POWERING THE FUTURE

Synchronizing and Load Sharing in Inverter-Based Technology and Synchronous Machines

A focus on Battery Energy Storage Systems (BESS)

White paper by
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The transition to renewable energy sources necessitates robust energy storage solutions to mitigate intermittency and ensure a stable power supply. Battery Energy Storage Systems (BESS) have emerged as a pivotal technology in this transition, offering a more flexible and resilient solution for both grid-tied and off-grid operations. BESS play a crucial role in balancing supply and demand, addressing the intermittency of renewable energy sources, and providing ancillary services to the grid. These systems enhance grid stability, efficiency, and reliability.

In addition to BESS, other inverter-based power sources, such as hydrogen fuel cells, photovoltaic (PV) systems, and wind turbines, are becoming increasingly integral to modern power systems. As these technologies are integrated into synchronous grid-tied applications, off-grid applications, or setups utilizing inverters only, it is critical to synchronize and share loads across these sources to maintain power system stability. This paper explores the methods of synchronization and load sharing in inverter-based BESS and synchronous machines, ensuring efficient and reliable operation in diverse energy applications.

SYNCHRONIZING IN AC POWER SYSTEMS

Synchronizing an AC power system involves aligning the parameters of a generator set or any power source with those of the electrical grid or other AC power sources. The three critical parameters for synchronization are voltage, frequency, and phase angle. Additionally, waveform shape and phase rotation (clockwise A-B-C or counterclockwise A-C-B) are important considerations, although these are more relevant to the design of alternators in synchronous machines and inverters in inverter-based power sources. Phase rotation can be adjusted during power cable installation.

To parallel or connect AC power sources, the AC voltages must match or be within an acceptable range, typically within a 5-10% tolerance. The frequency of the two sources must be within 0.1 Hz, and the phase angle must be within approximately 10 degrees. Successful synchronization ensures that one AC power source can be seamlessly connected into the grid or another AC power system without causing disturbances or catastrophic failures. For example, closing out of phase, such as at t_1 (frequency and voltage) or approximately 80 degrees (phase angle) as shown in Figure-01, can lead to issues. In this case, source 2 being at a higher potential than source 1 will push source 1, potentially causing catastrophic failures.

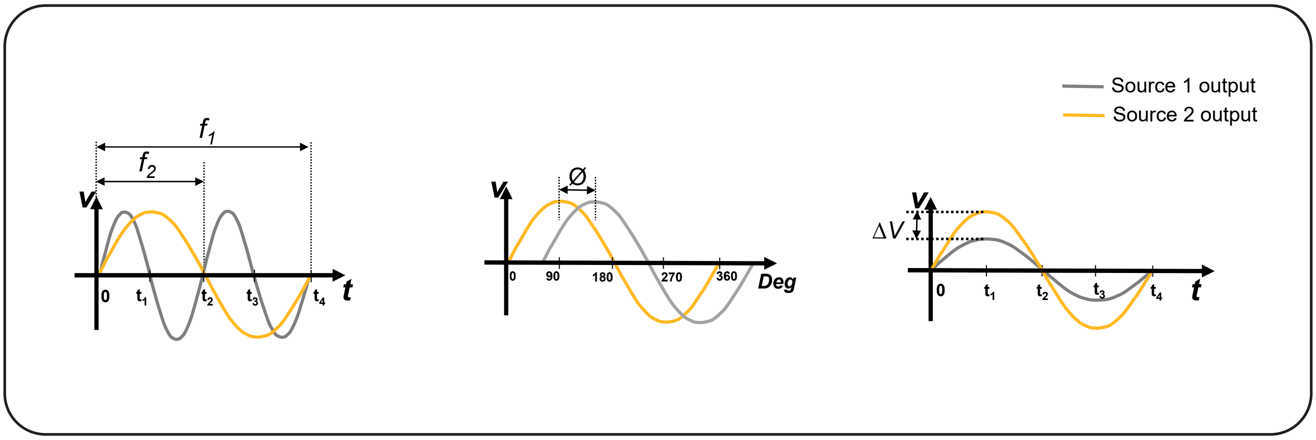

Figure 01 - Synchronizing Frequency, Phase and Voltage Sources

HOW A SYNCHRONOUS AC GENERATOR ADJUSTS ITS OUTPUT VOLTAGE, FREQUENCY, AND PHASE ANGLE

A synchronous AC generator produces AC electricity by rotating a magnetic field within a set of stator windings. Adjusting the output voltage, frequency, and phase angle is crucial for maintaining stable and reliable operation, particularly when connecting to a grid or other power sources. A Proportional–Integral–Derivative (PID) control loop can be implemented to fine-tune these parameters. The PID controller continuously monitors and adjusts the generator's output to ensure that voltage, frequency, and phase angle are within acceptable ranges before connecting the generator to the grid or another power source. Here's how these adjustments are accomplished:

1. Voltage Adjustment

Excitation System: The output voltage of a synchronous generator is primarily controlled by the strength of the magnetic field, which is determined by the current supplied to the rotor windings (field windings).

The excitation system, which includes an exciter and an automatic voltage regulator (AVR), adjusts the field current. Increasing the field current strengthens the magnetic field, raising the output voltage, while decreasing the field current weakens the magnetic field, lowering the output voltage. The AVR continuously monitors the generator's output voltage and adjusts the excitation current to maintain a constant output voltage. It senses the output voltage, compares it with a set reference voltage, and adjusts the excitation current accordingly to bring the output voltage back to the desired level.

2. Frequency and Phase Adjustment

Prime Mover Speed: The frequency and phase angle of the AC output are directly proportional to the rotational speed of the generator's rotor. For a synchronous generator, the frequency is determined by the speed of the prime mover driving the generator. For example, 1800 RPM corresponds to 60 Hz, and 1500 RPM corresponds to 50 Hz for directly-driven AC generators.

The speed of the prime mover is controlled by a governor system. The governor adjusts the fuel supply (in internal combustion engines) or steam/water flow (in turbines) to regulate the speed. For instance, in a steam turbine, adjusting the steam flow alters the turbine speed, which in turn adjusts the generator frequency. The governor maintains a constant rotational speed by sensing the output RPMs and comparing them with a set reference point. If the output deviates from the reference, the governor adjusts the fuel supply accordingly to bring the RPM, and thus the output frequency, to the desired level. Additionally, by fine-tuning the speed of the prime mover, the governor can adjust the output phase angle to align with that of the other AC source.

Synchronous generator sets are typically equipped with autonomous paralleling controls, such as the Cummins PowerCommand® Control, which incorporate synchronizing functions (voltage, phase, and frequency), synch check, and additional protection features to ensure maximum reliability and autonomy.

HOW AN INVERTER ADJUSTS ITS OUTPUT VOLTAGE, FREQUENCY, AND PHASE ANGLE

Inverters are essential components in modern electrical systems, especially for converting DC power from sources like batteries, solar panels, and fuel cells into AC power compatible with the grid or local loads. Adjusting the output voltage, frequency, and phase angle of an inverter involves sophisticated control mechanisms. Here's a detailed look at how these adjustments are made:

1. Voltage Adjustment

Pulse Width Modulation (PWM): PWM is a technique used to control the output voltage of the inverter. By varying the width of the pulses in a high-frequency signal, the inverter can effectively adjust the average voltage output. The inverter switches on and off at high speeds, controlling the duration (width) of each pulse. Longer pulses result in higher output voltage, while shorter pulses result in lower output voltage. The average value of the resulting waveform determines the output voltage. (See Figure-02)

Feedback control loops, such as PID controllers, continuously monitor the output voltage and compare it with a reference value. The controller adjusts the PWM duty cycle to correct any deviations from the desired voltage. This ensures that the inverter maintains a stable output voltage despite changes in load or input conditions.

2. Frequency Adjustment

Oscillator and Reference Signal: The frequency of the inverter's output is determined by an internal oscillator or a reference signal generator. The inverter's control system uses this reference frequency to time the switching of the power electronics devices (transistors or IGBTs). By precisely controlling the timing, the inverter can produce an output AC waveform with the desired frequency.

Phase-Locked Loops (PLLs) are commonly used to lock the inverter's output frequency to the grid frequency or the frequency of another AC power source. The PLL dynamically adjusts the inverter's switching frequency to ensure synchronization.

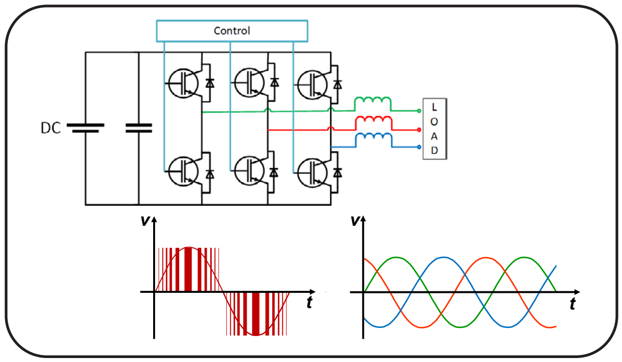

Figure 02 - Typical PWM Inverter

PWM is the most common method for controlling both the magnitude and frequency of AC voltage. This technique involves comparing a reference signal, usually a sine wave, with a carrier signal, such as a triangular or sawtooth wave.

Controlling AC Voltage Frequency - The frequency of the AC voltage is controlled by changing the frequency of the reference signal.

Controlling AC Voltage Magnitude - The magnitude of the AC voltage is controlled by adjusting the amplitude of the reference signal relative to the carrier signal, which modifies the pulse widths.

Improving AC Voltage Quality - A higher quality of AC voltage can be achieved by increasing the frequency of the carrier signal, although this comes at the cost of higher power losses.

3. Phase Angle Adjustment: A PLL is a control system that generates a signal that has a fixed relation to the phase of a reference signal. It is used to synchronize the inverter's output phase with the phase of another AC power source. The PLL continuously monitors the phase of the grid or other AC source voltage and adjusts the inverter's output to align with it. This involves controlling the timing of the inverter's switching events to match the phase angle of the other AC source.

Inverters, such as those from Cummins, are typically equipped with controls that incorporate synchronizing functions (voltage, phase, and frequency), synch check, and additional protection features to ensure maximum reliability and autonomy.

LOAD SHARING IN AC POWER SYSTEMS

Load sharing in AC power systems, including those with synchronous generators and inverters, involves distributing the electrical load among multiple power sources to prevent overloading and maintain system stability. Essentially, load sharing ensures the proportional division of real power (kW or P) and reactive power (kVAR or Q) among sources in a parallel configuration. The two primary methods utilized for load sharing are isochronous and droop control.

In the **isochronous** load sharing method, all the AC power sources, such as generator sets, maintain a constant output voltage and frequency regardless of the load applied (see Figure-03). Achieving isochronous load sharing requires precise control methods implemented in the onboard controllers of the generator sets (e.g. the Cummins PowerCommand® Control), necessitating real-time communication across the sources. Typically, this is accomplished by connecting two shielded twisted pairs of wires across the generator sets to share the kW and kVAR proportionally. To distribute kW equally across the generator sets, the governor adjusts the fueling level to the prime mover. For equal kVAR sharing, the Automatic Voltage Regulator (AVR) adjusts the excitation to the field winding as described earlier in the paper. Similarly, inverter-based AC power sources, share kW and kVAR by adjusting the voltage and frequency as described earlier in the inverter section of the paper.

It is important to note that there is no industry standard for designing isochronous load sharing schemes, leading different manufacturers to employ various methods. For instance, companies such as Cummins have developed isochronous load sharing gateway modules to interface their Cummins PowerCommand® Control with generator set controllers from other manufacturers.

Synchronous generator sets equipped with onboard compatible controls, such as the PowerCommand® Control, are capable of autonomously performing isochronous load sharing. However, this is not the case for inverter-based technology. Although a few papers have been published in IEEE discussing methods for true isochronous load sharing in inverters, these schemes have yet to be adopted in commercial applications.

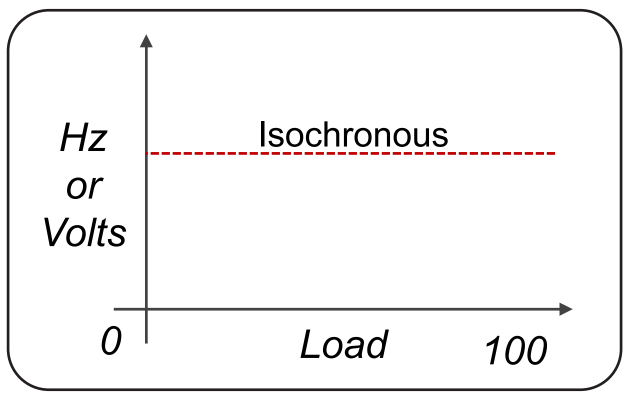

Figure 03 - Isochronous Load Sharing

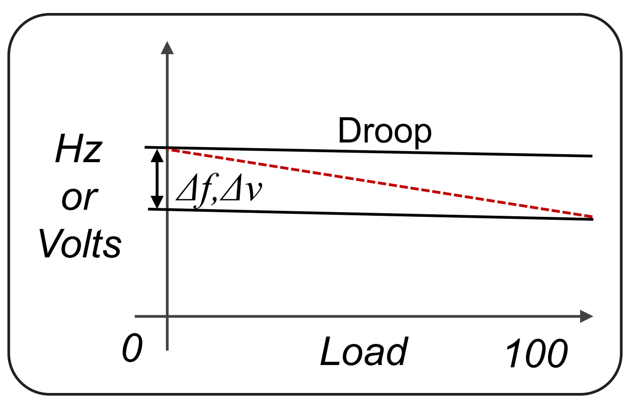

Figure 04 - Droop Load Sharing

In the **droop** load sharing method, the frequency and voltage of each AC power source decrease (or droop) proportionally with increasing load. As a result, the frequency and voltage vary with the load, as shown in Figure-04. This drooping characteristic enables multiple AC power sources to share load changes without requiring complex communication systems or communication wires between the sources. It only necessitates setting the droop curves appropriately for each power source.

For loads that require constant voltage and frequency, the isochronous load sharing method should be implemented. On the other hand, droop control is used when sharing load across inherently different AC power sources without compatible control schemes and the loads are not sensitive to variations in voltage and frequency.

Synchronous generator sets equipped with onboard paralleling control can typically operate in either isochronous or droop control modes and can seamlessly switch between these modes without shutting down. Droop load share method is commonly used in inverter-based power sources. In scenarios where synchronous generators and inverter-based sources, such as BESS are connected to the same common bus, the synchronous generators should operate in isochronous mode while the BESS inverters should operate in droop mode. This topic will be explored in further detail in this paper.

PARALLELING FUNCTIONS OF GRID-FORMING AND GRID-FOLLOWING INVERTERS

The two main control strategies or modes for inverters are grid-forming [V-F mode: constant voltage (v) and frequency (f)] and grid-following [P-Q mode: real (P) and reactive (Q) power]. Another form of grid-forming is grid-supporting; however, this type will not be discussed in this paper.

Grid-Forming Inverters (V-F mode):

Role - Grid-forming inverters act as voltage sources, establishing and maintaining the voltage and frequency of the bus to which they are connected. Grid forming inverters provide inertia and short circuit capacity to the power system.

Function - They can create and regulate bus voltage even if no voltage is initially present. Grid-forming inverters maintain their output voltage and frequency as their connected loads vary.

Grid-Following Inverters (P-Q mode):

Role - Grid-following inverters function as current sources, injecting real power (kW or P) and reactive power (kVAR or Q) into the bus (grid and loads) to which they are connected. Therefore, an external control must send the inverter these P-Q commands or setpoints. Grid-following inverters closely track the source (i.e. the grid) voltage, frequency, and phase angle to provide precise active and reactive power control. The source voltage must remain within a ±7% deviation for effective operation.

Function - These inverters require a pre-existing grid or reference voltage and frequency to synchronize their output voltage, frequency, and phase angle before connecting. If no voltage is present on the bus, grid-following inverters will not connect. They depend on the grid (or a synchronous generator set) to provide a stable voltage and frequency reference and cannot operate in islanded or off-grid mode.

This distinction is critical in designing and operating power systems, as each inverter type has specific roles and limitations in grid stability and integration. BESS inverters can operate in either grid-following or grid-forming mode. It is essential for system designers or consultants to specify the appropriate inverter type based on the application's requirements. For instance, specifying a grid-forming inverter for BESS provides the flexibility to operate in either grid-forming or grid-following modes.

In contrast, synchronous generator sets naturally produce AC voltage and operate in two main modes: load sharing, which is analogous to grid-forming as shown in Figure-05, and load governing, which is analogous to grid-following. In this context, grid-following in synchronous generator refers only to power management, both real and reactive, indicating that synchronous generators can establish and maintain their own AC source, voltage, and frequency while acting as current sources responding to P-Q commands. See Figure-06.

These terms describe the generator set's paralleling functions and their integration with the power system. Typically, each synchronous generator set is equipped with an autonomous control system, such as the Cummins PowerCommand® Control, which can function in either grid-forming (load-sharing) or grid-following (load-governing) mode. Additionally, the control system is responsible for synchronization, protection, voltage and current regulation, and metering.

In Figure-05, each synchronous generator set is configured as a grid-forming power source due to the compatible control and communication scheme among all units. In this mode, the generators can determine the amount of real and reactive power needed to power the load and share the load proportionally across all units.

Conversely, in Figure-06, the generator sets are configured in load-govern mode or grid-following mode. In this configuration, the generator sets synchronize to the bus (or can establish the reference voltage if none is present), and an external system controller or microgrid controller sends the P-Q commands to the units, essentially controlling their excitation and fueling as described earlier in the paper.

Photovoltaic (PV) inverters are generally grid-following devices, as described earlier they depend on a reference voltage from the grid or an external source to operate. Without this reference, they will disconnect or "trip." To address this, BESS are often used alongside solar PV installations to maintain a stable grid reference. When the grid is unavailable, a BESS can operate in grid-forming mode to provide a stable reference voltage, allowing other inverters to continue operating in grid-following mode. A microgrid controller is responsible for managing power distribution among all generation sources and loads, ensuring stable and efficient operation.

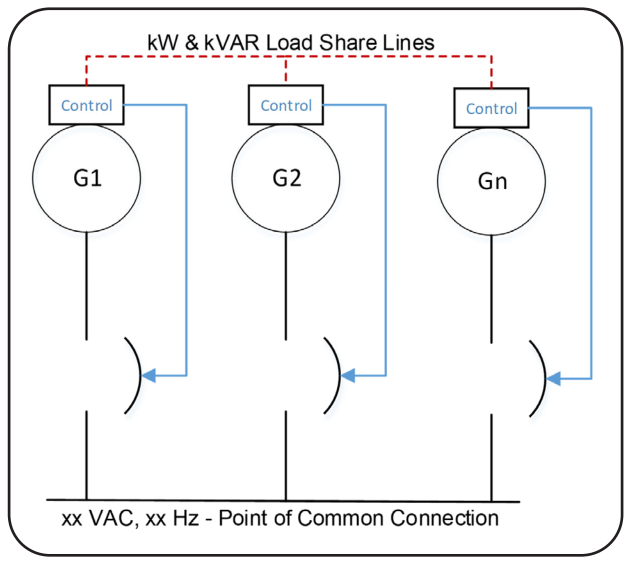

Figure 05 - Synchronous Generators: Grid-Forming (Load Share Mode or V-F Mode)

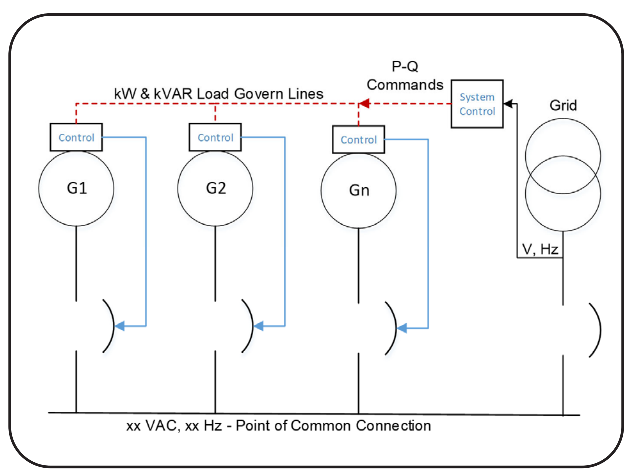

Figure 06 - Synchronous Generators: Grid-Following (Load Govern Mode or P-Q Mode)

Load Sharing Scenarios: Two or more load-sharing (grid-forming) synchronous generator sets can be connected to the same common point or bus because they utilize a common communication and control scheme within their autonomous control systems. These systems use dedicated control wiring for real power (kW) and reactive power (kVAR) management, as previously described in the paper. However, this is not the case for grid-forming inverters. Currently, implementing a common communication control scheme across multiple inverters, or between inverters and synchronous machines, is complex, and there are no established methods for true isochronous load sharing.

Connecting two or more grid-forming inverter power sources to a common bus or combining grid-forming inverters with synchronous machines in a load-sharing (grid-forming) configuration (as shown in Figure-07), can cause the sources to conflict. Each unit attempts to establish the voltage, phase, and frequency and evenly distribute the load, potentially leading to an unstable state. This often results in one unit shutting down due to reverse power conditions.

In Figures 08a through 08c, the inverters operate in PQ mode (grid-following), with the anchor sources being either the generators or the grid. The synchronous generators (Figure 08-a) and the grid (Figures 08b and 08c) are considered ideal sources that establish the reference voltage, phase, and frequency. The inverters follow these references and inject real power (kW) and reactive power (kVAR) as required by the system-level controls. In the event of a generator set stopping (Figure 09) or a utility breaker opening, the Cummins BESS inverter switches from PQ mode to VF mode within 100ms.

In scenarios where only inverters are connected to a common bus (Figure 07), one inverter must be configured as grid-forming, while the remaining inverters must be configured as grid-following. If the grid-forming inverter stops working or is taken offline, one of the other inverters will switch to grid-forming mode within 100ms.

Some inverter manufacturers require that the entire system be shut down before switching an inverter from grid-following mode to grid-forming mode. It is important to note that when a power source is offline, the system's capacity may fall below the load demand unless the system is designed with N+1 redundancy or higher. Without such redundancy, load shedding of non-critical loads may be necessary to balance capacity with consumption. Therefore, system designers or consulting engineers must consider these factors when specifying or designing the system.

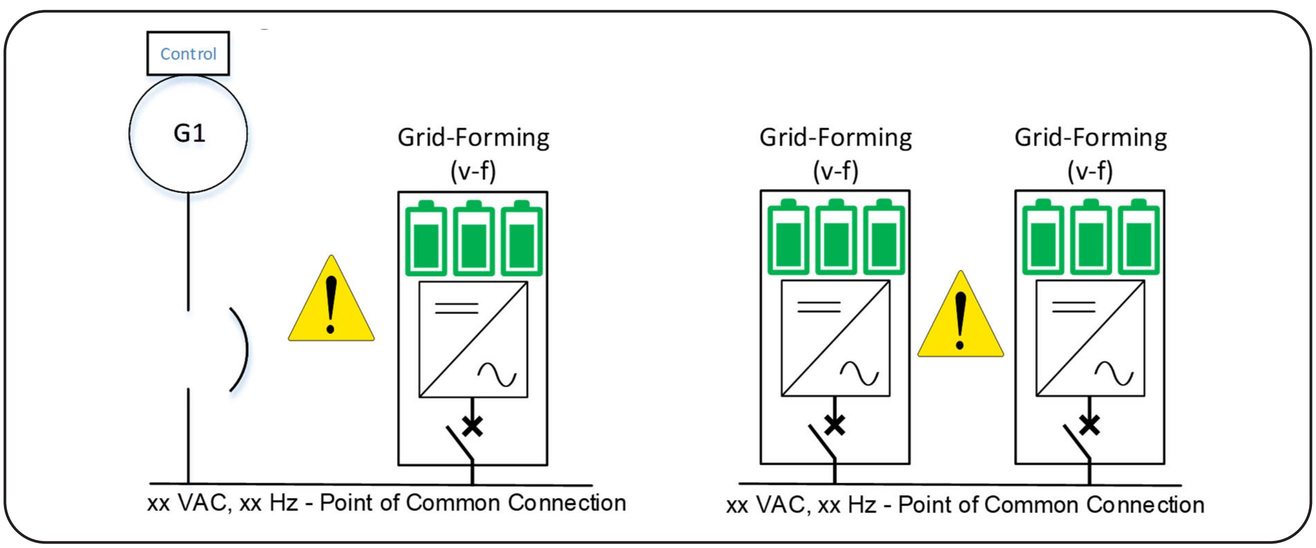

Figure 07 - Grid-Forming Inverters/Synchronous Machines W/O Common Communication

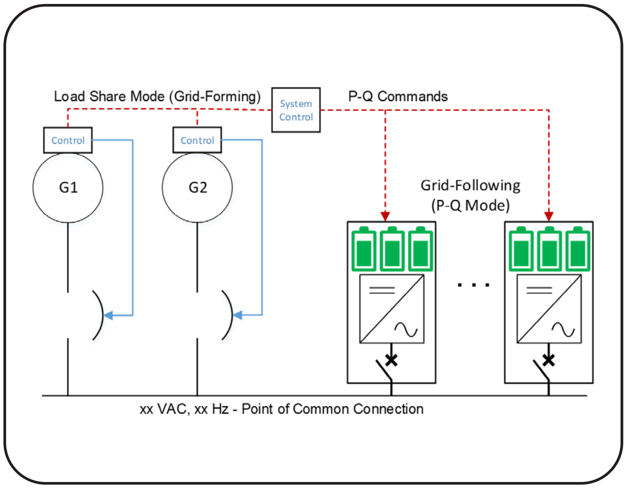

Figure 08a - Synchronous Generators Act as Anchors

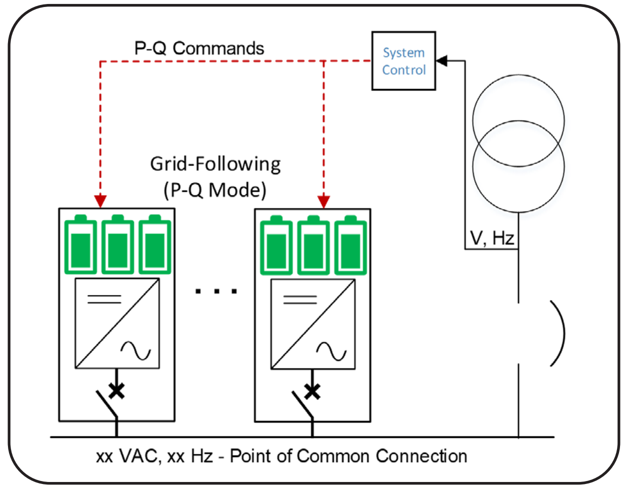

Figure 08b - Grid Acts as Anchor

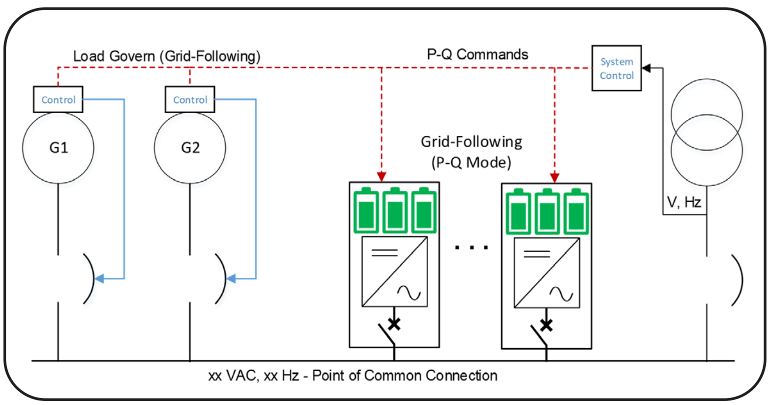

Figure 08c - Grid Acts as Anchor

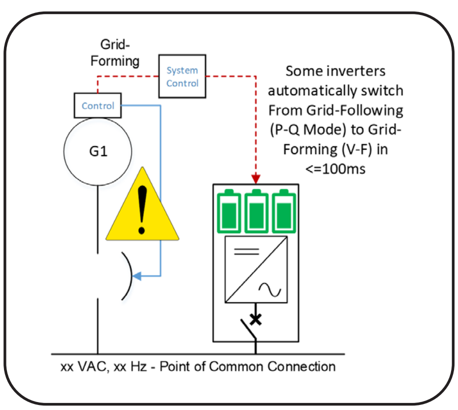

Figure 09 - Inverter Switching From P-Q To V-F

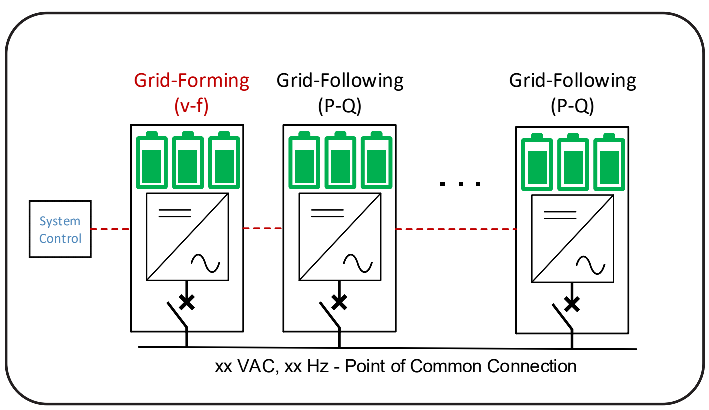

Figure 10 - Multiple Inverters On A Common Bus

LOW VOLTAGE RIDE THROUGH (LVRT) CAPABILITY IN INVERTERS

Low Voltage Ride Through (LVRT) capability in inverters refers to the ability of an inverter to remain connected and operational during short periods of low voltage conditions in the power grid. This capability is crucial for maintaining grid stability, especially in systems with a high penetration of renewable energy sources such as wind and solar power.

LVRT capability is essential because power grids can experience voltage dips or sags due to faults, sudden large loads, or other disturbances. Without LVRT, inverters might disconnect during these events, which can exacerbate grid instability and lead to wider-scale power outages.

The inverter continuously monitors the grid voltage. When a voltage dip below a certain threshold is detected, the LVRT function is activated. Instead of disconnecting from the grid, the inverter reduces its power output to match the available voltage while maintaining synchronization with the grid frequency and phase. The inverter's control system adjusts the operation to ride through the low voltage period without causing damage to the inverter or the grid, similar to a generator set, the inverter can inject the reactive power during LVRT conditions to help stabilize the grid voltage. Figure-11.

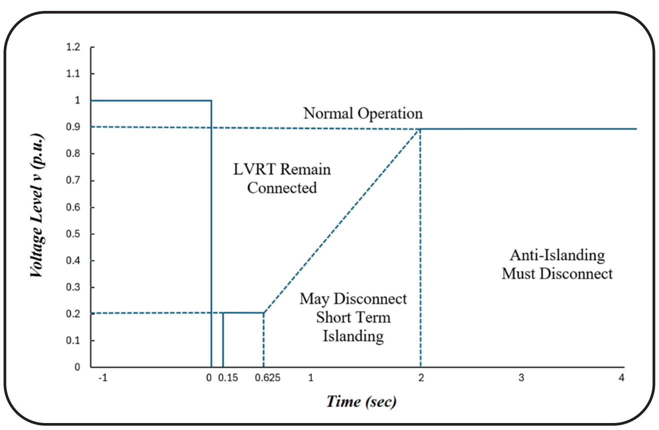

Figure 11 - Low Voltage Ride Through

Benefits of LVRT:

Enhanced Grid Stability - By remaining connected during voltage dips, inverters with LVRT capability help to stabilize the grid and prevent cascading failures.

Improved Reliability - Systems with LVRT are more resilient to grid disturbances, leading to fewer interruptions in power supply.

Compliance with Grid Codes - Many grid operators require LVRT capability as part of their interconnection standards for renewable energy systems.

Another related capability is High Voltage Ride Through (HVRT), which functions similarly to LVRT. However, during high voltage conditions, power generation sources such as generator sets and/or BESS are expected to absorb reactive power to help restore the voltage to its nominal value. The consultant specifying engineer, or the power system designer must determine if grid code compliance is needed for the application.

CONCLUSION

The transition to renewable energy sources necessitates robust energy storage solutions to mitigate intermittency and ensure a stable power supply. Battery Energy Storage Systems (BESS) have emerged as a pivotal technology in this transition, offering a more flexible and resilient solution for both grid-tied and off-grid operations. BESS play a crucial role in balancing supply and demand, addressing the intermittency of renewable energy sources, and providing ancillary services to the grid. These systems enhance grid stability, efficiency, and reliability.

In addition to BESS, other inverter-based power sources, such as hydrogen fuel cells, photovoltaic (PV) systems, and wind turbines, are becoming increasingly integral to modern power systems. As these technologies are integrated into synchronous grid-tied applications, off-grid applications, or setups utilizing inverters only, it is critical to synchronize and share loads across these sources to maintain power system stability. This paper explores the methods of synchronization and load sharing in inverter-based BESS and synchronous machines, ensuring efficient and reliable operation in diverse energy applications.

Synchronizing an AC power system involves aligning the AC parameters of an inverter, generator or any power source with those of the electrical grid or other AC power sources. The three critical parameters for synchronization are voltage, frequency, and phase angle. Additionally, waveform shape and phase rotation (clockwise A-B-C or counterclockwise A-C-B) are important considerations, although these are more relevant to the design of alternators in synchronous machines and inverters in inverter-based power sources. Phase rotation can be adjusted during power cable installation. Successful synchronization ensures that one AC power source can be seamlessly integrated into the grid or another AC power system without causing disturbances or catastrophic failures.

Load sharing in AC power systems involves distributing the electrical load, both real (kW) and reactive (kVAR), among multiple power sources to prevent overloading and maintain system stability. The primary methods for load sharing are isochronous and droop control. Isochronous load sharing requires precise control methods and real-time communication between sources, whereas droop control enables load sharing without complex communication systems. When load sharing across different sources, such as synchronous generators and inverters, droop control should be used.

Grid-forming and grid-following inverters serve distinct roles in power systems, each with specific capabilities and limitations. Grid-forming inverters establish and maintain bus voltage and frequency, acting as voltage sources. In contrast, grid-following inverters act as current sources, requiring an existing voltage and frequency to synchronize with before injecting real and reactive power based on P-Q commands. Properly specifying these inverter types based on application requirements is essential for optimal system performance.

Synchronous generator sets naturally produce AC voltage and operate in two main modes: load sharing, which is analogous to grid-forming and load governing, which is analogous to grid-following. In this context, grid-following in synchronous generator refers only to power management, both real and reactive, indicating that synchronous generators can still establish and maintain their own AC source, voltage, and frequency while acting as current sources responding to P-Q commands. Each synchronous generator set is typically equipped with an autonomous control system, such as the Cummins PowerCommand® Control, which can function in either grid-forming or grid-following mode.

In situations where only inverters are connected to a common bus, only one inverter must be configured as grid-forming, while the others should be set as grid-following. When synchronous generators or the main grid are connected to the same bus as BESS inverters, the inverters should operate in grid-following mode, responding to P-Q commands.

Low Voltage Ride Through (LVRT) capability in inverters is crucial for maintaining grid stability during voltage dips. Inverters with LVRT remain operational during short periods of low voltage, supporting grid stability and preventing wider-scale outages. This capability enhances grid stability, improves system reliability, and ensures compliance with grid codes. Another related capability is High Voltage Ride Through (HVRT), which functions similarly to LVRT. However, during high voltage conditions, power generation sources such as generator sets and/or BESS are expected to absorb reactive power to help restore the voltage to its nominal value.

In summary, the integration of BESS and other inverter-based power sources into modern power systems requires robust synchronization and load sharing mechanisms to ensure stability, efficiency, and reliability. Advanced control systems and capabilities are essential for achieving these goals, enabling the seamless integration of renewable energy sources and supporting the transition to a sustainable energy future.

About the author

Hassan Obeid is a Global Technical Sales Leader – New Energy Solutions at Cummins Inc., focusing on technical vision, business strategy, and solving a wide range of complex problems. Hassan has been with Cummins since 2007 in various roles, including global technical advising, power systems design engineering, project engineering, and applications engineering. He has designed power systems involving switchgear, controls, paralleling, BESS, PEM hydrogen fuel cells, transfer switches, generator sets, DERs, microgrids, and digital solutions. Additionally, Hassan has developed and conducted technical power seminars on several topics and products, including BESS, PEM hydrogen fuel cells, paralleling, grounding, power systems, and controls. He holds a bachelor's degree in Computer Science and a master's degree in Electrical Engineering from Minnesota State University, Mankato.

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