A New Operation Paradigm for a Bulk Power System with Very High Levels of Inverter-Based Resources

Abstract

The changing resource mix of the bulk power system, particularly the increasing deployment of wind power and solar PV, has resulted in an increasing portion of the resource mix being asynchronously connected through inverters - 'Inverter Based Resources (IBRs)'. These resources behave differently than traditional synchronous resources, which has necessitated investigation into viable alternate control schemes for use during operation of the system. A major theme of alternate schemes proposed in research has been on ensuring that inverter-based resources conform to the operational norms and limits that are presently enforced. However, as a faster response can be obtained from IBRs, this white paper poses the question of whether there is a need to make IBRs conform to a slower operational paradigm which reflects synchronous machine operation. Or can the fast response characteristics of an IBR be leveraged to obtain superior frequency control? Several simulation results are included to support this new operational paradigm while additional open research questions are also noted.

I. THE SYSTEM TODAY

Since the early 1900s, with the proliferation of alternating current rotating generators and development and setup of electric grids, the electrical frequency in the network has nobly served as the pulse of the electric power system. Due to Newton's laws of physics, frequency has a natural relationship with the speed of the rotating machine and hence the mismatch between generation and load. As a result, the electrical frequency connects the speed of rotation of the generators to the power consumed by the loads. Thus, akin to noting the state of the human body by measurement of the pulse at either the neck, or wrist, or behind a knee, the state of today's electrical grid can be determined by measurement of the electrical frequency at any location on the grid.

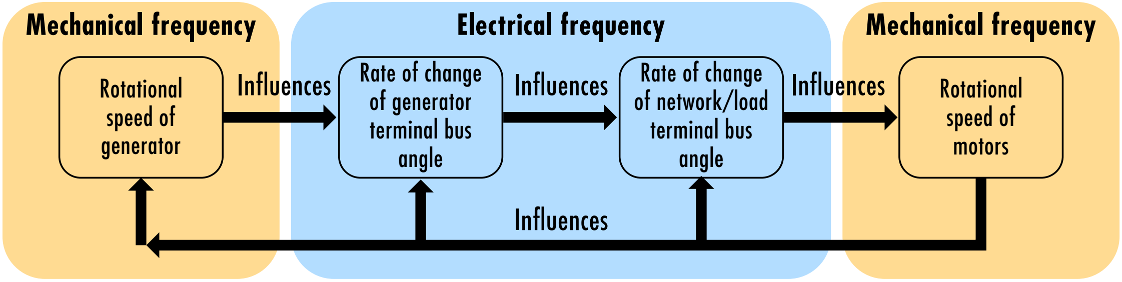

Figure 1. Intertwined relationship between behavior of generation sources and load due to frequency in today's power system

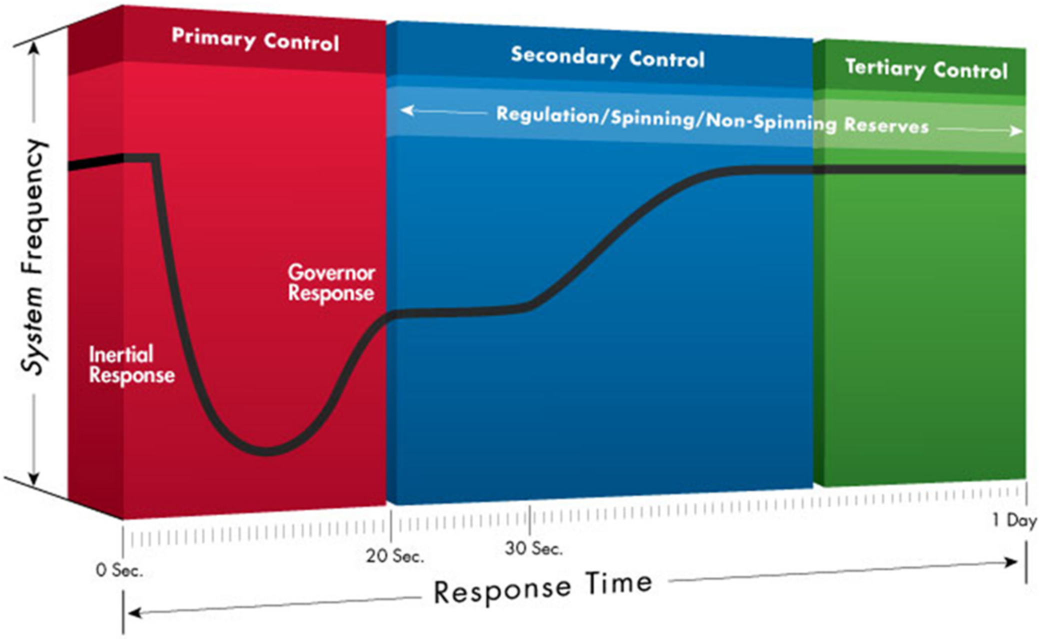

Figure 2. Trend of frequency response in today's power system for a generation trip (or load increase) event

Due to historical events in the bulk power system, where large deviations in frequency from the nominal value caused extensive mechanical damage to rotating synchronous generators, frequency typically is a major consideration for the reliable and secure operation of today's bulk power system. Following a disturbance in the network (like the loss of a generator), a decrease in frequency is intuitively related to the slowing down (or deceleration) of the rotating machines, which in turn leads to the conclusion of consumption being greater than supply, while a rise in frequency intuitively leads to the conclusion of supply being greater than consumption. In order to maintain machine speed of rotation within a safe operation band, deviation in rotor speed is used as a control input to initiate change in active power commands of participating generators and thereby bring about a balance of supply and demand. Although tight frequency control is desired, the heavy rotor mass of large synchronous machines in the bulk power system necessitates slow control of electrical frequency resulting in a frequency trend as shown in Figure 2 wherein the frequency first settles to an off-nominal value based on droop/governor control, followed by a slower recovery to nominal value through automatic generation control (AGC) (including both secondary and tertiary control).

The acceptable region of frequency deviation from nominal is governed by various system factors, chief among them being the durability of the turbine blades of the generator. In a synchronous machine, a significant energy buffer exists comprised of the kinetic energy stored in the rotating rotor mass as a function of speed of rotation, the potential energy stored as a function of the phase displacement between the rotor shaft and the rotating stator magnetic field, and the magnetic energy stored in the flux within the machine. Due to this energy buffer, the rate at which frequency (rotor speed) changes following a disturbance is reasonably slow in systems with a lot of synchronous machines and is thus considered to be representative of a stable system. The kinetic energy delivered from the rotor not only serves to minimize the generation and load imbalance but also allows for the slower governor controls to start acting. As a result, when a fast rate of change in frequency is observed, it is sometimes considered to be an indicator of system instability/separation.

The displacement of rotating machines (either due to retirement or as a result of market dispatch/schedule) brought upon by an increase in penetration of inverter-based resources (IBRs) in the power system has changed the nature of electrical frequency observed in the aftermath of a disturbance such as a change in load. As most of today's IBRs operate in a maximum power output mode (unless explicitly curtailed by the system operator) the profile of spinning reserve allocation within the network has changed. Now, a smaller number of rotating machines are called upon to individually provide more MW of response through increased governor action. However, due to the reduction in the number of online units, there is now a reduced amount of kinetic energy that can be injected into the network immediately upon occurrence of a disturbance. As governor control on a synchronous machine has an appreciable time constant, although a similar value of off-nominal settling frequency may be obtained, such an operational scenario can result in a lower value of frequency nadir (for an under frequency event) as the magnitude of the rotating energy buffer available in the system has reduced. This reduced energy buffer (colloquially referred to as a reduction in system inertia) results in a faster rate of change in frequency while also reducing the time duration within which governor controls may have to start acting, before frequency reaches the under frequency load shed threshold. While there are interim mitigation proposals that can be implemented [1], a longer-term solution might require a change in bulk power system operation practice regarding frequency control and response.

II. THE CHANGING SYSTEM

Many states and countries around the world have clean energy targets that could result in a power system which operates in certain periods with 100% of energy delivered through IBRs. In the United States, the Bonneville Power Administration (BPA) service area has several times experienced 100% wind generation at night; the ERCOT system had instances of 50% instantaneous penetration of wind; while the Southwest Power Pool (SPP) has also experienced a record generation of over 70% from IBRs at night. In Australia (Tasmania), the power system routinely experiences more than 70% instantaneous inverter-based generation [2]. In Ireland, the operators routinely accommodate up to 65% instantaneous non-synchronous generation as a percentage of total generation [2]. Here, although BPA and SPP have seen large percentages of wind power generation, they are also respectively interconnected as part of much large synchronous area. In contrast, systems like ERCOT and EirGrid are smaller networks that do not have synchronous connections with other networks. Due to this, the impact of large IBR percentage can be different in both these types of systems.

As the system moves towards 100% IBR penetration, whether for short periods of time, or over longer time frames, it is intuitive that the IBRs would also have to be responsive to power imbalances and contribute towards maintaining balance between generation and load. But in such a scenario frequency (the pulse of the system) may no longer hold the same meaning as it does today and can thus be lost as a natural control/communication variable. In IBRs, the source of energy is either stationary (solar and battery) or electrically isolated from the network by the inverter (Type 4 wind). A change in electrical frequency in the power network (due to any system event), would thus be decoupled from the source. In a 100% IBR power system, using coordinated control algorithms, it has been demonstrated that is possible to artificially mimic the operation of a synchronous machine power system and obtain a response as shown previously in Figure 2.

But is that the best way to tackle the challenge? Conceptually, it is the most convenient way as the operating paradigm of a large power system retains all its existing characteristics and performance metrics, while mainly requiring a change only from the source side. There are many research groups around the world working on development of inverter control solutions for an all inverter network. Some articles in literature, among others, are references [3] – [15]. All researched control schemes however appear to have a main theme with regard to the operation of the bulk power system wherein, the response to a generation or load event is assumed to require compliance with traditional frequency droop control such that upon the occurrence of a disturbance, the aim is to allow frequency to settle to an off-nominal value.

It is possible that this most convenient way is not the most efficient way, or it could even be a restrictive way, as it involves holding onto the past (i.e. keeping the characteristics and performance metrics of the system the same) and forcing a new technology to conform its behavior to a set of predefined rules. In trying to mold the performance behavior of inverters to provide well recognized responses to disturbance, one may be sub-consciously trying to keep the system characteristics the same, and only asking the inverter to adapt to the existing system. Such an operation paradigm could result in underutilization of the capabilities of the inverters [16].

Unlike a synchronous machine where the injection of current into the grid is linked to electrical frequency through physical properties, an IBR is a frequency independent device. As the bulk power system moves towards an all IBR system, this frequency independent operation could potentially allow for faster control. Electrical frequency could be just a short lived transient due to the change in angles brought about by fast injection of current. The bulk power system could thus potentially be operated at constant frequency even for large changes in generation and load balance as shown in Figure 3 for a 2 GW reduction in generation. Here, the most conservative rate of change of frequency (RoCoF) is -0.6 Hz/s, which is within acceptable limits for rotating machine load [17].

While, an all inverter system is still in the distant future for the power system, there are certain systems around the world that can soon reach 80% inverters for few hours of the day. In such a system, with synchronous machines still on-line, the juxtaposition of fast inverter controls to bring about a constant frequency operation along with slower synchronous machine control could be a legitimate cause for concern as it could result in a significant share of the power burden being borne by inverters while also possibly causing additional torsional stress on the rotor shaft of the machines. Additionally, being a global signal, electrical frequency has been used by operators as a pseudo communication signal to indicate mismatch in generation and load balance. In [18], the impact of fast inverter control schemes on the rate of change of speed on few remaining synchronous machines was investigated. It was observed that the impact on the rotor shaft of the remaining synchronous machines was lower than the impact observed during a bolted three phase fault. While this doesn't imply a generalization of the applicability or suitability of using fast inverter control methods to bring about constant frequency operation with the presence of synchronous machines, it does point towards the possibility of doing so, provided adequate studies are carried out.

III. THE ANGLE DROOP CONTROL

A constant frequency control scheme would invalidate the use of frequency as this global signal. If control of the system indeed moves towards constant frequency, what would be the mechanism of power sharing? A variable which is more representative of the electrical characteristics of an inverter dominated network is the voltage phase angle. By making use of this variable, sharing of power across IBRs could also be more directly linked to the power flow solution of the network through a concept which is similar to the concept of a distributed slack bus. When solving a distributed slack bus power flow problem, rather than allocating the power mismatch (generation - load) to a single slack generator, the mismatch is distributed among every generator in the system. The percentage of the mismatch allocated to each generator is proportional to the losses in the network [19] which is a function of bus voltage angle at the generator bus between two iterations of the power flow solution.

The key element in implementation of this method of power sharing is not to vary active power in proportion to change of angle difference across buses, but to vary active power in proportion to change in angle of the IBR *with respect to its previously held angle*. This would allow for electrical frequency to undergo fast transients (which may be alright in an inverter

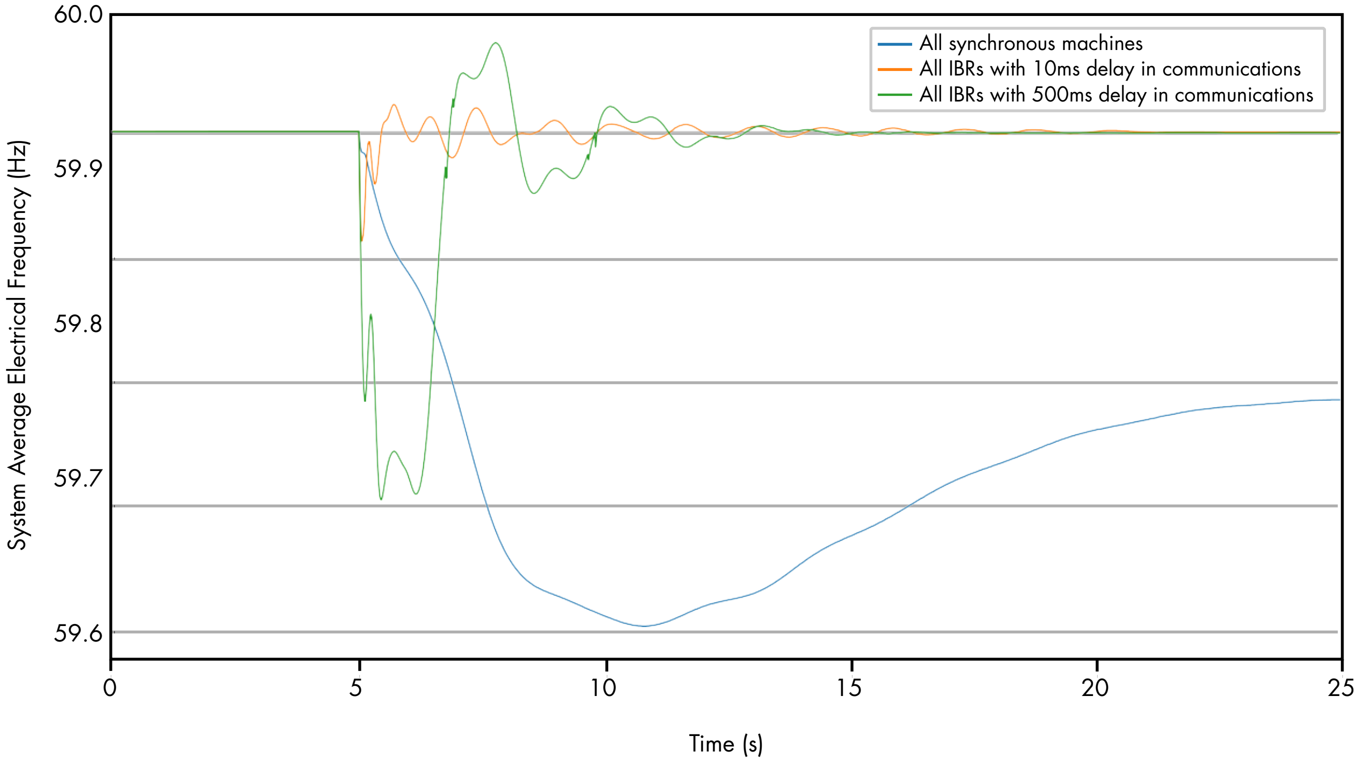

Figure 3. Comparison of frequency response in all-IBR system as compared to system with all synchronous machines for 2 GW generation trip

dominated network), subject to not activating unintentional islanding protection schemes. However, as frequency would essentially be at a constant value barring a transient of few seconds, conventional secondary control would also have to be modified to only include change in tie line power. In an islanded network, the inverter sources within the network would share the power burden based upon the deviation of the angle at their terminals. An example operation of this control to bring about sharing of power across inverters in two areas of a system both in the short term and long term is shown in Figure 4 for a 2 GW generation trip event in Area Here, Case 2 and Case 3 refer to two different forms of inverter models [18]. In the first 5 - 10 seconds after the generation trip, inverters in both Area 2 and Area 5 increase their power output to help support the system and bring the frequency back to nominal value of 60 Hz. This is due to the angle droop control algorithm. Due to Area 2 contributing towards supporting the loss of generation in Area 5, the flow of power across the tie lines between Area 2 and Area 5 deviates from its pre-disturbance value. Gradually as secondary controls become dominant the contribution from Area 2 reduces as Area 5 picks up the total share of the generation loss.

IV. CONCLUSION AND OPEN QUESTIONS

To conclude it is seen that the constant frequency control mode can bring the entire system electrical frequency back to the nominal value within a few seconds after the disturbance, even with the presence of synchronous machines. Additionally, sharing of power across inverters both in the short term, and across balancing areas in the long term is feasible. This validation is important in the context of constant frequency operation because in today's state of the art operation of the bulk power system, deviation in frequency plays a very important role in defining the sharing of power across energy sources both in the short term (primary frequency response) and in the long term (secondary frequency response). But by bringing about an operation at constant frequency, the deviation in frequency is made zero within few seconds of the disturbance. In such a scenario, whether inverter resources would share power across multiple areas is a valid concern and the angle droop scheme is able to provide a viable alternative.

Though it has been shown that this new operation paradigm is possible through leveraging the fast controls of an IBR, its applicability and importance to the bulk power system is yet to be fully assessed. A few open research questions that come to mind are:

1) Is such an operation paradigm needed and/or suitable for the bulk power system?
   - Traditionally, as the dynamics of the bulk power system has been dominated by slower moving machines, a fast

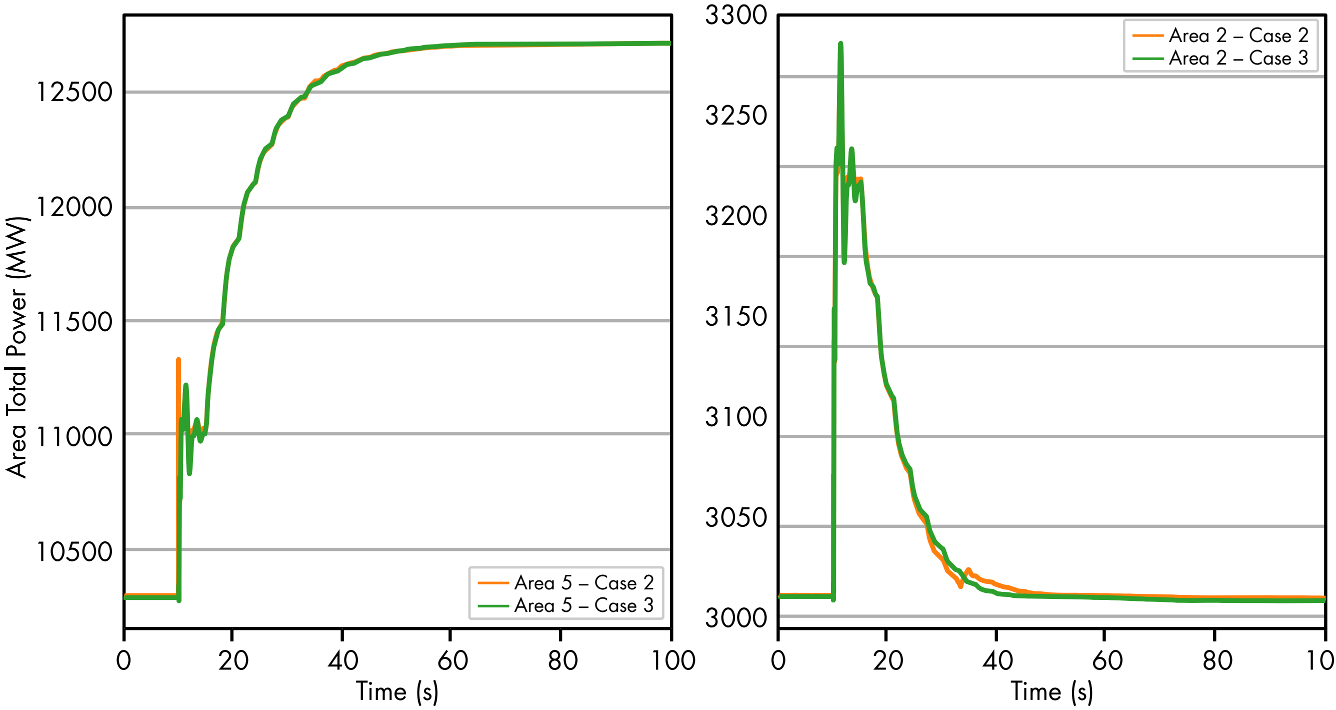

Figure 4. Active power sharing across two areas showing provision of long-term power support for 2 GW generation trip in Area 5

transient has inherently been linked to a reduction in stability of the system. However, with an increase in inverter-based resources, the dynamics of the system naturally becomes faster resulting in newer definitions for stability (and instability) [20]. In such a paradigm, the question of whether it would be prudent to leverage this fast-dynamic behavior to be advantageous to system operation is to be studied in future research.

2) Would there be an additional energy injection burden on IBRs to bring about a fast settlement of frequency?

   - Initial EPRI research [21] has shown that for a system with 85% of the load served by IBRs, for an approximately 5% increase in load, 10kWh of additional energy was required to bring about a constant frequency operation within a few seconds of the increase in load. However, the widespread application of this control for a large system with multiple resources trying to carry out a similar operational mode is to be further studied.

3) Would such an operational paradigm require a separate market solution?

   - In today's power system, although new IBRs are required to have the capability to provide droop response [22] they are not required to compulsorily maintain an energy headroom to provide under frequency response. Now in this new operational paradigm, the IBRs would have to provide sustained frequency response and there may need to be a market solution that brings about the maintenance of energy headroom in IBRs.

4) Will a system operator continue to have visibility of occurrence of a generation/load event?

   - System electrical frequency has been conventionally used as a universal metric across the system to signify changes in load/generation imbalance. Now if IBRs control frequency to the nominal value within few seconds of the disturbance, then it is possible that depending on the SCADA/EMS refresh rate, a system operator may not see a change in system frequency. In such a scenario, depending on the size of the disturbance, change in line flows might be a way for a system operator to obtain visibility of the event in the system which is to be studied.

5) Would this operation paradigm require a change in the methodology used to evaluate a balancing area's performance regarding NERC's Control Performance Standards (CPS)?

   - Frequency deviation, along with tie line deviation, make up the CPS metrics. However, with IBRs following this new control paradigm, frequency deviation would essentially become 0.0 in few seconds. The viability of using only tie line deviation in the evaluation of this metric is to be further studied.

These questions are topics presently being considered within EPRI's Program 173 on Bulk System Renewables and Distributed Energy Resource Integration and Program 39 on Transmission Operations.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA • 800.313.3774
• 650.855.2121 • askepri@epri.com • www.epri.com