Existing Methods for Grid Strength Assessment and Role of Hydropower in Future Grids

Pranav Sharma,[1] Vahan Gevorgian,[1] Shahil Shah,[1] Weihang Yan,[1] S M Shafiul Alam,[2] Yemi Ojo,[2] Bharat Vyakaranam,[3] Qin Chuan,[3] Yu Liu,[4] Yilu Liu,[4] Bin Wang,[5] and Bruno Leonardi[6]

1 National Renewable Energy Laboratory
2 Idaho National Laboratory
3 Pacific Northwest National Laboratory
4 Oak Ridge National Laboratory
5 ISO New England
6 New York Independent System Operator

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List of Acronyms

ARIES	Advanced Research on Integrated Energy Systems
BESS	battery energy storage system
CAISO	California Independent System Operator
EMT	electromagnetic transient
ESCR	effective short-circuit ratio
FRE	Fall River Electric
GFM	grid forming
Hy-DAT	Hydrological Dispatch and Analysis Tool
HYPERBOLE	HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies
IBR	inverter-based resource
IFP	Idaho Falls Power
NREL	National Renewable Energy Laboratory
POI	point of interconnection
PV	photovoltaic
SCR	short-circuit ratio
VAR	volt ampere reactive
WiRES	Wildfires Risk Evaluation of the System
WSCR	weighted short-circuit ratio

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1 Introduction

Power systems are undergoing a rapid evolution with increasing penetrations of inverter-based resources (IBRs), large loads, microgrids, and power electronic devices. Ensuring reliable and stable operation of the modern power grid is a multifaceted challenge that requires a detailed understanding of these complex systems. Dynamic stability is a major concern in maintaining the security of power grids as the generation mix and large loads transition to include high shares of power electronic devices. The grid is dynamically stable if it can maintain a normal operating state after being subjected to small or continuous disturbances, such as changes in load or generation. In a stable system, the main system state variables—frequency and voltage—oscillate around their scheduled values and quickly return to a stable state after a disturbance [1], [2].

The operation of IBRs in regions with low system strength and higher grid impedances [3] has been found to be the main reason behind many of the power system instabilities that manifest in various types of oscillations and interactions that, if not properly addressed and damped, can jeopardize the reliable operation of power systems [4]. Weak grid conditions compound such stability problems, particularly when many IBRs operate in proximity to and connect to weak power grids [5], [6]; therefore, it is important to assess grid strength for the planning, integration, and operation of IBRs for a given power system.

In this report, we aim to understand and classify existing methodologies for grid strength assessment along with their limitations and future needs. Further, we aim to use the huge untapped potential in hydro energy resources to address some of the pertinent challenges of grid strength and reliable operation in modern power systems. Historically, hydropower has been valued for its flexibility and dispatchability, yet it faces new constraints due to the reduced share of synchronous machines in the generation mix and the variability of the decreasing available water resources. Still, these plants present untapped potential beyond energy generation—notably, as providers of critical grid services. This report explores how hydropower plants, particularly through operation as synchronous condensers, can play a pivotal role in strengthening the grid amid evolving system dynamics to improve system resilience.

2 Existing Methods for Grid Strength Assessment

Power systems are inherently complex nonlinear dynamical systems in which millions of components (small and large) behave and interact through their dynamic characteristics. For the power systems to provide the required power to the loads, they need to operate in a stable manner across both temporal and spatial scales. Power system stability is defined as the ability of the grid to maintain operating equilibrium after being subjected to disturbances [1], [2]. Although this definition might seem broad, this essentially informs the desired behavior of a stable grid. Instabilities, on the other hand, are studied and classified based on the physical parameters that undergo perturbation—namely, rotor angle stability, voltage stability, and frequency stability. The increasing penetrations of IBRs introduces complex dynamics, and their interactions with the rest of the grid can cause various oscillations and instabilities. To accommodate this evolution of power systems in recent decades, a new category of converter-driven instabilities is being added to the broad categories of power system stability classification [1].

IBRs have fast switching controls, and those dynamics can interact with the fast dynamics of the transmission network, the stator dynamics of synchronous machines, and other power electronic-based devices. If they are not properly tuned, these interactions can often lead to high-frequency oscillations and resonance issues [7], [8], [9]. Along with this, the slower controls of IBRs can interact with the electromechanical dynamics of the grid, which can lead to system instabilities. For example, outer control loops for voltage or power and phase-locked loop control can lead to low-frequency oscillations in a grid with high penetrations of IBRs. System strength at the point of interconnection (POI) of the IBRs has a significant influence on the stability of low-frequency oscillations. A weak grid at the POI can often interact with the dynamics of the IBRs, leading to various oscillations. System strength at a point in a gird can be understood as the ability of the grid to support perturbations at that point—one way system strength can be quantified is in terms of the available fault current at that specific location on the grid. Although there is an intuitive understanding of system strength and weak grid conditions, there is not a universal way to quantify grid strength. In this section, we further detail various methods for grid strength characterization along with their limitations.

2.1 Steady-State Grid Strength Characterization

2.1.1 Short-Circuit Ratio

Grid strength measures the ability of a power grid to sustain a fault on a given bus and thus recover from such events. Grid strength is measured in terms of the available short-circuit current or short-circuit power (MVA) at a given bus. As increasingly more IBRs are integrated into the power grid, it is necessary to ensure that there is sufficient grid strength available at the IBR-connected buses, known as POI buses. One way to quantify grid strength is to use the short-circuit ratio (SCR) for the IBRs at their POIs. Although the SCR metric is ideally suited for a single IBR linking to the larger power system, it still serves as a useful preliminary measure in the context of a long-term integration study for wind and other converter-based resources [10].

The SCR metric is traditionally used to represent the bus voltage stiffness in a grid. The stiffness of the grid refers to its ability to maintain stable voltage during load fluctuations. Absolute stiffness would mean that there is no voltage change at any load variation, which can be achieved only if the load is connected to an ideal voltage source [6]. The SCR metric is well defined and can be uniquely calculated for power grids with a single POI of IBRs. In this case, the SCR is the ratio between the short-circuit MVA at this POI and the total megawatt capacity of the connected IBR:

$$SCR = \frac{Available\ Short\text{-}circuit\ power(MVA) at\ the\ POI}{IBR'injection\ limit\ (MW) at\ the\ POI} = \frac{SCMVA_i}{P_{MW_i}} \quad (1)$$

If the SCR is higher, then there is a stronger grid condition at this POI such that the grid is more capable of withstanding and recovering from short circuits or faults. In contrast, a lower system strength condition implies that the connected IBRs might be more likely to exacerbate perturbations and disturbances, resulting in oscillatory instabilities and/or maloperation of protection relays [8]. In general, there is no unique, clear threshold for SCR to distinguish a weak grid condition from a strong grid condition. A general rule of thumb is to classify a grid to be weak if SCR <3 and strong if SCR >5. Note that an SCR <3 does not necessarily mean system will be unstable; a power grid having several POIs with SCRs <3 can still be stable. Still, thanks to its simplicity, SCR can be used as a screening tool to identify the most vulnerable locations in a grid. A low SCR indicates that more detailed studies, such as electromagnetic transient (EMT) simulations and frequency scan analysis [11], [12], would be needed to further investigate the system dynamic performance.

Note, however, that the SCR is not an ideal metric for quantifying grid strength because it depends on the grid impedance response only at the single frequency, and it does not consider system characteristics at other frequencies. It is possible that an IBR might become unstable even when the SCR level at its POI is higher than what is required for stability if the grid impedance response at other frequencies is not compatible with the impedance response of the IBR. Although such nuances are not captured by short-circuit-capacity-based grid strength metrics, they are still useful as a screening tool and for quantifying the improvement needed in grid strength.

2.1.1.1 Effective Short-Circuit Ratio

IBRs are often installed with large shunt capacitor banks to provide the necessary reactive power support, especially when they are located remotely from the bulk power grid; however, this capacitor compensation increases the short-circuit impedance of the system, thereby reducing its short-circuit capacity. For such systems, the effective short-circuit ratio (ESCR) is defined as:

$$ESCR = \frac{SCMVA_i - C_i}{P_{MW_i}} \quad (2)$$

where $SCMVA_i$ is the short-circuit capacity (in MVA) at the i^{th} POI, P_{MW_i} is the real power (in megawatts) rating of the IBR, and C_i is the capacitive compensation capacity (in MVAR) at the same POI.

2.1.1.2 Weighted Short-Circuit Ratio

The SCR matric is suitable to capture the grid strength for a single POI in the system; however, when considering the integration of multiple IBRs, the SCR matrix cannot capture the interaction of IBRs with each other. Further, the available short-circuit capacity is often shared between neighboring IBRs, and thus the SCR can overestimate the system strength for individual POIs.

For this purpose, a weighted short-circuit ratio (WSCR) is used for collectively identifying the available short-circuit MVA for a pool of POIs [13]. The WSCR is computed as follows:

$$WSCR = \frac{\sum_i^N SCMVA_i \times P_{MW_i}}{\left(\sum_i^N P_{MW_i}\right)^2} \qquad (3)$$

Here, N is the number of POIs that are clustered together for analysis. This is equivalent to considering that all IBRs are connected at one bus. The WSCR provides an excessively conservative estimate of system strength. This method is highly useful for studying highly concentrated IBR POIs, but it provides limited information for system strength.

2.1.1.3 Short-Circuit Ratio With Interaction Factors

To address the shortcomings of the SCR and WSCR, a more practical measure is considered, called the short-circuit ratio with interaction factors (SCRIF). While the WSCR assumes full interaction between IBRs, and the SCR assumes no interaction between IBRs, the SCRIF considers the electrical distance and sensitivity of the POIs to quantify their interactions. The SCRIF for a given POI is computed as:

$$SCRIF_i = \frac{SCMVA_i}{P_{MW_i} + \sum_{j \neq i}^N (IF_{ij} \times P_{MW_j})} \qquad (4)$$

where IF_{ij} is the voltage sensitivity of the i^{th} POI with respect to the voltage change at the j^{th} POI. IF_{ij} is computed as:

$$IF_{ij} = \frac{\Delta V_i}{\Delta V_j} \qquad (5)$$

where the voltage change is computed for the injection of fixed MVA power at bus j, thus providing a practical limit of system strength when multiple POIs are studied in a grid.

Similar to the SCRIF, a few other variations are developed—such as the site-dependent SCR [14], the generalized SCR [15], and the generalized operational SCR [16]—where the core idea remains the same, but the mutual interaction of the IBRs is accounted for through various sensitivity indices. SCR and its variations are widely used in planning studies when considering the location and sizing of IBRs in a grid. These methods only require a steady-state power flow model of the grid to compute the short-circuit capacity at the POIs. One major limitation of quantifying grid strength using the SCR is that it only accounts for the grid behavior at a single frequency and not at other frequencies. Although those characteristics are generally true and predictable for conventional generation resources, IBRs have highly nonlinear and complex dynamics, and thus one cannot often accurately generalize the characteristics of an IBR based solely on the response at a single frequency.

2.2 Time-Domain Characterization of Grid Strength

2.2.1 Q/V Sensitivity

SCR-based metrics are typically calculated using nominal voltage. Nevertheless, a higher operating voltage results in a higher active power transfer within the voltage stability limits [17], [18]. Further, the impact of various flexible AC transmission system devices and synchronous condensers on system strength is not always well described by SCR-based methods. But such devices can introduce a meaningful improvement in system strength, and they are common solutions applied in industry. Also, on-load tap changer operations are ignored, which affects the voltage stability threshold and power transfer limits. For this purpose, we look at the sensitivity of the voltage at POIs with respect to the reactive power injection. This method addresses some of the aforementioned challenges by calculating the voltage sensitivity, $\partial Q/\partial |V|$, as a system strength metric. For low active power with no load, $\partial Q/\partial |V| \approx$ SCR, while $\partial Q/\partial |V| = 0$ indicates the voltage stability limit. Similar effects can be seen for varying X/R ratios and operating voltages. These important differences are not always captured by the SCR-based methods presented here. Further, $\partial Q/\partial |V|$ curves can offer continuous and more intuitive quantification of system strength than SCR. Nonetheless, although $\partial Q/\partial |V|$ addresses several challenges presented, it is derived for a single IBR POI.

2.3 Frequency-Domain Characterization

SCR and its variations can only capture the grid characteristics at the fundamental frequency. Due to the complex dynamic characteristics of the controls of IBRs, it is crucial to understand their impedance characteristics across frequency ranges because a seemingly strong grid could interact with IBR dynamics at different frequencies, causing resonance and spurious oscillations.

2.3.1 Impedance Scans

The impedance responses required for stability analysis can be obtained by performing either real measurements or a frequency sweep on EMT simulation models. Model-based impedance estimation, however, is possible only when high-fidelity, black-box, “real-code” EMT models are provided by vendors. Moreover, depending on how the vendor-supplied EMT models are validated, the impedance responses obtained using such models might not be accurate at all frequencies; hence, impedance measurement is an important grid integration test to understand the dynamic stability characteristics of IBRs and to validate EMT models over a broad frequency range. Impedance measurements can also be used for real-time stability monitoring and for the adaptive control of IBRs during changing grid and operation conditions. Frequency scans can be obtained by injecting small voltage or current perturbations in different domains (d-q or sequence) using EMT or dynamic models of IBRs and then measuring and quantifying the responses in the form of impedances [11], [12].

We explain the frequency scan process here by using the example in the d-q domain. Small dq-axis perturbations in voltage (ΔV_d, ΔV_q) and current (ΔI_d, ΔI_q) are linked by the dq-frame impedance matrix, $\mathbf{Z}_{dq}$, of the generator or inverter as follows:

$$\begin{bmatrix} \Delta V_d \\ \Delta V_q \end{bmatrix} = \mathbf{Z}_{dq} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} = \begin{bmatrix} Z_{dd} & Z_{dq} \\ Z_{qd} & Z_{qq} \end{bmatrix} \begin{bmatrix} \Delta I_d \\ \Delta I_q \end{bmatrix} \quad (6)$$

where Z_{dd} and Z_{qq} represent the impedances in the d- and q-axis, respectively; and Z_{dq} and Z_{qd} represent the cross-coupling impedances between both axes. Depending on the inverter mode of operation (grid following or grid forming [GFM]), Eq. (6) can be presented using the admittance matrix as well. The same equation can also be easily represented in the sequence domain.

The impedance model of the generator or inverter represents all components of the unit, including the physical circuit components and the control system. For example, the impedance response over a broad frequency range of a hydropower plant captures its characteristics from the grid perspective over different timescales. The impedance response is shaped by both the generator machines in the hydropower plant as well as the control system components, such as plant governors, the automatic voltage regulator system, and the power plant controller. These components shape the impedance characteristics in different frequency ranges depending on their control bandwidths. An ideal voltage source, which represents absolute stiffness for grid strength, has zero internal impedance; hence, the impedance response of a hydropower plant can be used to quantify its voltage stiffness or its contribution to the grid strength.

The purpose of impedance-based analysis is to obtain the elements of $\mathbf{Z}_{dq}$ either analytically or by measurements. Obtaining an analytical impedance model is often not possible because it requires access to the full detailed model and configuration settings of the unit. Such vendor information is normally not available. The models are normally provided in the form of a black-box model, so modelers have no access to the internal structure of the model; therefore, the measurement-based method is a common approach in stability studies for IBR-based systems. The measurement-based approach can be implemented in EMT models by conducting numerical experiments or by lab experiments using real hardware. The National Renewable Energy Laboratory (NREL) developed the capability to evaluate impedances using PSCAD models of the inverters and real measurements using multimegawatt testing capabilities at NREL's Advanced Research on Integrated Energy Systems (ARIES) facility [19].

To evaluate the impedance of the inverter using EMT simulations, small perturbations in voltage or current can be injected into the POI. Then the response of the system in the form of d-q or sequence current and voltage can be measured and applied for impedance identification. In actively controlled devices, such as generators or inverters, the presence of coupling between quantities in the d- and q-axis can lead to inaccurate impedance evaluations because the perturbation injected in one axis can cause a response in the opposite axis. This, in turn, could lead to inaccurate stability analysis using the Nyquist criterion. To avoid such a coupling influence, a technique using two uncorrelated perturbations can be implemented. Two uncorrelated perturbations are sequentially injected into the system, forming a set of four equations, and allowing the calculation of an impedance matrix that is combined as follows:

$$\begin{bmatrix} Z_{dd} & Z_{dq} \\ Z_{qd} & Z_{qq} \end{bmatrix} = \begin{bmatrix} V_{d1} & V_{d2} \\ V_{q1} & V_{q2} \end{bmatrix} \begin{bmatrix} I_{d1} & I_{d2} \\ I_{q1} & I_{q2} \end{bmatrix}^{-1} \quad (7)$$

where V_{d1}, V_{q1} and I_{d1}, I_{q1} are the d-q voltages and currents measured during perturbation 1; and V_{d2}, V_{q2} and I_{d2}, I_{q2} are the d-q voltages and currents measured during perturbation 2. Perturbations 1 and 2 are linearly independent. The first perturbation signal is generated in the d-axis, and a perturbation signal in the q-axis is set to 0. The second perturbation signal is generated in the q-axis, and a signal in the d-axis is set to 0. This way, the individual components of the impedance matrix can be calculated from (7) using simple matrix transformations. Figure 1 shows examples of the NREL-measured d-q admittance (left) and sequence admittance (right) for a utility-scale wind turbine generator. Similar characteristics have been measured for photovoltaic (PV) and battery energy storage system (BESS) inverters as well.

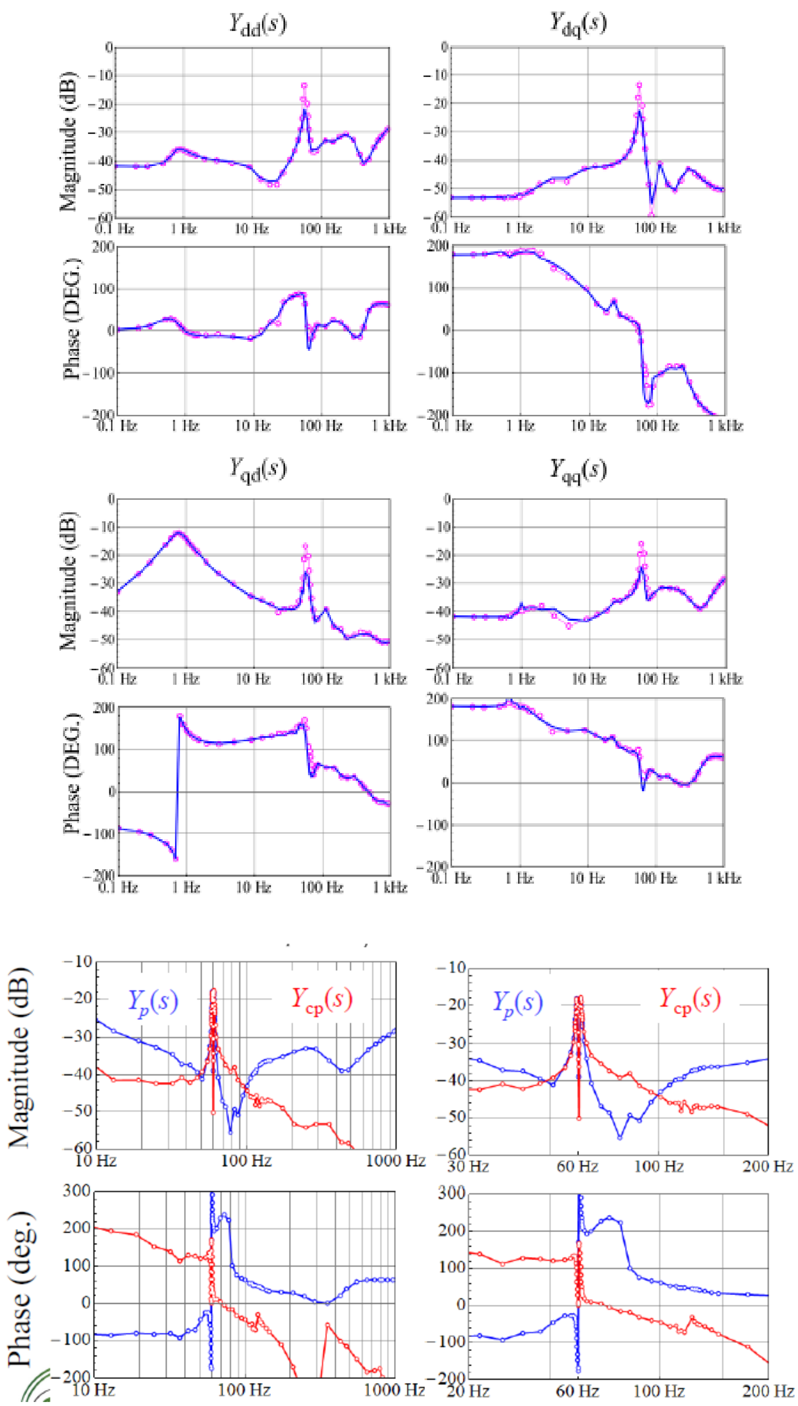


Figure 1. Examples of d-q and sequence admittance measurements for a utility-scale wind turbine

2.4 Grid Strength Assessment for Various Applications

So far, we have looked at various methods that are in practice for grid strength assessment. Their uses and applicability vary based on the actual need. For example, with all its limitations, the SCR is a suitable index for grid strength assessment for generation expansion planning, where the exact details of the IBR dynamics are not yet determined. On the contrary, while investigating the root cause of spurious oscillations in an IBR-dominant grid, we need detailed dynamic models and frequency-domain scans to determine the exact cause, the participating IBRs, and mitigation strategies. Table 1 summarizes the uses and needs for the described grid strength assessment approaches.

Table 1. Summary of Existing Grid Strength Assessment Methodologies

Methodology	Model and Data Requirements	Uses	Limitations
SCR (and variations)	Steady-state power flow model with accurate source impedance for various components	• Suitable for generation and transmission planning studies • Suitable for determining the need for additional resources, such as synchronous condensers or GFM batteries • Suitable as a preliminary check for deployment and integration studies where actual IBR models are finalized.	Only captures grid strength characteristics at a single frequency
Q/V sensitivity index	Dynamic models for the system (positive-sequence models are sufficient)	• Suitable for determining the impact of different system components and operating conditions on system strength • Provides empirical indicator for voltage stability with changing operating conditions and actions of flexible AC transmission system devices and on-load tap changers • Helps quantify reactive power reserve requirements.	Cannot capture nonlinear characteristics of IBRs
Impedance scan	Detailed EMT model of converters and grid	• Most accurate representation of grid strength in IBR-dominant systems • Suitable for identifying subsynchronous or high-frequency oscillatory modes • Suitable for deployment studies when converter models, control capabilities, and grid requirements are defined • Suitable for post-event analysis for identifying root-cause and mitigation strategies for converter-driven instabilities.	Computationally intensive and requires detailed EMT models for grid

Note that this report focuses specifically on grid strength assessment methods. Although there is a plentitude of methods for stability characterization that can describe the overall system stability characteristics (such as selective modal analysis/eigenvalue analysis), grid strength characterization aims to quantify the interactions of IBRs with the bulk system.

2.5 Path for a Comprehensive Stability Analysis

As power systems evolve with increasing integrations of IBRs, traditional methods for assessing grid strength and stability are becoming inadequate. The common SCR metric is often used to screen for weak grid conditions. Although SCR can provide a first-order indication of potential issues, it is inherently limited in its ability to capture the complex, frequency-dependent dynamics introduced by IBRs. In systems with high IBR penetrations, stability challenges often stem from interactions across a wide frequency range, including subsynchronous, harmonic, and high-frequency control-driven phenomena. These effects are not fully represented in traditional positive-sequence power flow models or dynamic studies based on synchronous machine assumptions. As a result, conventional tools might underestimate or mischaracterize the true stability risks present in modern grids. Moreover, the lack of standardized, multidimensional metrics that combine transmission capacity, voltage and frequency support capabilities, impedance characteristics, and transient stability limits hinders comprehensive assessments at both the local (POI) and system-wide levels. Current practices rarely incorporate geographic diversity, network topology, or the impact of planned interconnection upgrades into strength assessments. There is a clear need for a more integrated approach to grid strength and stability evaluation that considers the:

- Full range of system dynamics from DC to several kilohertz
- Complex coupling between different devices and control systems
- Variability across dispatch scenarios and network conditions
- Visualization and interpretability of system-wide stability metrics.

Such an approach is essential for ensuring reliable grid operation, informed planning, and the efficient interconnection of new resources in the evolving energy landscape. One challenge the current grid faces is to optimally use the existing generator mix for the reliable and stable operation of the grid. In this regard, hydropower has been a go-to resource. In the next section, we discuss the uses of hydropower resources to address the increasing challenges in the grid.

3 Role of Hydropower in Future Grids

Hydropower plants can support more variable IBRs in power grids, such as enabling stable operation by ramping up generation to balance load-generation deficits. But limited water availability caused by hydrological changes, strict regulations on water storage, turbine release for fish support, downstream impacts, and water quality issues can hinder this potential [20]–[22]. These and other drivers have reduced the U.S. hydropower capacity factor by 23% since 1980, indicating a decrease in hydropower generation [23].

Meanwhile, new markets are emerging for hydropower plants to operate below capacity. Although they are meant for providing ramp-up services [23], these markets can be adapted for hydropower plants to serve as synchronous condensers. This allows these plants to operate below capacity while increasing the inertia and SCR at coupling points. By adjusting the excitation levels, they can generate or absorb reactive power to stabilize the grid voltage and reduce sensitivity to voltage-reactive power variations. Operating as synchronous condensers also prevents hydropower plants idleness because it does not require water flow as in generation mode. This capability can increase the grid strength and enhance stability in networks with large shares of IBRs; therefore, hydropower plants have a significant role to play in strengthening future grids.

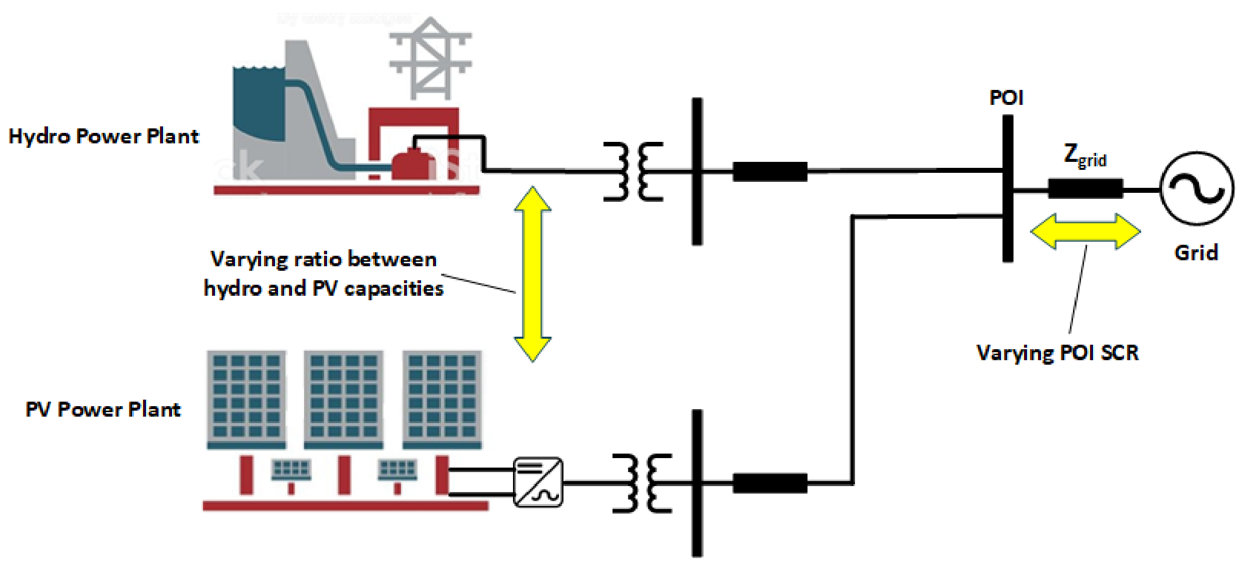


Figure 2. Hydropower and solar PV plant gird interconnection at various capacities and grid strength levels

We demonstrate the importance of hydropower-based generation on the overall grid stability and the performance of IBRs. As shown in Figure 2, we analyze the performance of a PV plant connected in the vicinity of a hydropower plant; the performance of the PV power plant and the overall grid stability is analyzed with respect to the proportion of PV/hydro generation capacity. As shown in Figure 3, a PV plant of 100 MW alone requires an $SCR \geq 2.5$ to maintain the voltage limits, whereas a hydropower plant connected alongside the PV plant can maintain the voltage limits for an SCR of up to 1.75. Similarly, Figure 4, shows the POI voltage with respect to the proportion of PV to a hydro generator connected at the POI. We can deduce that a hydropower plant can improve the overall system stability and viability of operation for grids with high IBR penetrations.

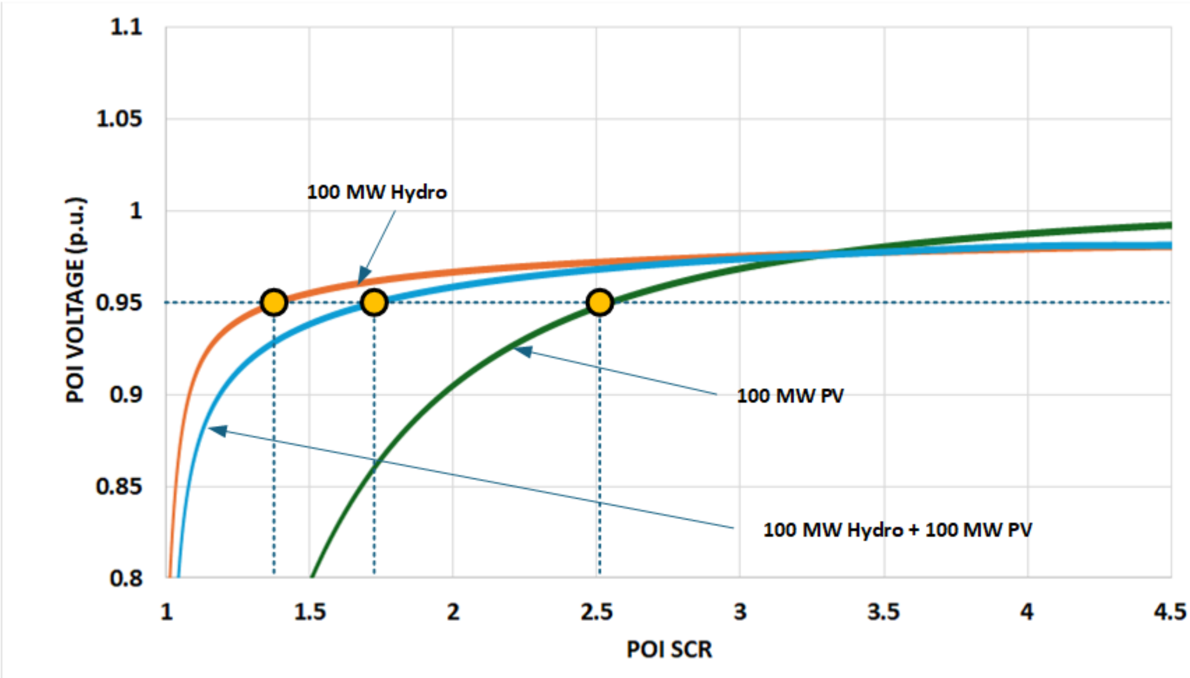


Figure 3. Impact of POI SCR on steady-state voltage for a 100-MW hydropower plant, a 100-MW PV power plant, and a combined hydropower-PV plant operation.

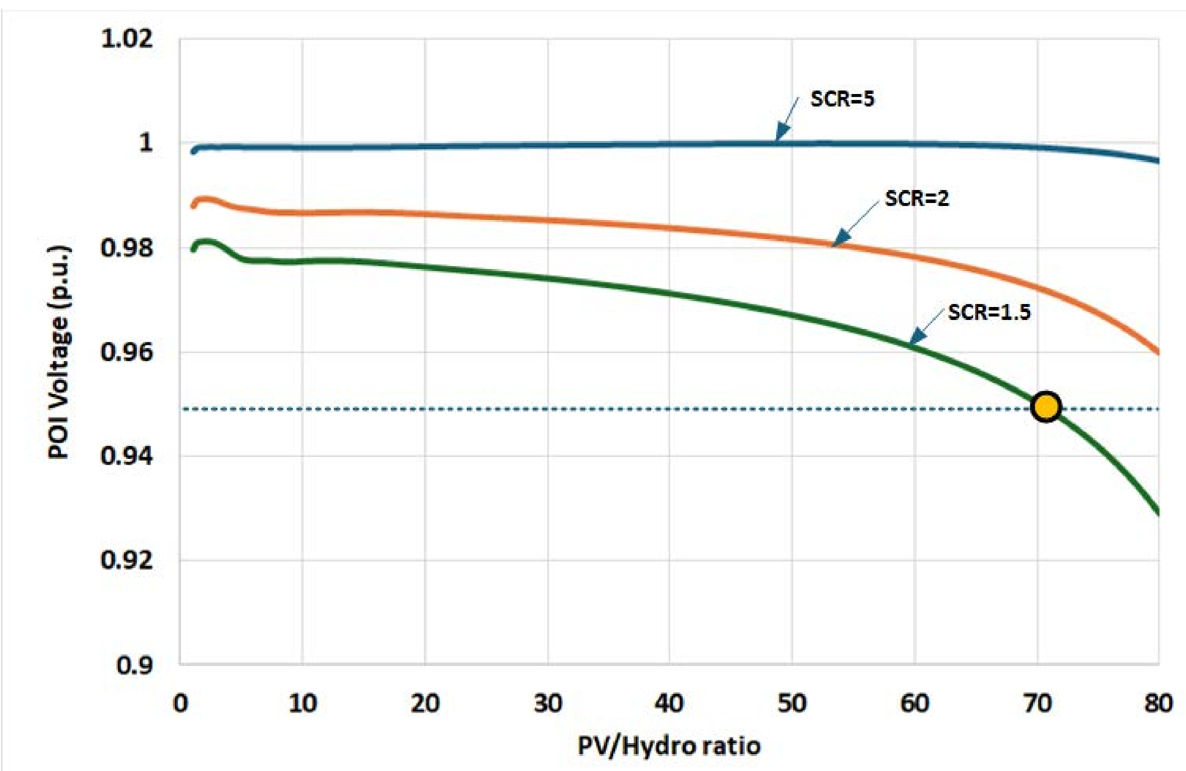


Figure 4. POI voltage at different ratios between PV and hydropower and different SCRs

In this simple study, we considered hydropower as a simple generation source; however, it could happen that hydropower cannot provide active power to the grid due to resource constraints. In such a scenario, we can use the same generator resource to support the grid as a synchronous condenser. The use of hydropower plants as synchronous condensers is gaining attention. The Australian Energy Market Operator explores using hydro generators as synchronous condensers to boost grid strength and meet inertia needs [24]. Recent studies, such as the HYdropower plants PERformance and flexiBle Operation towards Lean integration of new renewable Energies (HYPERBOLE) Consortium, have developed ways to predict and assess the behavior of hydropower plants operating as synchronous condensers outside normal operating regions [25]. The phenomenon affecting hydro operation as a synchronous condenser has also been demonstrated [26].

Hydro generators have advantages over other technologies used as synchronous condensers. Converting these plants to synchronous condensers is relatively simple, and their full inertia can be retained [24]. Also, the lead time for retrofitting these plants is much less than those of gas and steam turbines and the time needed to implement new synchronous condensers [24]. Various aspects associated with using hydropower plants as synchronous condensers are discussed as follows.

3.1 Operating Vertical Hydropower Plants as Synchronous Condensers

Operating horizontal generating plants such as gas and steam turbines as synchronous condensers usually involves decoupling the synchronous generators from the turbines and using synchronous or induction motors to accelerate the generators to a speed that permits synchronization with the grid [27]. In contrast, vertical hydropower plants, such as those using Francis turbines, often require switching from generating mode to synchronous condenser mode and vice versa without stopping the plant and decoupling the synchronous generators from the turbines [28]. This helps to maintain the plant at a speed that facilitates synchronization to the grid. Additionally, it helps to retain the plants' full inertia, as opposed to gas and steam turbines whose inertia is reduced due to de-blading during synchronous condenser operations [24].

Operating vertical hydropower units, such as Francis turbine, as synchronous condensers involve rotating the units in dewatered conditions [26], [29]. This requires that the turbine guide vanes are closed and pressurized air is injected into the draft tube to keep the water level below the runner. This allows the runner to spin in air, reducing friction losses and active power consumed because the units operate as motors. It also mitigates torque swings and power oscillations that can occur when switching from generating mode to synchronous condenser mode and vice versa. Water is injected into the turbine labyrinth seal for cooling purposes, and a recycling pipe is required to drain the cooling water flowing from the runner to the spiral case. Sensors and monitoring devices can be installed to monitor the mechanical stress and pressure in the draft so that the tail water is maintained below the runner [26], [29]. Retrofitting existing hydropower plants to operate as synchronous condensers would require installing air compressors; creating air and recycling ducts in draft tubes to allow air injection and cooling water removal, respectively; and installing sensors for pressure and stress monitoring to prevent strain and damage of hydraulic units. As deemed fit by the operator, the plant can be retrofitted to operate temporarily or permanently as synchronous condensers, or even for a more versatile functionality that allows the plants to switch between generating mode and synchronous condenser mode as the need arises.

Switching between generating mode and synchronous condenser mode can take a few minutes (e.g., 3 minutes [28]), though this varies based on the ability to rapidly adjust and close the guide vanes, pump in pressurized air, and adjust the generator excitation levels. Mechanical stress and vibrations are greater when switching from generating modes to synchronous condenser mode, with pressure mostly experienced at the pressure side of the blade and near the crown [28]. Before switching to synchronous condenser modes, high-pressure fluctuations might be experienced due to the plant operating at a low load (e.g., 6% of the rated power [28]), but these are eliminated once the guide vanes are closed and pressurized air is injected.

3.2 Thermal Aspect of Operating Hydropower Plants as Synchronous Condensers

Hydropower plants might need to operate outside normal operating points to provide voltage support to the grid. During faults and grid energization they can temporarily provide extra reactive power support without damage referred to as boosting mode operation. To facilitate this, the plants' thermal behavior must be known, which can be studied using capability diagrams. This maps the rotor and stator copper thermal limits at specified active power levels and their impacts on the plants' thermal behavior over time [25]. In the boosting mode, the stator copper losses dominate the first 5 minutes, while the rotor copper losses affect the remainder of the transient (i.e., 5–15 minutes) and steady state [25].

Consequently, the rotor copper losses restrict the steady-state operation of the plant due to the lack of further cooling. These losses can be mitigated if the terminal voltage is reduced during boosting operations; however, this introduces limitations due to the stator copper losses. The thermal resilience of the plant can be enhanced through upgrades of the cooling system, generation insulation classes, ventilation systems, and winding layouts. For example, the boosting mode can be enhanced by upgrading the generator insulation to Class H [25].

3.3 Maintenance of Hydropower Plants as Synchronous Condensers

It is essential to consider maintenance aspects when operating hydropower plants as synchronous condensers. Proper maintenance helps to mitigate losses and maintain or enhance the plants' performance. Key considerations include:

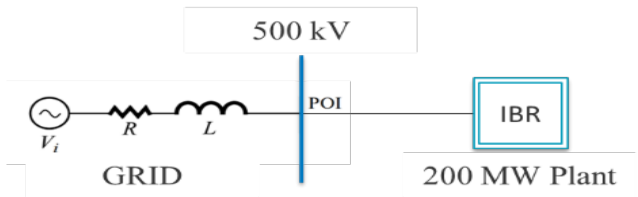
- Regularly inspect excitation and control systems.
- Regularly inspect shaft, turbine parts, and seals to identify the onset of wear, corrosion, or damage.
- Regularly lubricate bearings, seals, and other hydraulic parts to reduce friction and wear.
- Ensure adequate cooling of the rotor, stator, and turbine parts.
- Monitor turbine vibration levels, temperature, and noise to detect abnormalities.
- Maintain shaft alignment to mitigate mechanical stresses and strains.
- Automate functions such as dewatering, cooling, excitation, and protection to reduce operations and maintenance costs.

4 Case Studies and Use Cases

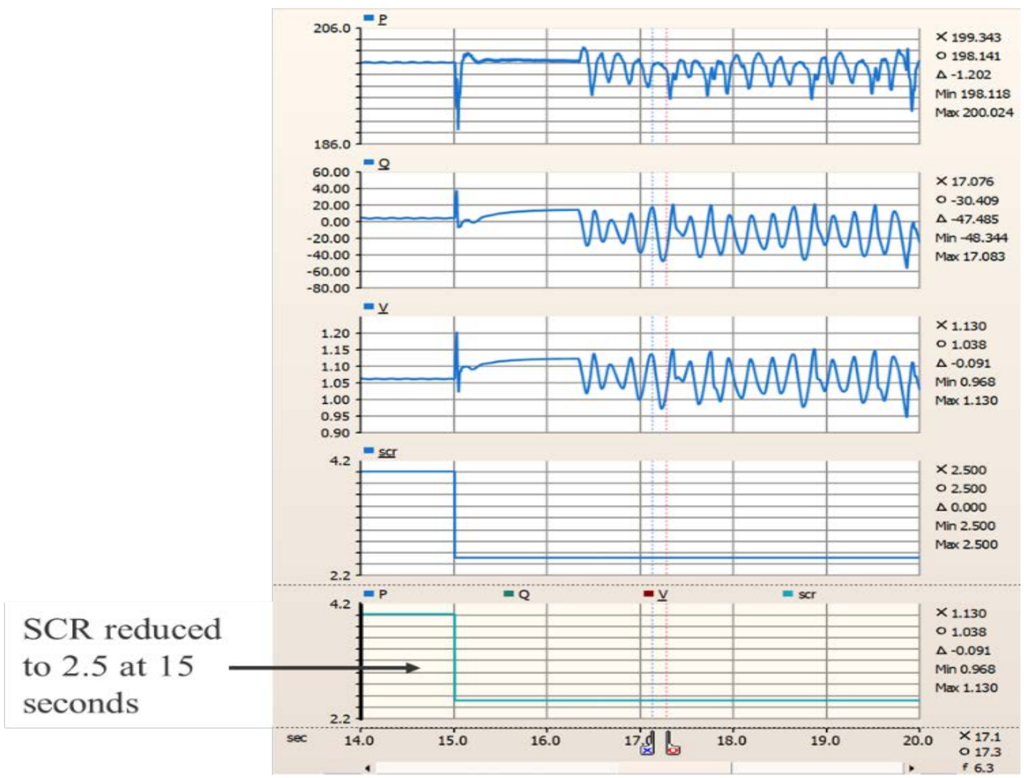
In this section, we detail some of the recent experiences with grid stability challenges associated with grids with high penetrations of IBRs, and we describe some case studies associated with the use of hydropower generators for additional grid support.

4.1 Weak Grid Stability of a Renewable Energy Plant

This case study demonstrates the sizing of a GFM plant, such as conventional synchronous hydro generators, for stabilizing a renewable energy plant under weak grid conditions.



(a)



(b)

Figure 5. Weak grid instability of a 200-MW renewable energy plant: (a) a 200-MW renewable energy plant connected to a single-machine infinite bus and (b) simulations showing the instability of the 200-MW plant when the grid SCR is reduced to 2.5.

Figure 5 shows the simulated response of a 200-MW renewable energy plant or IBR that becomes unstable when the grid strength at its terminal in terms of the SCR is reduced to less than 3. The simulations show that instability is triggered when the SCR of the grid is reduced from a higher value to 2.5. The objective of this study is to size a GFM resource so that the 200-MW renewable energy plant can be stabilized for grid SCRs of at least as low as 1.5.

IBRs are usually designed to operate stably for a grid strength above a particular threshold value, and the transmission grid is modeled as a single-machine infinite bus, which is an ideal voltage source with a reactor for emulating a particular grid strength. Most of the weak grid instabilities happen within a subsynchronous frequency range from 4 to 40 Hz. Characteristics of an ideal voltage behind the reactor during the subtransient to transient timescales can be used for quantifying the voltage source behavior of GFM resources. Frequency scans, Q/V, P/theta, and V/I can also be used for quantifying the grid strength [11]. In this case study, we demonstrate the use of a Q/V scan for quantifying the grid strength improvement that can be achieved from a GFM resource such as hydropower plant.

The response of the Q/V frequency scan of a voltage source behind a reactor is that of a low-pass second-order filter with a negative DC gain and a corner frequency equal to the fundamental frequency of 60 Hz—that is, the Q/V scan of a voltage source should have an almost constant magnitude and a phase closer to 180 degrees at subsynchronous frequencies [12]. It can be shown that a grid with an SCR of 3 (as required by the 200-MW renewable energy plant) with base values of 200 MW and 500 kV has a gain of 1,470 volt ampere reactive (VAR)/volt in its Q/V frequency scan. On the other hand, the grid with an SCR of 1.5 with the same base values has a gain of 735 VAR/volt in its Q/V frequency scan. This means that for the 200-MW renewable energy plant to operate stably with a grid having an SCR of 1.5, the remaining 735 VAR/volt response must come from another resource connected at the POI. This resource can be a conventional generator, such as a hydropower plant, or it can be a GFM BESS.

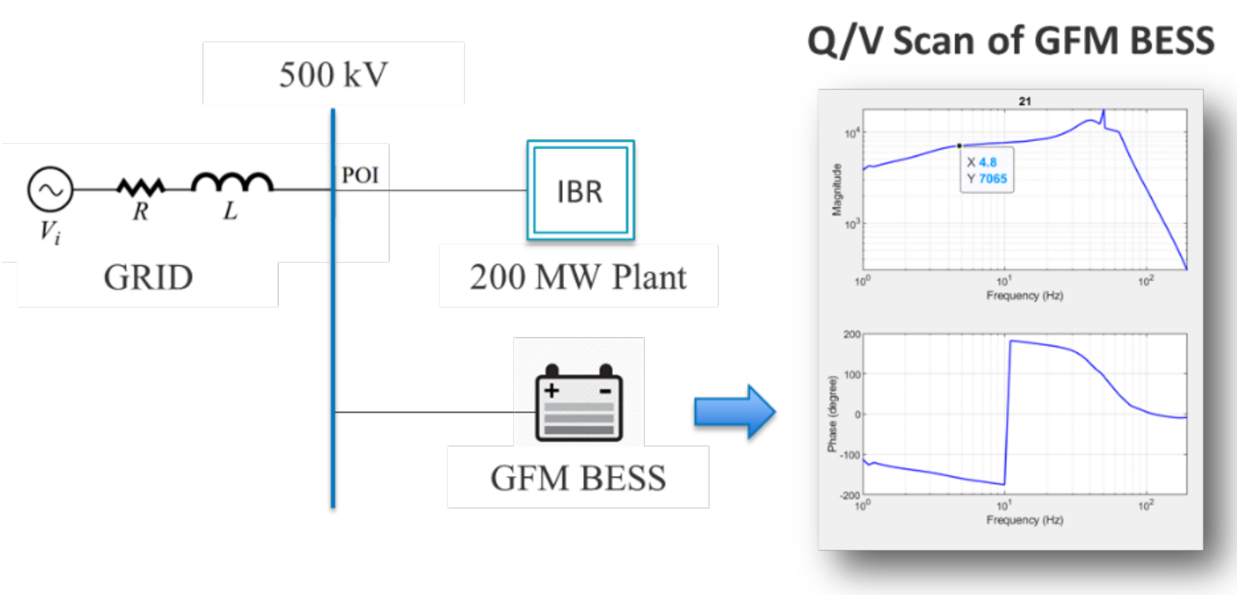


Figure 6. Use of a GFM BESS for improving the dynamic grid strength at the 500-kV POI of a 200-MW renewable energy plant

Figure 6 shows that a GFM BESS is connected at the POI of the 200-MW IBR to stabilize the IBR under weak grid conditions. Figure 7 shows the Q/V scan of the GFM BESS measured at the 66-kV bus connection. It shows that the magnitude of the Q/V is approximately 7,000 VAR/volt, and the phase response is closer to 180 degrees within the subsynchronous frequency range. This VAR/volt response translates to a 924-VAR/volt response at the 500-kV bus, which is the base voltage level of the POI of the 200-MW renewable energy plant.

Note that if the 1,470-VAR/volt corresponds to an SCR of 3, it can be concluded that the GFM BESS with a 924-VAR/volt response provides grid strength equivalent to around 1.9. So, in the presence of the GFM BESS, the 200-MW renewable energy plant would need grid strength from the transmission of only approximately 1.1 (= 3 – 1.9), which is less than our target grid strength of 1.5; hence, the GFM BESS is sufficient to stabilize the 200-MW renewable energy plant for an SCR at least as low as 1.5.

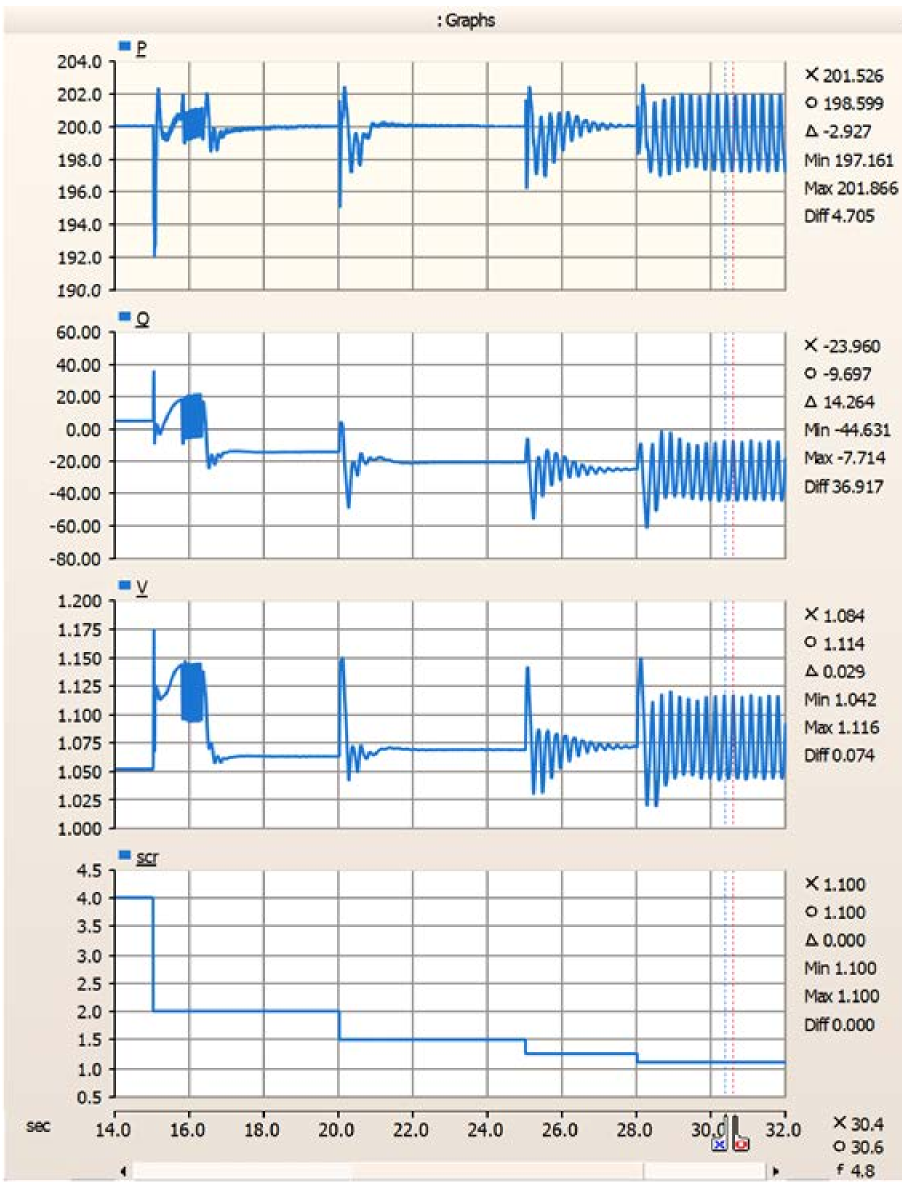


Figure 7. Response of the 200-MW renewable energy plant in the presence of a GFM BESS at its POI as the grid SCR is gradually reduced from 4 to 1.1. The plant remains stable for an SCR as low as 1.25; it loses stability when the SCR is reduced to 1.1

Similarly, we can also characterize the Q/V scan of hydropower plants with different design configurations to quantify their grid strength contributions.

4.2 Temporary Synchronous Condenser Pilot Project in Canada

In a recent project [28], the synchronous condenser operation of a Francis turbine prototype was experimentally analyzed to understand its mechanical impact on the system. The turbine was instrumented with strain gauges and vibration sensors and tested under synchronous condenser mode and during transitions to and from generating mode. Various signal analysis techniques, including time-frequency analysis and fatigue-life estimation, were applied. The study found that the most critical mechanical stress and vibration occurred during the fast transition from generating mode to synchronous condenser; this was primarily due to the rapid guide vane closure and air injection. In contrast, operation in synchronous condenser mode and the reverse transition caused significantly less fatigue to the machine. Fatigue analysis confirmed that optimizing transient procedures could help extend the turbine's operational life.

4.3 Case Study: Idaho Falls Power Black-Start Field Demonstration

In April 2021, Idaho Falls Power (IFP), Idaho National Laboratory, and American Governor Group of Emerson carried out a field demonstration testing the ability of IFP's hydro units to perform a black start and support critical loads on the distribution network in isolation from the grid [30]–[31]. During normal on-grid operations, IFP's five hydropower plants operate at full capacity while deficit generation is balanced by the power purchased from other energy generators within the region. Demonstrating that IFP's hydro units have black-start capability and can partially support city residents guarantees that IFP can operate its local grid if the transmission system is down. Prior to 2021, it was determined that IFP's units have black-start capability and support up to 2.5 MW off the grid. The 2021 field test builds on this by using a grid-following ultracapacitor to provide support and reduce the likelihood of the generators tripping during islanded operations. Overall, the 2021 field test explored three ways by which IFP's ability to perform a black start and support stand-alone operations can be improved: innovating the hydropower controls through isolated tuning of the hydro governors, synchronizing IFP's three hydro units (City Bulb, Lower Bulb, and Old Lower), and integrating an ultracapacitor system. The test showed that hybridizing IFP's units with an ultracapacitor enhances operational stability and flexibility as characterized by the reduced magnitude and duration of the frequency excursions as well as the increased load-carrying capacity during off-grid operations.

Additionally, NREL investigated the black-start capability of IFP's distribution system through a computer-aided transient analysis simulating the dynamic models of the utility's hydro fleet and response when a GFM battery is incorporated [31]. The study showed that locating the battery near the load reduces frequency oscillations during the distribution grid's black start, the battery capacity needed to support the black start is reduced when there is a pre-synchronization of the battery with the hydropower fleet, and the battery storage with GFM capabilities enhances the loading capability during the multiplant distribution grid black start.

4.4 Case Study: Fall River Electric Black-Start Field Demonstration

In July 2023, Fall River Electric (FRE), Idaho National Laboratory, and Mercury Governor performed a field test demonstrating the ability of FRE's hydro generators to perform a black start and support the local loads off the transmission system [32]. The test provides insight into the upgrades that are needed to enhance the hydro generators' ability to provide black-start services. The field test shows that FRE' hydro generators can provide a black start and support off-grid operation if a black-start mode is programmed to allow recloser and turbine guide vane control, the DC excitation system is properly rated and durable, high-fidelity gate and guide vane sensors are installed to prevent inaccurate dam head and flow rate estimations, switches and relays are configured to allow power injection into the distribution system off the grid, and battery storage is used to improve the frequency regulation and boost the load-carrying capacity. Ensuring these aspects enhances the hydropower plants' black-start capability, supports islanded operations, and improves grid flexibility and stability.

4.5 Hydropower's Contributions to Grid Reliability and Resilience

Hydropower plays a critical role in maintaining grid stability during unexpected generation losses, and it offers essential flexibility when renewable output drops during extreme weather events. In Western Interconnection studies [33], hydro provided up to 60% of primary frequency response despite accounting for only 25% of the generation capacity. Its high rotational inertia and responsive governors allow fast frequency stabilization. Additionally, hydro units offer substantial reactive power support, outperforming baseload units operating near capacity. This capability helps maintain voltage regulation during extreme disturbances. Hydropower's synchronous characteristics also provide essential inertial response and support black-start operations. Modeling and real-event data show that hydropower mitigates the rate of change of frequency, reduces underfrequency tripping, and accelerates recovery time. Its operational flexibility, ability to remain online under wide frequency ranges, and ramping speed make it irreplaceable in resilience planning.

4.5.1 Operational Transformation of Portland General Electric's Hydropower Under CAISO's Energy Imbalance Market Framework

The study on Portland General Electric's hydropower plants [34] illustrates how participation in the California Independent System Operator's (CAISO's) energy imbalance market redefined hydro's operational role. Before the energy imbalance market, dispatch was manual and predictable. After integration, hydropower units began receiving high-frequency (5-min) dispatch signals, leading to dynamic load-following and regulation service. Hydro output patterns shifted: lower average megawatts during peak hours and increased nighttime generation for both ecological (fish passage) and grid balancing needs. The frequency of the unit ramping and startup/shutdown cycles substantially increased, with a rise in regulation-only mileage—a key indicator of responsiveness to real-time imbalance. This intensified usage enables better integration of variable renewables but raises engineering concerns around increased mechanical stress and wear. Engineers must adapt asset management and operations and maintenance strategies to support this new paradigm while ensuring long-term system reliability.

4.5.2 Co-Optimizing Hydropower for Energy Needs

The study on Designing Hydropower Flows to Balance Energy and Environmental Needs evaluates how hydropower flow management can be designed to serve both grid flexibility and other uses of water resources [35]. Through national-scale flow data assessments and case studies—including Glen Canyon Dam and the Yadkin-Pee Dee River Basin—researchers demonstrate that hydropower can deliver grid services—such as peaking, frequency regulation, and ancillary support—while meeting ecological flow targets. Tools such as CHEOPS, DDP, and PLEXOS were used to model and optimize reservoir releases, revealing that smart reservoir operation—particularly using automated dispatch and forecast-informed reservoir operations—can improve fish survival and reduce ecological risks without compromising generation revenue. At Glen Canyon, thousands of reservoir release scenarios were tested to find the operational criteria that improved both energy economics and native fish growth. In the Yadkin-Pee Dee case, policies that restricted nighttime ramping improved young fish survival while maintaining or improving grid responsiveness and revenue. These results confirm that hydropower, when coordinated with advanced modeling tools and ecological considerations, can meet emerging energy market needs without sacrificing other uses.

4.5.3 Identifying and Addressing Hydropower Modeling Gaps

Hydropower is a key asset in supporting grid reliability, especially as renewable penetration levels increase; however, traditional steady-state and dynamic power system models often misrepresent hydropower capabilities due to modeling gaps [36]. These include ignoring seasonal water availability, oversimplifying turbine efficiencies, omitting interdependencies among cascade plants, and using outdated governor models. Additionally, rough zones and nonlinear turbine performance are often excluded, leading to unrealistic dispatch scenarios that risk incorrect frequency response estimations and system reliability. For instance, generator operations in rough zones can cause mechanical damage, but they are typically not modeled. Moreover, low-water head during droughts significantly alters capacity, yet this is rarely factored in planning tools. As a result, planning studies might overestimate the available hydro capacity or underprepare for critical events, such as frequency disturbances or load shedding. To address these challenges, the study recommends incorporating real-world hydro constraints—such as environmental rules, seasonal variations, and turbine-specific efficiency curves—into planning models to ensure realistic grid simulation and reliability assessments.

4.5.4 Hy-DAT—A Tool for Modeling Realistic Hydropower Operations

To close key modeling gaps in hydropower simulations, the Hydrological Dispatch and Analysis Tool (Hy-DAT) was developed [37]. Hy-DAT integrates hydro resource data, turbine characteristics, and machine learning to improve unit-level dispatch accuracy in power system models. It bridges gaps by incorporating real-time and historical data on water availability, turbine efficiency curves, and interdependencies between upstream and downstream plants. Using a database of 10 years of hourly data from Columbia River Basin plants, the tool applies deep neural networks to predict unit-level behavior from plant-level parameters such as water head and flow. The graphical user interface allows users to input hydro scenarios (e.g., dry or wet year, season) and outputs updated dispatch values validated against turbine efficiency thresholds. For example, efficiency curves from different turbine types (Francis, Kaplan, propeller) are used to ensure that operations stay within optimal zones. The tool also accounts for time-lag correlations in cascading systems and environmental flow constraints. Ultimately, Hy-DAT enables more realistic power flow studies and enhances the reliability of grid simulations by ensuring that hydro plants are dispatched within feasible physical and environmental boundaries.

4.5.5 Operational and Strategic Hydropower Enhancements for Wildfire-Resilient Grids

Hydropower enhances grid resilience across multiple timescales during wildfires by providing inertia, ramping, frequency response, and islanding capabilities. Wildfires pose direct threats to hydroelectric infrastructure—for example, the 2023 Sourdough Fire caused shutdowns at Seattle's Skagit River plants, requiring $2.6 million in emergency market power purchases [38]. These outages compromise voltage stability, capacity delivery, and critical grid services.

Despite this, hydropower is uniquely positioned to recover faster than other assets. Hydro turbines operate independently of ambient air temperatures and can remain online during severe frequency deviations, making them ideal for black-start and post-wildfire system restoration [38].

Resilience strategies involve deploying hydro in microgrid configurations with energy storage and PV. A techno-economic case in Idaho showed that hydro-based microgrids provide value-stacked services—public safety power shutoff backup, energy cost reduction, and peak shaving—while achieving a breakeven in less than 10 years [39]. Further, retrofitting non-powered dams with low-head turbines opens a path for distributed energy resilience, especially in wildfire-prone, socioeconomically vulnerable regions.

By using tools such as the Wildfires Risk Evaluation of the System (WiRES) Framework Tool and the NPD HYDRO Tool, engineers can prioritize investment in hydro resources that are co-located with critical loads, high fire risk, and limited grid connectivity. These integrated frameworks guide grid hardening, wildfire adaptation, and optimal dispatch under constrained operations. Hydropower is not only a generation source, but also a multidimensional resilience asset for a fire-prone, climate-impacted future.

5 Conclusion

With more power electronic devices in the power systems, ensuring system stability in weak grid conditions becomes increasingly vital. This report reviewed existing methodologies for assessing grid strength, including steady-state, time-domain, and frequency-domain approaches. Although these methods offer valuable insights, each carries limitations that highlight the need for a more comprehensive and application-specific framework for stability analysis. To meet these evolving challenges, leveraging flexible and underused assets such as hydropower plants is essential. Once primarily regarded for their energy generation and load-following capabilities, hydropower facilities are being reconsidered as dynamic assets capable of contributing to grid strength. Their operation as synchronous condensers offers a unique opportunity to inject inertia, manage reactive power, and support voltage stability—all without the need for water flow.

The case studies and pilot projects presented in this report demonstrate the growing viability of hydropower's expanded role—from black-start capabilities to contributing to wildfire-resilient grids. These examples underscore the practical potential of hydro resources in enhancing system resilience, especially in regions with high IBR penetrations. In conclusion, advancing both grid strength assessment methodologies and the strategic use of hydropower resources will be critical for building a reliable, flexible, and future-ready power system. Continued research, supportive policies, and innovative operational strategies will ensure that legacy assets such as hydropower can meet modern challenges and help shape the grids of tomorrow.

Deploying hydropower in microgrid configurations integrated with energy storage can provide resilience benefits to the power system in addition to value-stacked reliability and market services. Non-powered dams, if retrofitted with generation and energy storage capacities, can potentially open a new path for more resilient distributed energy systems.

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