System Services from Inverter Based Resources for Reliable Operation

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***Abstract*—With the increasing penetration of inverter based resources (IBRs) in present and future power systems, it is important to consider the different grid services needed from/provided by IBRs. To ensure network stability after a contingency such as trip of a synchronous generator or a fault, a grid may require services (for example, fast voltage control) from various IBRs. New IBRs to be installed with future capabilities (inherent blackstart capability) are often seen as a potential source for such services. However, the capability of many existing IBRs today are underutilized and if the capability from existing IBRs is utilized efficiently, it could greatly improve the network performance and reduce services needed from the future IBRs. This paper provides few illustrative examples detailing some of the services that may be needed by an IBR-dominated grid and the impact of asking these services from future IBRs and/or supplementing with services from existing IBRs.**

***Index Terms*—fast frequency response, fast voltage response, inverter based resources (IBRs), power system stability, weak grid**

I. Introduction

The share of inverter-based resources (IBRs) in the power grids is expected to continue to rise in the coming years. This increased share poses certain challenges but can also bring new opprtunities and services [1]. Successful operation of a power grid relies on different grid services at different time scales in the form of energy, capacity, and essential reliability services [2]. With the increased share of IBRs, it is important to investigate the grid services that could be provided by the IBRs. This paper focuses on the services from IBRs *within a short time scale i.e. from a stability perspective.*

There have been efforts to identify and categorize the services needed from IBRs in recent years. Challenges involved in running a system with a high penetration of IBRs from the perspective of stability are discussed in [3], and the risks associated with the different stability services are identified for power systems of different sizes and with different penetrations of IBRs. The grid needs are divided into 'stability and power quality' and 'security and service quality' buckets in [4], and the stability needs are further divided in terms of synchronization and angle stability, damping, frequency regulation, and voltage regulation. The authors of [5] analyze the different grid services needed from IBRs from a stability perspective and consider how these change as the penetration levels of IBRs increase from moderate to IBR-centric grids to grids operated by 100% IBRs. Note that all grid needs/services may or may not become market products, some needs may be incorporated into grid codes. A review paper [6] discusses that IBRs could provide voltage and frequency stability services and mentions that several grid operators already have frequency response and voltage ride through requirements/services for IBRs. However, the existing grid codes/services are limited to a few services and a study of the services provided by IBRs to satisfy the grid needs is still valuable. If IBRs are to be provided an incentive to deliver various services to the grid, then it is important to identify value and time frame during which the services are required.

Out of the different grid needs/services identified from a stability perspective, fast frequency response has been given a lot of attention in the research and utility community. Frequency response inherent to different generation technologies is considered in an aggregated model of the grid in [7] with a conclusion that a mix of technologies rather than a single technology might be needed for improving grid frequency response. The fast frequency response services in different existing markets are detailed in [8], with a discussion on the intricacies of obtaining these services from different resources. Note that different utilities may use different nomenclature such as fast frequency response, inertial response, or dynamic containment for frequency response services in different timescales. Authors of [9] discuss the importance of another grid service - robust and fast inverter-level voltage control. They also assess the differences in new a IBR required to ensure stable operation of a system with and without the existing IBRs providing fast voltage response. While this paper focuses on fast voltage/frequency response, more services (such as ones described in [2]–[5], some already utilized in a few networks) from IBRs may be relevant for different systems/disturbances and should be investigated in the future.

This paper aims to investigate a few types of disturbances from the perspective of understanding what aspects/services are needed for maintaining grid stability, focusing on a short time-scale of a few seconds after a disturbance. The paper also assesses the impact of obtaining these services from existing IBRs to supplement services required from new IBRs.

For the purpose of this paper, the IBR devices are categorized in four buckets:

- *legacy IBRs* - inject active power at unity power factor and provide no grid services (also called as grid following IBRs and are not considered in this paper),
- *conventional IBRs* - provide frequency and voltage response over multiple seconds,
- *enhanced IBRs* - fast voltage/frequency response within 1s of an event may be provided in addition to the slower response similar to conventional IBRs, and
- *future IBRs* - provide the above services, are capable of surviving/riding through severe load/generation mismatch, and are potentially able to provide blackstart services (sometimes called as grid forming IBRs).

This categorization does not correspond to a particular IBR technology and IBRs using different technologies may be categorized in the same bucket if they provide similar services. With the advances in inverter technologies, it might initially appear to be attractive to focus only on services from a particular IBR technology. However, from a system perspective it is beneficial to focus on performance from a variety of IBRs rather than only one particular IBR technology. A performance-based specification is recently released under the UNIFI consortium for future IBRs [10]. Existing standards such as IEEE Std 2800-2022 [11] also focus on performance-based specification. Hence, this paper does not focus on a particular IBR technology, rather, the focus is on investigating the services provided by existing/new IBRs that may be useful during grid disturbances. One of the aims of this paper is to show the value in this approach of considering particular services from IBRs rather than using a single term like 'voltage source behavior' to explain the behavior from future IBRs.

The rest of the paper is organized as follows: Section II describes the network and IBR models used while the different case studies conducted are presented in Section III, the impact of active power headroom assumptions are discussed in Section IV and Section V concludes the paper.

II. Network and IBR Models Used

A microcosm system, shown in Fig. 1, is considered for this study. This system represents a transmission network and contains a 270 MW, 90 MVAr load cluster and two 100 MVA synchronous generators connected to Bus 1, while the IBRs are connected at a distance on Bus 4 (200 MVA), Bus 5 (50 MVA) and Bus 3 (52 MVA). In the steady-state solution considered, the IBRs at Bus 4, Bus 5 and Bus 3 provide approximately 150 MW, 40 MW and 50 MW, respectively. The load cluster is modeled using a static model.

The IBRs are modeled using a generic EMT IBR model [12]. The IBR units are considered to be conventional IBRs i.e. with plant-level voltage and frequency support, provided over multiple seconds. This generic model is also used to represent enhanced IBRs for case studies with inverters equipped with fast voltage and/or frequency response. In addition, these IBR units are assumed to be equipped with a fault ride through (FRT) mode and are assumed to not trip for the events considered in this paper. For the future IBRs in the case studies, another generic model is used [13] – the implemented future IBR uses droop-based control architecture from this generic model. Future IBRs are assumed to continue supporting the grid regularly even through abnormal voltages/frequencies rather than switch to a separate fault ride through mode.

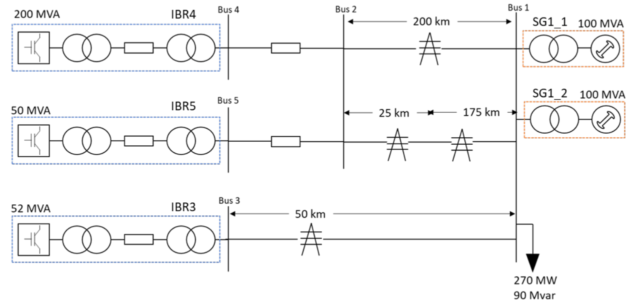

Fig. 1. A schematic of the microcosm network used in the study

III. Case Studies

The performance of the modeled microcosm network under two disturbances is studied: (i) trip of one synchronous generator and (ii) simultaneous trip of both synchronous generators creating a 100% IBR system.

A. Trip of one synchronous generator

Using EPRI's Grid Strength Assessment Tool (GSAT) [14] on the selected network, it can be seen from Table I that some of the IBR locations potentially face a weak grid condition if one synchronous generator is tripped. The table shows the short circuit ratio (SCR) and remaining short circuit capacity (SCC) MVA calculated by GSAT on the original network as well as after tripping a synchronous generator. The SCR at the IBR terminal for the IBR at Bus 4 reduces to below 1 after the trip of a synchronous generator – potentially indicative of a weak grid scenario where networks with IBRs that have conventional slow plant-level control may show unstable behavior. The unstable behavior is reflected in Fig. 2, which shows the voltages and active powers with one synchronous generator (injecting 13 MW pre disturbance) trip at 20.0s.

When a 25 MVA future IBR is added at Bus 2, the system is able to ride through this event, as shown in Fig 3(a). Since a future IBR provides numerous services to the grid compared to a conventional IBR, the mere use of a future IBR does not necessarily highlight the service that was useful during this disturbance. With 20 MW active power setpoint for the new future IBR, due to initial active and reactive power exchanged by this new IBR with the grid, it operates relatively close to the maximum current limit of 1.2 p.u. considered, and the limit

TABLE I
GRID STRENGTH ASSESSMENT OF MICROCOSM NETWORK

Location	Original Network		After synchronous generator trip	
	SCR	Remaining SCC MVA	SCR	Remaining SCC MVA
Bus 1	12.36	1028	6.44	466
Bus 2	6.44	460	4.30	244
Bus 3	8.75	752	5.34	390
Bus 4	6.02	424	4.1	288
Bus 5	6.02	437	4.1	238
Bus 3 (IBR Terminal)	4.91	197	4.17	151
Bus 4 (IBR Terminal)	1.13	19	0.96	-16
Bus 5 (IBR Terminal)	4.51	160	3.85	119

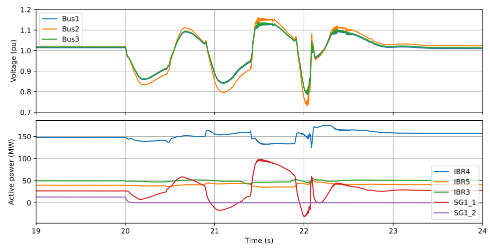

Fig. 2. Network behavior after trip of one synchronous generator

is hit after the synchronous generator is disconnected. Future IBR controls with Q-priority and P-priority are tested since these dictate whether the IBR gives priority to active/d-axis or reactive/q-axis current once the maximum current limit is hit. Fig 3(a) referenced before corresponds to the simulation with the future IBR with a Q-priority mode. However, as seen in Fig. 3(b), if P-priority mode is used instead for the 25 MVA future IBR, the system loses stability – and with P-priority a larger size IBR (30 MVA) is needed for the system to remain stable through this disturbance. These simulations indicate that the grid service needed during these network conditions and disturbance is potentially voltage/reactive power support.

To further test this hypothesis that the grid service needed during this disturbance is primarily fast voltage/reactive power support, instead of adding a future IBR, an enhanced IBR with the capability for inverter-level voltage and/or frequency control is added to Bus 2. With just the fast voltage control (i.e. slow/conventional plant-level voltage and frequency controls and the fast inverter-level voltage control but no fast inverter-level frequency control), a 10 MW new IBR is sufficient to keep the network stable through the disturbance, as seen in Fig. 4 (blue trace). However, even with a 50 MW new IBR with just the fast frequency control (i.e. slow/conventional plant-level voltage and frequency controls and the fast inverter-level frequency control but no fast inverter-level voltage control), the network is not able to stay stable for the disturbance, as shown in Fig. 4 (orange trace). In fact, if fast inverter-level voltage control is implemented on existing IBRs, no new IBR is required for the system to remain stable for this disturbance, as shown in Fig. 4 (green trace).

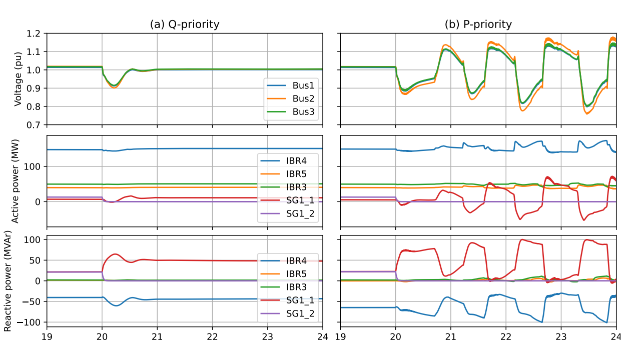

Fig. 3. Trip of one synchronous generator, with new 25 MW future IBR at Bus 2 with Q-priority (a) or P-priority (b)

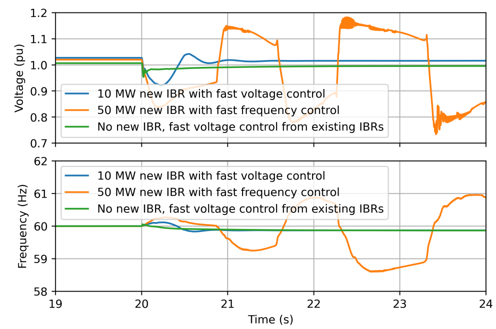

Fig. 4. The voltage and frequency at Bus 2 for different combinations of services from new/existing IBRs

These results further indicate that for this disturbance and system conditions, fast voltage/reactive power support is the grid service needed to keep the grid stable. Please note that the purpose of these simulations is not to compare 25 MW future IBR with the 10 MW enhanced IBR with fast voltage control needed to stabilize the grid. Such a comparison may not necessarily imply that the enhanced IBR is "better" than the future IBR since the exact size of IBR required will depend on factors such as controller tuning and it would be possible to obtain a similar response from different control architectures with proper controller tuning.

B. Trip of both synchronous generators

The second contingency considered is a simultaneous trip of both synchronous generators, where the resultant system would have a 100% IBR penetration. For this contingency, it is observed that the voltages drop below 0.85 after both synchronous generators trip, as shown in in Fig. 5. Thus, all three IBRs go into FRT mode, freezing the control states. Hence, the network is unable to achieve a viable operating point. Unlike the case described in Subsection III-A, a viable operating point is not achieved when the existing IBRs have fast inverter-level voltage control– in fact, sustained oscillations are observed, as shown in Fig. 6 (orange trace). With a 100 MW future IBR added to Bus 1 (with either P-priority or Q-priority) with existing IBRs with conventional control, a viable operating point is still not achieved, as shown in Fig. 6 (blue trace). However, if the existing IBRs are assumed to have fast inverter-level voltage control, the network with such IBRs and the additional 100 MW future IBR is able to achieve a stable and viable operating point, as shown in Fig. 6

(green trace). Instead of the future IBR, if a 100 MW enhanced IBR with fast voltage control is added, it is observed that the system survives the disturbance even with the existing IBRs with conventional control, but unstable behavior is observed when the existing IBRs have fast inverter-level voltage control, as shown in Fig. 6 (red and purple traces).

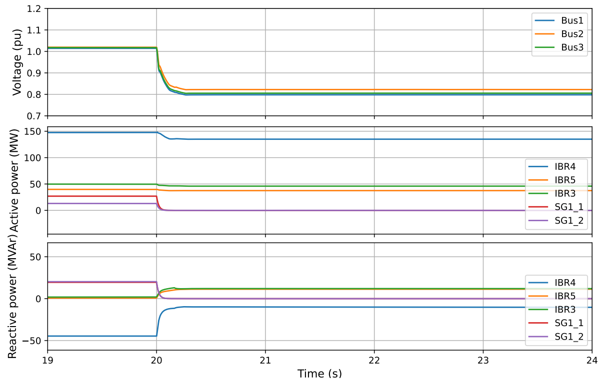

Fig. 5. Network behavior after trip of both synchronous generators

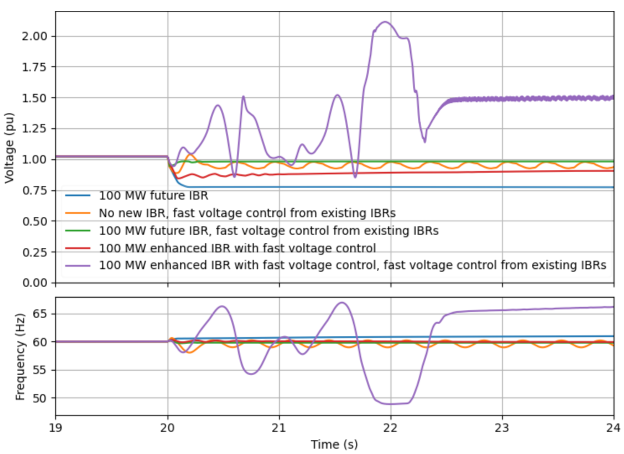

Fig. 6. The voltage and frequency at Bus 2 for different combinations of services from new/existing IBRs

This case study shows that the services provided by existing IBRs may help reduce the burden of providing grid services from a new IBR. Here, while additional 100 MW future IBR or the fast voltage control on the existing IBRs do not lead to a viable operating point on their own, when combined, are able to share the burden of the services to be provided and ensure a stable and viable operating point through this disturbance. Further, fast voltage response service is observed to be important for this disturbance, similar to Subsection III-A. However, the adverse interactions observed when the existing as well as new IBRs have fast inverter-level control point towards the need to avoid such interactions when sharing the burden of grid services between different resources. The findings from this case study are illustrated through Fig. 7. Again, the purpose here is not to compare the response from enhanced/future IBRs, since the IBR performance depends on factors such as controller structure and tuning.

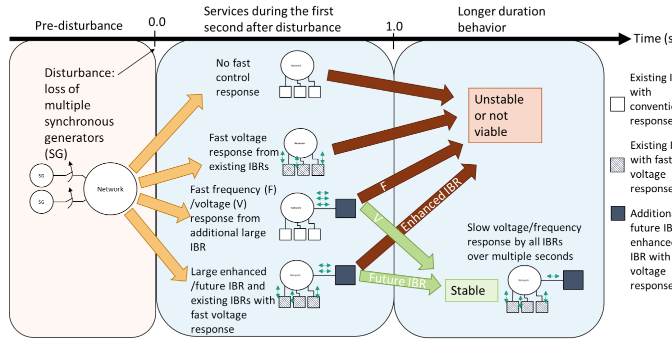

Fig. 7. Impact of different services from existing/newly added IBRs on the network behavior after a simultaneous trip of two synchronous generators.

IV. Impact of Active Power Limit Assumptions

With the increase of IBRs in the generation mix, frequency events from loss of generation may become more severe. Hence, in this section, the impact of IBR active power limit assumptions will be highlighted from the perspective of frequency response in a large interconnected system. Consider the frequency response of a large interconnected system for a loss of generation event as shown in Fig. 8. Here, the base case is a low load/low inertia scenario. Subsequently, 40% of the generation mix is assumed to be IBRs and the response is compared against the base case with minimal IBRs. When evaluating the response, it is assumed 25% of the IBRs are conventional, enhanced, or future, with 6% headroom; and the rest are legacy IBRs. As expected, with increase in IBRs there is a drop in the frequency nadir. Further, as more of the IBR capability is utilized, the frequency response improves.

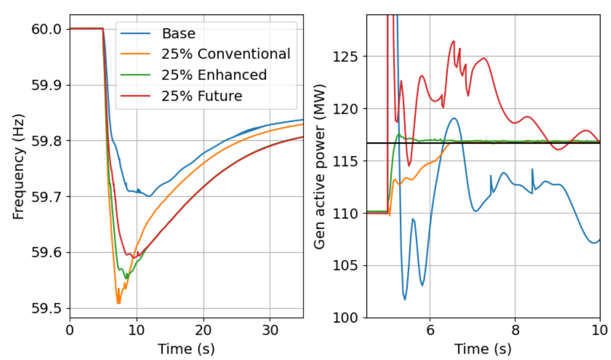

Fig. 8. Frequency response (left) and active power output of a single unit (right) in a large interconnected network with IBRs

Here however, a deeper look into the active power output of one generation unit (synchronous in the base case and replaced by IBR in all other cases) is required. As shown in Fig. 8, the active power output provides detailed insight. Since a restricted headroom of 6% is assumed for IBRs (maximum power denoted by black line in figure), the observed generation unit hits its maximum output when represented as an IBR. However, the time to reach the limit differs between conventional, enhanced and future IBRs, and the impact is reflected in the frequency response. The enhanced IBR, due to its fast frequency response characteristics, reaches the maximum output within 1s. However, the future IBR, due to having more relaxed controls, actually violates the limit for many seconds, before settling down. Note, the assumption here is that the future IBR also has only a 6% headroom. Whether it can operate above this limit for a short duration would depend on the manufacturer. This additional power above the limit injected by the future IBR during those 5 seconds helps the frequency response nadir to be higher.

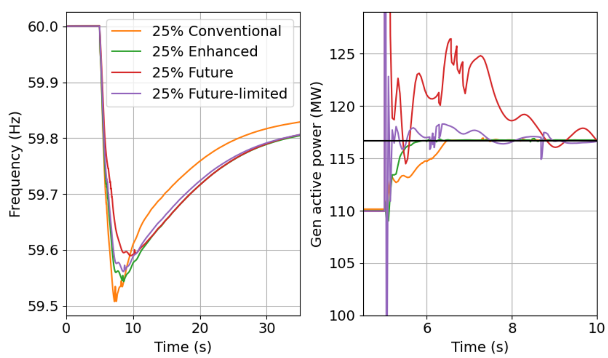

Fig. 9. Frequency response of an large interconnected network with IBRs and strict power limits on future IBRs

This impact can be verified by forcing the future IBR to meet its active power limits in a more strict/timely manner as shown in Fig. 9. Although the response is more oscillatory (can be improved with further tuning of the controls), the power limit is enforced quickly which results in the frequency nadir dropping and infact being almost similar to the response when 25% of the IBRs are enhanced IBRs.

While this section focuses on the frequency response of IBRs, similar studies involving voltage/reactive power response would help define the behaviors and services needed from IBRs related to those aspects. Note that the intention here is not to state that future IBR controls are not required or need not be developed. Rather, the intention is to provide more insight into the behavior of power networks with high share of IBRs, that can subsequently allow a reader to go further and study the actual services provided at different time scales by the IBRs rather than just assuming that the improved behavior of a network is due to 'voltage source' nature of future IBRs since identifying these services can lead to more clearly defining the behaviors needed/wanted from existing and future IBRs.

V. Conclusions

This paper examines some of the grid services that may be needed from IBR devices, either existing or new, especially in IBR-dominated networks, considering the network performance in response to contingencies/disturbances such as trips of synchronous generators. It is observed that the grid services required by the network may vary depending on the contingency. These services can either be provided by a single/few new "future" IBRs with advanced capabilities or through a combination of such new IBR with additional services from existing IBRs, and the existing IBRs can share the burden of providing these services to a certain extent. Further, the paper provides insight into the impact that assumptions and control tuning may have on the network response. It hopefully allows a reader to go beyond a reasoning of 'voltage source' behavior.

The approach presented here can be extended to include other factors such as the impact of IBR locations, the IBR services needed in different network conditions and topologies as well as different disturbances. Such an effort may provide a more holistic picture of the services from IBRs needed and may be useful to both IBR manufacturers/operators as well as network operators in the form of establishing the value added to the network by asking different services from new and existing IBRs.

Acknowledgment

The authors acknowledge the various feedback and comments received from the Energy Systems Integration Group (ESIG) Services Task Force.

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