Additionally, the switching of IBRs' power switches and the filters of IBRs can also participate in these high-frequency oscillation modes. Potentially this could be averted through design rules and standards but it might also be that system operators will need to ensure damping across super-synchronous range is present. Work is required to establish whether generic design rules that are able guarantee stability across a wide range of circumstance would be too conservative and costly. Alternatives would be specific terms in connection agreements for each location or procurement of damping services according to need.
Influence on Relevance or Scale of Need	The parameters and bandwidths of these fast control loops of IBRs play a key role. The parameters of filters (such as resonance frequency point, passive dampers values, etc.) of IBRs also play an important role. The fast control loops could also interact with slow control loops (such as synchronization loops, voltage regulation loops, etc.) and interact with transmission/distribution line impedances.
Expected Volume of Service to meet Need	Quantification is not straightforward, because the oscillation modes are tightly related to the parameters of apparatuses. The quantification is also locational and system dependent. For instance, properly designed parameters and properly decoupled control bandwidths of IBRs can participate in the active damping, but improperly designed parameters can worsen the oscillations.
Physical Limits on Availability	The switching frequency of IBRs is limited by the conversion efficiency and thermal limitation. The passive dampers in filters are limited by the filtering ability. The active dampers are limited by the control bandwidths of corresponding control loops. The control bandwidths of IBRs are limited by the switching frequency and control delay.
Overlap with other needs	The active damping is linked to the control parameters of IBRs. Independent active damping apparatus may introduce new oscillation modes if not properly designed. Passive damping may compete with the conversion efficiency and the filtering effects of passive filters.
Supporting Tools & Analysis Techniques	Small signal stability evaluation (either eigenvalues [9] or impedance diagrams [10] [11]); EMT analysis; harmonic stability analysis [53] such as harmonic state space [54], generalized averaging [55], dynamic phasor [56].
Market, Mandatory or Inherent Need	As for sub-synchronous case.
Redundant, legacy, enduring or new need	This need appears in existing IBRs such as apparatuses in wind farms, PV farms. This need will become more important with the increasing penetration level of IBRs into power systems [53].
Readiness for IBR Supply	At present this is not a service but there have been examples of IBR needing re-tuning after installation to mitigate a problem. 
Return to Damping Needs or Types of System Need & Service	

7 Protection Needs

Return to *Types of System Need & Service*

Note, the discussion in this section is limited to short-circuit faults for lines and cables etc. at his time. It does not yet address protection for other issues such as under/over frequency (which crosses over to the discussion of frequency services) and synchronisation checking (which crosses over to the discussion of restoration).

Preamble on Protection for Short-Circuit Faults

Protection systems detect, locate, and isolate of faults (short circuit paths) so as to protect life and property while allowing the remaining system to continue to function. Protection is traditionally based on flow of large fault currents from SM and that substantial overcurrent being detected by protection relays. There are variations of detection relays that detect negative sequence current or ground current or estimated distance (impedance) to fault or residual current differences between two measurements but essentially the presence of large abnormal currents are the basis of detecting and locating faults.

Fault current is normally very much larger than maximum load current and also larger that in-rush current and other temporary overloads and without this discrimination of faults is not easily possible. IBR do not have a meaningful short term overcurrent rating since over-currents in semiconductors lead to damaging temperature rises very quickly because of the very low thermal mass. Where short-term ratings are provided, they are through over-sized semiconductors, and so are costly, and over-sized cooling provision. Some saving in secondary cooling (the chilling of water in water-cooled heatsinks) might save some cost. To a first approximation, additional short-term rating is as expensive as additional normal rating.

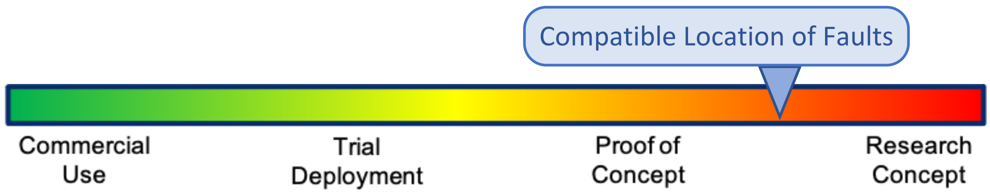
In keeping with the desire to define system needs independent of a particular technology, general descriptions will be given first but there is a fundamental fork in the road ahead. One road is that over-current and distance-based relaying is so pervasive that wholesale replacement is economically prohibitive and the protection-need should be defined as the need to operate existing types of protection relay. The other road is that the cost of providing over-current from IBR to match SM is also seen as economically prohibitive and that new approaches should be sought that balance cost between enhanced features of IBR and new protection relaying. New approaches could be unit protection or travelling wave detection. This topic has received some but not much research attention and it is far from clear what the best approached is at system level. It is probably the case that continued use of simple over-current relays will lead to excessive cost in IBR enhancement but much less clear whether distance protection can be made to operate satisfactorily with lower fault currents with modest cost increases in relaying and IBR equipment. The following descriptions of needs will try to accommodate all the various paths forward.

Need Type	Reason for Need
Detection of Short-Circuit Faults	Rapid detection needed for safety of people and equipment. Transitionally based on flow of large fault current from SM.
Location of Faults	Estimation of location needed to identify minimum section of network consistent with safe removal of fault. Traditionally uses fault current magnitude or estimated fault impedance to locate fault.
Isolation of Faults	Not really a needed serviced by SM or IBR service but rather by circuit-breakers. Included for completeness

7.1 Detection of Short-Circuit Faults

Need	**Protection – Detection of Faults**
Importance / Consequence if unmet	Rapid detection needed in order to move on to location and isolation of short-circuit faults before the energy released in the fault endangers life and property. Redundancy in provision is also important with secondary protection in place in case of malfunction of primary protection.
Influence on Relevance or Scale of Need	In simple terms, detection must be provided everywhere. The volume of fault current, if over-current relaying is retained, is location specific.
Expected Volume of Service to meet Need	Provision of fault detection is ubiquitous and must protect all items of equipment.
Physical Limits on Availability	As noted in the preamble, provision of fault current above normal load current in IBR is an expensive addition to basic IBR function [43]. Further, very fast current limiting will be in place to ensure that current ratings are not exceeded. The form of current injected by an inverter into a fault is dependent on the form of current control used and method for setting the current reference, notably whether only positive-sequence current is injected, positive and negative or positive, negative and zero sequence. The ability to source zero-sequence current will depend on the circuit topology (such as whether a neutral leg is present or alternatively a dealt-star interface transformer).
Overlap with other needs	Detection and location of faults are closely associated with each other and relay on similar services of fault current provision. Enhancement of short-term current rating of IBR to offer a fault-current service may also contribute to short-term overload ability for cold-load pick-up.
Supporting Tools & Analysis Techniques	Fault flow studies [57] [58]with full and accurate representation of IBR accommodating a rich variety of current control and current limitation options. Not sufficient in future to model as voltage source behind impedance. Particular care needed to model response to asymmetric faults. Analytic methods based on sequence-circuits need great care since IBR change from voltage to current source on a per-phase bases complicated the sequence representation. New sequence tools or reversion to EMT simulation needed.
Market, Mandatory or Inherent Need	Unclear at this stage: likely mandatory service but it is not inherent service.
Redundant, legacy, enduring or new need	Enduring, with aspects that may be legacy (fault current) - new needs possibly if we change protection away from high currents detect
Readiness for IBR Supply	
Return to Protection Needs or Types of System Need & Service	

7.2 Location of Faults

Need	Protection – Location of Faults
Importance / Consequence if unmet	As for detection.
Influence on Relevance or Scale of Need	Location of faults should be such that it identifies the smallest unit for equipment that has to isolated to ensure safety. Fine granularity in location is important.
Expected Volume of Service to meet Need	Location can use a variety of traditional techniques such as (i) time grading on magnitude of over current (ii) distance protection based on estimated impedance to fault location (iii) differential current that identifies specific equipment and several alternatives not based on over-current. A future system might use a very different mix of these approaches to the traditional system but the picture is not clear at this point. It is unclear at this stage how the relative importance of these techniques changes in the light of increasing IBR presence.
Physical Limits on Availability	On over-current provision, the limits are the same as those under detection.
Overlap with other needs	Services to meeting location and detection needs are likely to be very similar
Supporting Tools & Analysis Techniques	Fault flow studies [57] with full and accurate representation of IBR, as for detection.
Market, Mandatory or Inherent Need	Unclear at this stage but not inherent.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	
Return to Protection Needs or Types of System Need & Service	

7.3 Isolation of Faults

Not really an SM or IBR service but placed here for completeness of the protection group. Isolation of faults is performed by circuit breakers, almost exclusively mechanical in nature.

In Multi-Terminal HVDC there are now hybrid semiconductor-mechanical circuit breakers and there are trials of smaller versions of these as bus-couplers with a breaking duty and a fault current limiting feature in AC distribution networks (e.g. in [59]). In a distant future IBR might have a role in limiting fault current and enabling alternative isolating devices.

8 Restoration Needs

Return to *Types of System Need & Service*

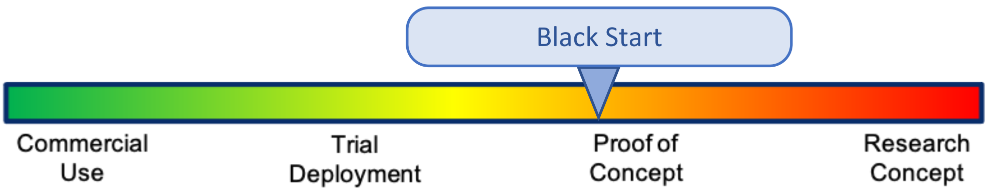
System restoration is the ability to black start and restore the power system after a major outage. It requires self-starting of a generator to establish a voltage and synchronizing torque to which other generators can synchronize. It needs to energize the local system. Then load (cold load pickup) is added to this system so that this unit can operate stably; this may be complicated by the presence of embedded generation or storage (DERs) in the blocks of load. Then other generators and other blocks of load are added to this system so that each step can be stably operated. Finally individual islanded systems are synchronized and closed to restore the full power system.

Need Type	Reason for Need
Black Start	Need to self-start then (i) establish voltage to which other IBR and SM can synchronise (ii) provide cold-load pick-up and (iii) synchronise and close onto adjacent areas
Cold Load Pick-Up	Need to maintain voltage and provide additional power flow during “in-rush” of network segments being returned to supply
Island Operation	Need to maintain core functions (frequency and voltage regulation) within an area after a system split. Need ability to synchronise to an adjacent area as in Black-Start.

8.1 Black Start

The first step of system restoration from a full system collapse is “black-start”, in which a single generating station reenergizes its local system, bringing the voltage and frequency up to normal. Traditionally, flexible hydro or fossil, such as simple cycle GTs or diesels, have provided the first step, black-start. It is important to note that the units which provide black-start not only need to be able to self-start and create a voltage and frequency but they need to able to accommodate a wide range of loading so that load and generation can be added to this island.

Units (and plants) specifically equipped with the necessary auxiliary equipment to provide black-start are known a priori, and normally compensated in some fashion for their ability to provide this service. Presently commercial wind and solar IBR generation is NOT used (or even considered) in system restoration. These resources cannot provide black-start, and their participation in the subsequent steps of system restoration are generally avoided. As the fossil resources that have traditionally provided the backbone of restoration are displaced, IBR resources will need to fill this need. Several categories of challenges need to be addressed.

Need	Restoration – Black Start
Importance / Consequence if unmet	This is an essential service for any power system and is typically provided by multiple generating resources sited across the power system. The risk of under provision is that it may thwart or slow the system restoration process.
Influence on Relevance or Scale of Need	Requirements for this service depend on the size and geographic extent of the grid. System operators typically have plans for which units provide black start, where and how they form island grids and then how these grids are synchronized. Sufficient capability is needed to energize transmission lines and transformers.
Expected Volume of Service to meet Need	The volume of this service is not necessarily expected to change but rather the units that provide the service may change as SM are retired. Depending on grid evolution, it may be that many small plants provide this service in the future rather than a small number of large SM.
Physical Limits on Availability	Grid-following IBRs cannot provide this service. Grid-forming IBRs can provide this service and a limited number of these systems have been deployed. Grid-forming IBRs that provide black start may need higher current capability to energize transformers and transmission lines as appropriate.
Overlap with other needs	Black start by its nature is in many ways a microcosm of all the other services.
Supporting Tools & Analysis Techniques	Positive sequence load flow tools; in the case of reduced short circuit strength due to fewer SM and high IBR penetrations, EMT will be needed; protection analysis tools [57] [58].
Market, Mandatory or Inherent Need	Because only some units are needed to provide black-start, it makes more sense for this to be either a market procurement or some sort of compensated service that only some units provide.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	NGESO has run a trial with a windfarm [60]. 
Return to Restoration Needs or Types of System Need & Service	

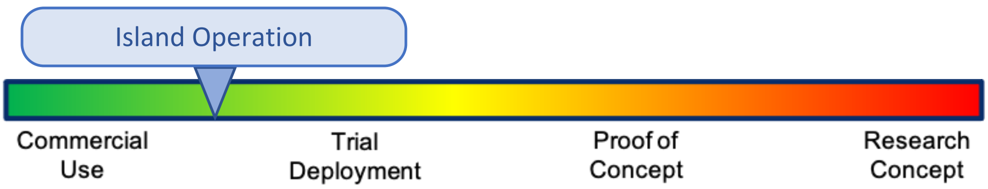
8.2 Cold Load Pick-Up

Following a black-start or restoration of a bulk supply point, individual sections of the grid, i.e. substations, lines, distribution feeders, and more generators are sequentially energized. Sufficient overcurrent capability for in-rush currents is needed. Each step is a complex data and decision making process (especially with high levels of DERs) to assure that each stage is viable, with missteps causing local collapses being a significant risk. Complications include transient stresses, failed closures, and multi-IBR control coordination.

The physical capability of the "pieces" being reassembled must be respected, and there must be sufficient control range in the controllable elements to maintain acceptable voltage, frequency and power balance.

Need	**Restoration – Cold Load Pick-Up**
Importance / Consequence if unmet	Need to maintain voltage and provide additional power flow during "in-rush" of network segments being returned to supply. Failure to provide sufficient capacity or system strength during such an operation could lead to voltage collapse. If volume of service is small, then restoration is impeded and slowed because finer-grained restoration sequences will be needed. Reserves and control functionality for handling dynamics is important. Managing system strength to enable cold load pick-up of grid-following IBRs and avoid control interactions is also critical. System protection functionality for safety and reliability during high IBR conditions and low fault current conditions needs to be managed.
Influence on relevance or scale	In-rush current is expected when energising a transformer. Direct-on-line starting of induction motors will also draw a very large starting current during acceleration of the load in high slip conditions. Electronically interfaced loads running as constant power loads will draw large currents during recovery through a voltage sag. The changing nature of loads and DERs embedded in load pockets complicate the needs of this service.
Expected Volume	This is dependent on grid characteristics and the system operator's restoration process.
Physical Limits on Availability	Limited (or non-existence) of short-term overload current of inverters limits the capacity to support in-rush current to the remaining normal rated current of the inverter after allowing for the load already being served.
Coaction or Competition for Service	Providing the power/energy for re-supply of loads is similar to other provision of energy as a service. The provision of additional in-rush current will reduce the ability of IBR to pick-up a load of a given steady state power rating.
Supporting Tools & Analysis Techniques	Two forms of analysis are needed here. One is the analysis of the load and other resource in a network segment needing return to service and the in-rush characteristic of that load or resource and algorithms for scheduling restoration with regard to this service. This needs to be paired with the analysis of active loads (such as constant power equipment) and current-limited IBR sources for assessing voltage stability and avoidance of voltage collapse (as discussed in voltage collapse mitigation need). During actual cold load pick up operations, tools are needed for situational awareness and advisory functionality. Weather and physical conditions, including plant capability, are needed.
Market, Mandatory or Inherent Service	Unclear at this stage. To an extent this is an inherent feature but arguably for a reduced extent with IBR compared to SM. Additional or enhanced service could be procured in a similar way to black-start services.
Legacy, enduring or new need	Enduring.
Readiness for IBR Supply	
Return to Restoration Needs or Types of System Need & Service	

8.3 Island Operation

Need	**Restoration – Island Operation**
Importance / Consequence if unmet	Need to maintain core functions (frequency and voltage regulation) within an area after a system split. These capabilities are similar in function to Section 4 and Section 5 above but the range of operation, the stress on the units, the decision-making and the communications needed are more extreme. Other capabilities such as Sections 3, 6, and 7 are also important during island operation in the event of a disturbance as the system is being restored. This service also needs the ability to synchronise to an adjacent area to complete the restoration of the whole system.
Influence on Relevance or Scale of Need	This is dependent on grid characteristics and restoration plans. Portions of a system that are loosely interconnected and susceptible to islanded operation may require these services over an extended period of time. Faster restoration plans may require a larger number of geographically dispersed units that provide these services.
Expected Volume of Service to meet Need	Dependent upon restoration plans and on some sort of prioritisation of locations and/or parts of the power system.
Physical Limits on Availability	Resources need sufficient control range and ramping capability over real and reactive power output to provide this service. For wind or PV plants, that will depend on real-time wind or PV resources.
Overlap with other needs	Islanding services are essentially the services in Sections 4, 5, 6, and 7, but with more range and agility than required for an intact system, therefore this is NOT a need that should be pervasive it should targeted at certain parts of the system.
Supporting Tools & Analysis Techniques	As this is a power system in its own right – the whole suite of tools is required.
Market, Mandatory or Inherent Need	Market procurement makes sense for this service because it is not needed by all units and it carries additional risk for the resources that provide it.
Redundant, legacy, enduring or new need	Enduring.
Readiness for IBR Supply	
Return to Restoration Needs or Types of System Need & Service	

9 Conclusion and Request for Feedback

As stated at the beginning, this document is designed to underpin, inform, and shape the research agenda of the G-PST and is also deemed to be a contribution in its own right to our collective knowledge and insight into the transformation of power systems. The document, as it stands, could expand in several directions but, before that is attempted, feedback is sought from experts in the field. This can be provided using the Needs and Services Deliverable Feedback Form. More in-depth feedback can be provided by marking up the document and/or emailing globalpst@nrel.gov. If a copy of the document in a more editable format is desired, please email globalpst@nrel.gov.

Finally, the IBR Research Team of the G-PST has developed an interactive presentation, "IBR Research Team Stability Tools Inventory: Status and Needs". This presentation analyzes a wide range of tools used by system operators and for each tool provides a list of related terms and brands associated with the tool; the key attributes and main uses of the tool; the relationship of the tool to stability tools; the gaps in the tool with respect to modeling or analyzing IBRs or high-IBR systems; and the maturity of the tool (ranging from widely commercialized to 'proof-of-concept'). Feedback on this document is also sought from experts in the field and can be provided using the Tools and Models Deliverable Feedback Form or emailing globalpst@nrel.gov.

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