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WHITE PAPER

Stability Challenges in Grids With Large Penetrations of Renewables

Grids across the world are increasingly faced with high penetrations of renewable energy resources. This phenomenon is being driven by policy, regulation and economics. We have conducted analysis on improving grid behavior in a test grid with near 100% renewable penetration and tested the needs of the system as it relates to grid stability. This evaluation is focused on use of synchronous condensers, tuning of inverter controls, use of grid-forming inverters and coordination of battery energy storage systems with load-shedding schemes. These factors were evaluated to determine relative impacts on improving an isolated grid operating with a high penetration of renewables; these findings can be applied to larger systems with high penetration of renewables.

Factors Driving Transition

Across the world, there is an increasing need to set up isolated microgrids to meet the demands of existing or new loads. The trend is driven largely by policy, economic factors, or the need to improve reliability and resilience. As calls increase for a sustainable future, it is paramount to have an ability to establish a microgrid powered by renewable energy sources, primarily wind and solar. Federal, state and local governments have developed a range of economic incentives to encourage integration of renewable resources. These programs are showing results and there has been a rapid increase in integration of renewable generation sources on the grid. This trend has, however, created several hurdles that must be resolved in order to integrate these renewables with existing grids.

In certain portions of the U.S., local governments and utilities have set goals that would result in 80% to 100% of load being served by wind and/or solar power within the next decade or two. In addition, there are certain industrial loads that are similarly trying to meet their power and energy needs from renewable generation and other forms of energy, such as clean hydrogen. These trends can pose many challenges related to design and operation of these grid systems.

Our analysis was conducted on a test system to assess a few solutions that help establish and even enhance stability on grids with large percentages of renewables meeting demand. Our results indicate that synchronous condensers are needed by a value of at least 20% of total load on the system to help stabilize grid operations. Our review also examined tuning of

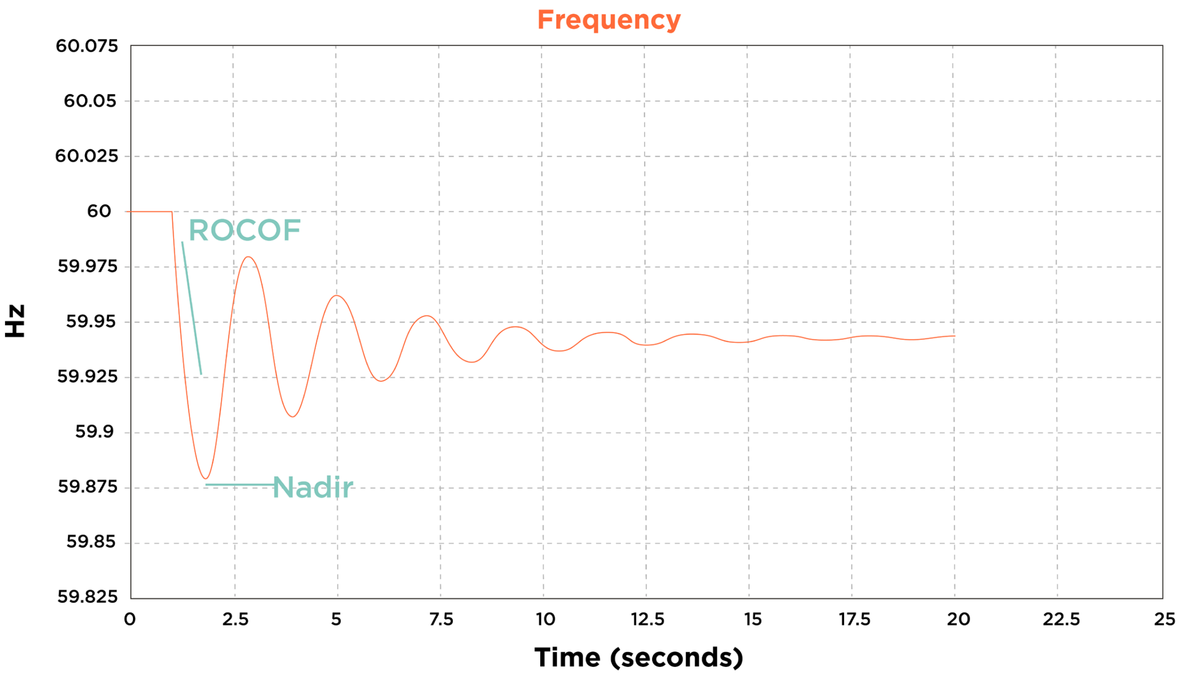

***Figure 1:** System frequency with ROCOF and nadir.*

inverter controls for weak grid system conditions, along with using grid-forming inverters to help improve stability and provide black-start capability.

Our findings indicate that studies to optimize protection systems would be beneficial to the design of protection systems to accommodate the needs of the ride-through capability of the inverters under large frequency and voltage deviations.

Role of Synchronous Condensers

Grids with high penetrations of inverter-based resources — primarily wind and solar generation — will have very low system inertia and poor system strength. This will result in large rates of change of frequency (ROCOF) in a disturbance resulting in low nadir frequency (see Figure 1). A recent ERCOT study confirms these disturbances are at times coupled with undamped oscillations with high penetration of renewable generations (~70% renewable generation in a 40 GW load system).

Our analysis utilized second-generation generic renewable dynamic models developed by Western Electric Coordinating Council (WECC) to represent wind generation, solar generation, battery energy storage systems (BESS) and inverter load. Other studies have confirmed that synchronous condensers may be utilized in many instances to help provide system strength in areas with high renewable penetration and to help improve system stability. To model the dynamic behaviors of a synchronous condenser, appropriate generator and exciter models were used. Typical parameters were assumed for all the dynamic models utilized in our analysis.

Synchronous Condenser Inertia Constant

To fully understand the factors affecting the required size of synchronous condensers in a grid with 100% renewable generation, stability sensitivity tests were performed in a series in which minimum synchronous condenser sizes were identified for a 1-GW system, scaling up to a 5-GW system.

Manufacturer data sheets examined in our analysis show that a typical range for synchronous condenser inertia constant can be 2.5 seconds to 8.3 seconds when used with a flywheel. We have utilized inertia values of 4.34 and 7 seconds in our analysis (See Figure 2). Our results indicate that in the test system, higher inertia synchronous condensers helped with a reduction in the size of the condensers needed to maintain stability. Higher inertia constant synchronous condensers help to damp the frequency and power oscillations in the system.

Synchronous Condenser Reactance

The synchronous condenser sub-transient/transient/synchronous reactance can vary by manufacturer. As part of our analysis, we tested different values of reactance for a synchronous condenser (See Figure 3) with the goal of observing their effect on the overall stability of the system following a disturbance. Our analysis concluded that utilizing smaller reactance values for synchronous condensers will help in minimizing the required size of synchronous condenser and would recommend system planners to consider the many manufacturer models as a part of optimizing the synchronous condenser sizes.

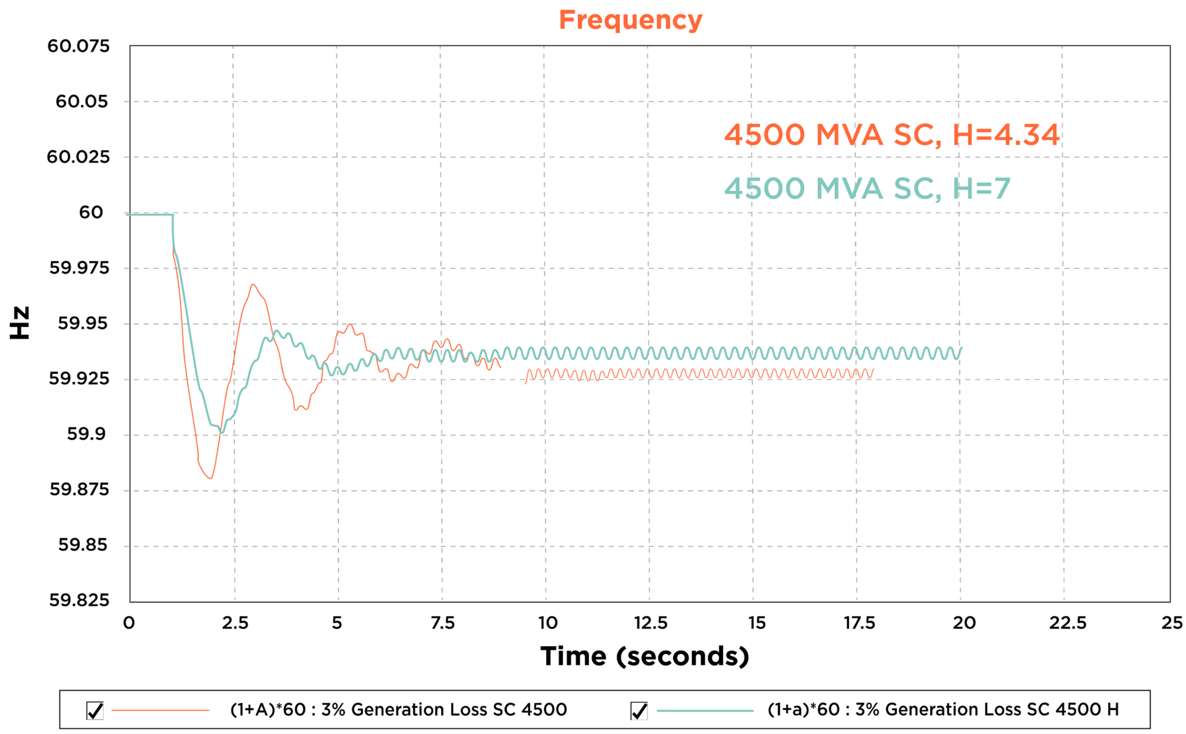

Figure 2: *System frequency with different synchronous condenser inertia constant (H)*

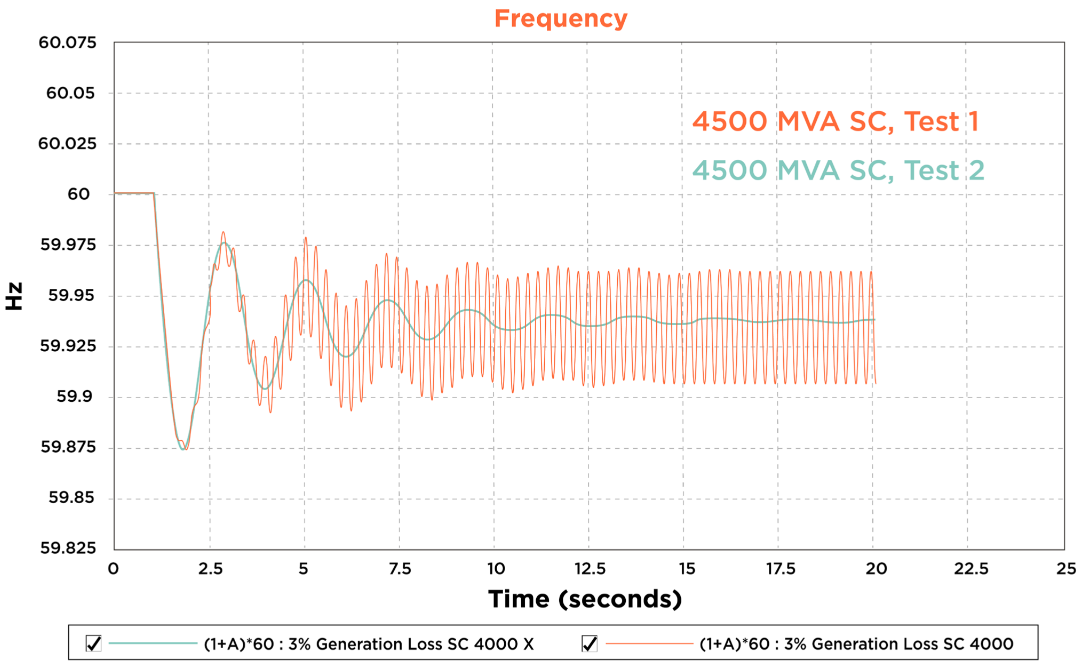

Figure 3: *Test results of system frequency with different synchronous condenser reactance.*

Grid-Following Inverter Controller Tuning

Our analysis covered tests related to grid-following inverters and how better tuning of the inverter controls can help restore and improve grid stability in many instances (See Figure 4). Most of the current wind and solar inverters are equipped with grid-following control schemes, where the inverter controller detects the grid frequency change and adjusts its generation output based on the grid frequency deviation. The controller parameters are normally designed for operation in a grid with nominal to high system strength. In a grid with high penetration of renewable resources, the controller parameters need to be retuned for a stable response by the wind and solar inverters.

Test	Wind Plant Controller (REPCTAU1)				Solar Plant Controller (REPCAU1)				Required Synchronous Condenser (MVA)
	Kp	Ki	Kpg	Kig	Kp	Ki	Kpg	Kig	
Test 1	0.5	6.6667	0.05	2	10	1	0.05	2	5000
Test 2	0.5	0.2	0.05	0.02	0.5	0.2	0.05	0.02	1500

Figure 4: *Grid-following inverter controller parameters.*

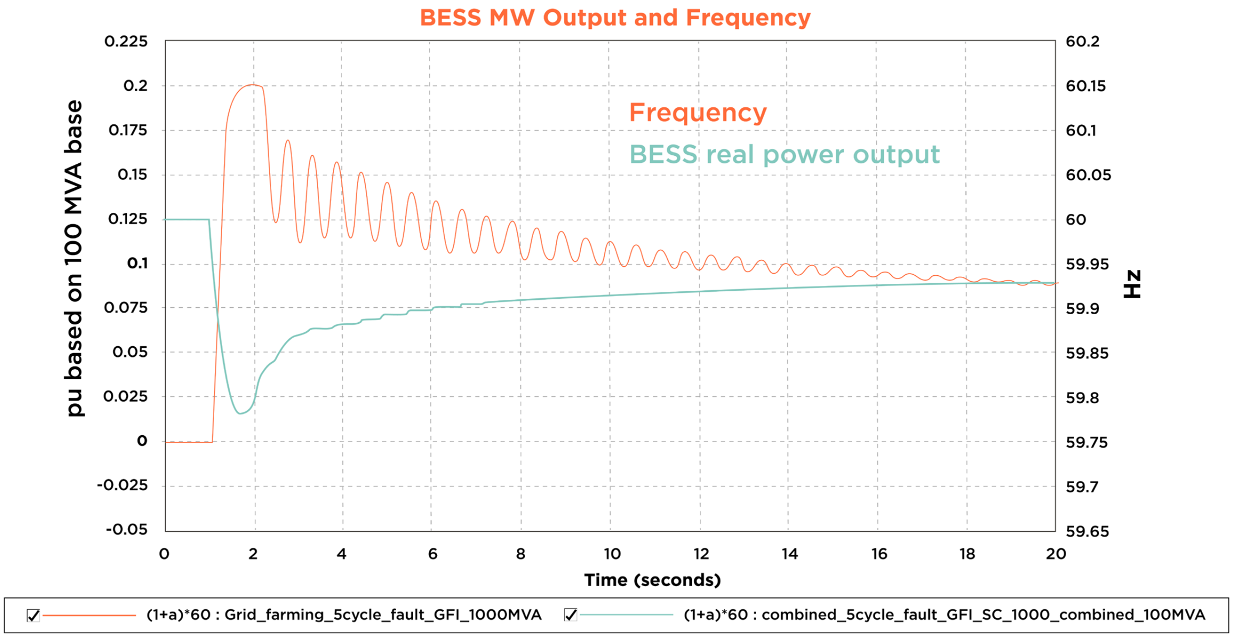

Figure 5: *System response with the tuning of load-shedding and BESS.*

Our analysis was conducted on two sets of controller parameters, with one utilizing typical plant controller parameters and the other carefully tuned for a weak grid operation. The controller response was intentionally sluggish, with reduced proportional gains and integral gains. As a sample, with the tuned parameters, only 1,500-MVA synchronous condensers was required for stable operation in our test system, compared with requiring 5,000 MVA of synchronous condensers with typical untuned controllers on a system with 100% inverter-based generation resources.

Load-Shedding Scheme and Fast Response BESS

For a low-inertia grid, the ROCOF could be large under disturbances. To help the system perform adequately following a disturbance, an appropriate load-shedding scheme and fast response BESS need to be installed. The load-shedding scheme and BESS can respond to the dynamic event in the grid within a few cycles. In general, the scheme and BESS will improve the frequency nadir and help the system frequency recover to normal value quickly.

For a 100% renewable generation grid without any connection to a utility grid, it is important to design the load-shedding scheme along with BESS control so that they can work collaboratively to keep the system stable under disturbance while minimizing the load shedding. With the tuning of the load-shedding scheme and the BESS control, the BESS injected more power to the grid when frequency dropped, and the load-shedding scheme was not activated. In our test system simulation, the system remained stable and no load was disconnected in a fault event that disconnected 3% generation (See Figure 5).

Grid-Forming Inverters

In recent years, grid-forming inverter controls have been available from several inverter manufacturers: SMA, ABB, Hitachi, Tesla and others. With grid-forming controls, other studies confirm our analysis that inverters generate their own frequency reference signal and adjust the generator output to set the frequency of the grid. Thus, grid-forming inverters can help with the frequency response of a 100% renewable grid. In addition, a grid-forming inverter can provide the

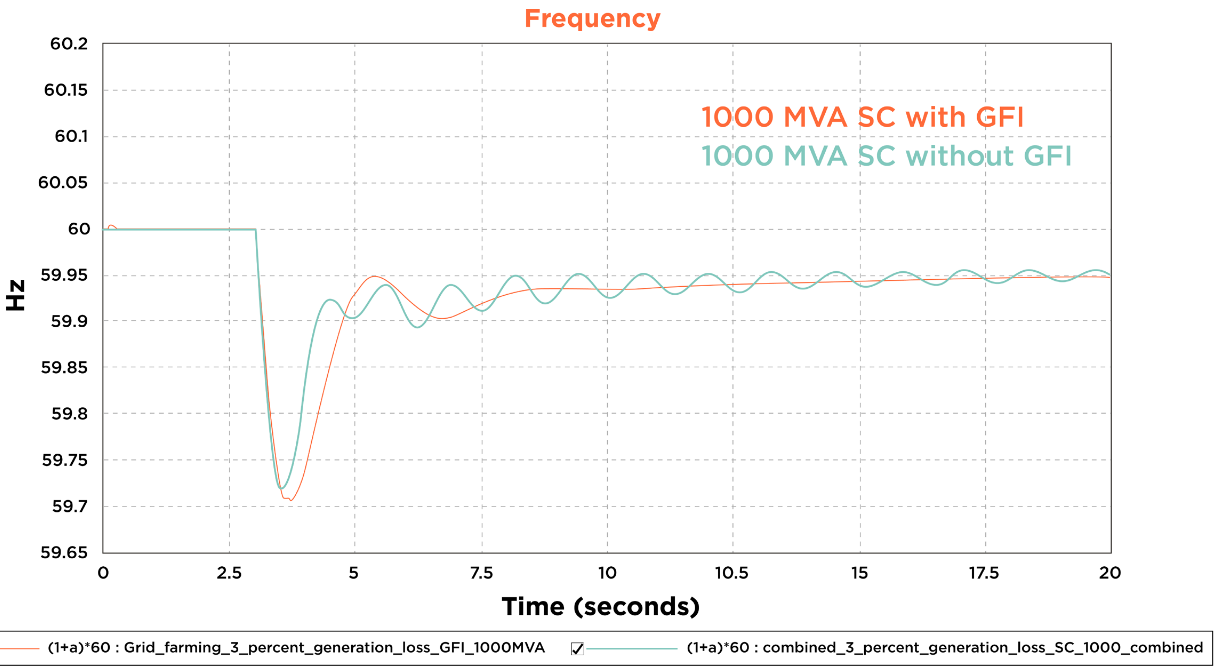

Figure 6: Frequency response with and without GFI in 3% generation loss event.

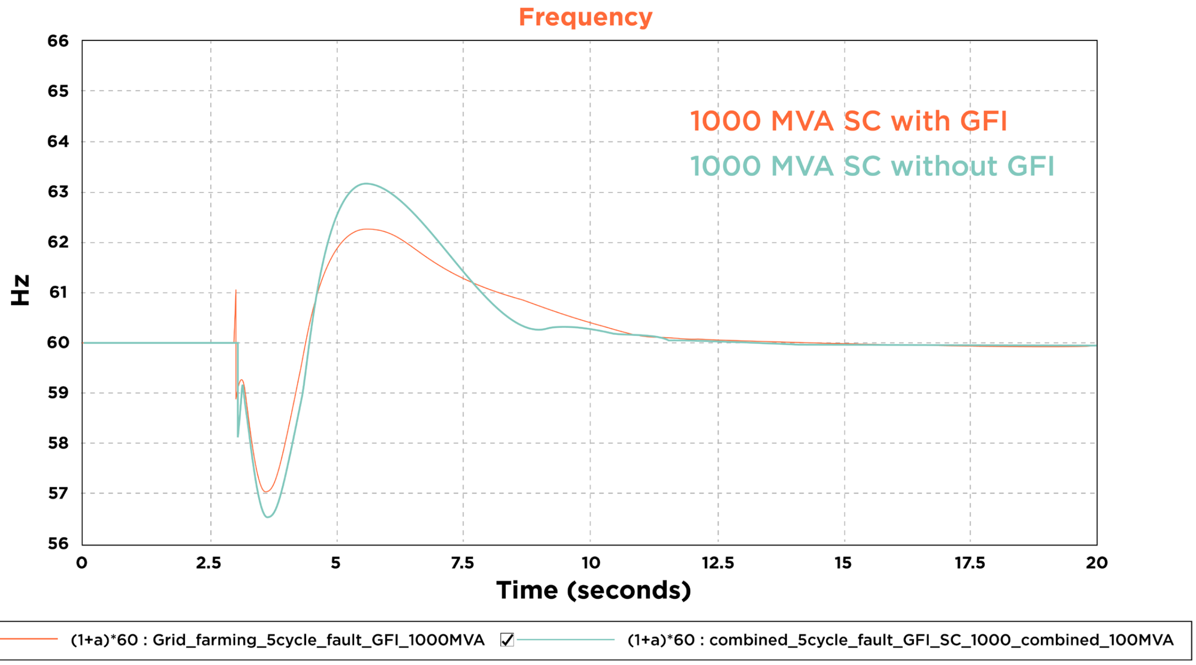

Figure 7: Frequency response with and without GFI in 3-phase fault event.

black-start capability much needed by a grid powered by 100% renewables.

Our analysis included utilizing a grid-forming inverter model in our test system; analysis was conducted to assess the reduction in need of synchronous condensers and/or help improve stability. The use of the grid-forming inverter model did not reduce the required size of synchronous condensers, but it helped reduce the oscillation in the 3% generation loss event (See Figure 6) and improved the frequency nadir in the fault event (See Figure 7) in our test system.

It should be noted that many manufacturers provide grid-forming inverter models that include a user-defined model in PSS/E and this makes it difficult to test the many variables to improve response. Working with the manufacturer is recommended in order to tune the grid-forming inverter model. This may allow the size of required synchronous condensers to be decreased.

Concluding Recommendations

Our analysis indicates that there are a few ways to enhance stability of grids powered exclusively or primarily by renewable energy. To recap, stability can be enhanced by:

- Use of synchronous condensers.
- Tuning of grid-following inverter controls.
- Use of grid-forming inverters.
- Including BESS in coordination with load-shedding schemes.

A detailed study should be performed to select the correct sizes and characteristics of each of these components and/or pieces of equipment with the object of determining how each will inform the overall stability of the isolated grids powered with renewables or grids with high penetration of renewables.

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