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Solutions to Improve Grid Code Compliance of Synchronous Generation

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SUMMARY

In response to increasing penetration levels of renewable energy sources [1], regulatory entities and utilities created grid codes to govern the performance requirements of new grid-connected energy resources. Eventually, grid codes were adopted on a universal basis such that all new generating sources, both renewable and conventional, were obligated to conform to established grid standards.

Although the complexity of grid codes can vary by region and country, these grid codes usually have two common elements. The first is known as "low-voltage ride through" or LVRT and the second is known as "rate-of-change-of-frequency" or RoCoF.

The importance of these two requirements was realized once the size of connected renewable plants became sufficiently large such that the loss of these plants during normal excursions of voltage and/or frequency could no longer be tolerated. The loss of a large renewable resource under a grid disturbance increased the severity of the contingency. In other words, the grid could not afford to lose this generation when it needed it the most.

Some of today's grid codes in Europe for example, do not allow the tripping of either conventional or renewable generation. The vendors of renewable generation equipment have incorporated enhanced control methods together with power electronics to increase the ride-through capability of these plants under grid disturbances. On the other hand, conventional generation have inherent physical characteristics and operating principles that have not changed significantly in over a century. These conventional characteristics and principles can limit transient stability performance when exposed to voltage and frequency events on the grid. As such, compliance with stringent grid regulations may be challenging and in some cases may not be possible with existing equipment and operating practices.

Although vendors of conventional generating equipment are fully aware of the requirements of the modern grid, only a few low-cost modifications are readily available for a conventional generating unit in the event of non-compliance with a grid code. When non-compliant, the plant owner will normally implement feasible and easily attainable modifications in the plant or unit software if possible; and if not successful, the plant may operate subject to operating restrictions imposed by the ISO or utility, such as curtailment [6]. As such, grid compliance is an on-going requirement whereby plant owners make feasible capital expenditures as required in order to comply with the code requirements.

The challenges of LVRT and RoCoF are immediately evident for system planners working with weak grid areas, especially those with high amounts of renewable penetration. In these scenarios, both

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LVRT and RoCoF code requirements may cause severe compliance complexity for conventional generators.

This paper presents solutions and representative estimates of the cost of capital expenditures to improve the LVRT and RoCoF margins for conventional generation. Solutions are presented for both new installations and existing commissioned plants, for applications in weak grid and/or high renewable penetration areas.

KEYWORDS

Grid Codes, LVRT, RoCoF, Transient Stability, Weak Grid, Renewable Penetration, Rate of Change of Frequency

Evolving Grid Code Requirements

Grid codes continue to evolve around the world. One of the most common features of the grid codes, which is often included as an interconnection mandate is the "ride-through" requirements during contingency conditions. Two common "ride-through" mandates are LVRT and RoCoF, both of which have their origin in grid codes developed for renewable generators (specifically wind plants).

Figure 1 displays one such example where a wind plant generator is required to stay connected to the grid for all voltage conditions defined by the envelope [2]. This envelope does not represent any single real event but encapsulates all possible low voltage conditions that can be experienced at the point of interconnection (POI). Conventional generating plants are now subject to similar stringent profiles that have become part of the interconnection requirements throughout the world [3]-[5].

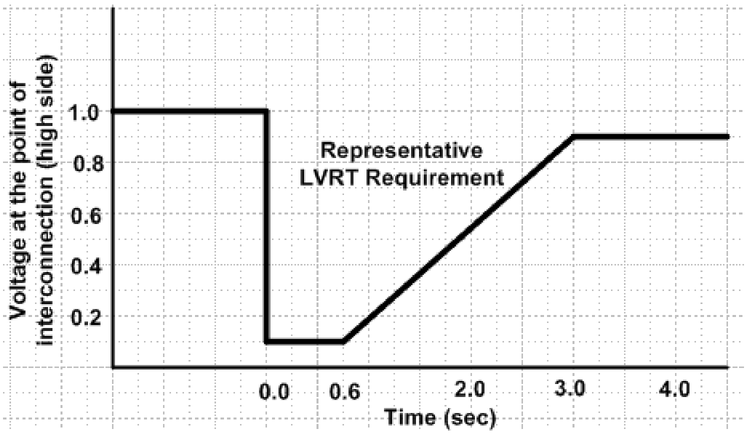


Figure 1. Example of LVRT grid requirement profile.

While power electronics-based wind and solar installations have quickly evolved to comply with these tough grid requirements, the design of conventional synchronous power sources has remained largely unchanged in many decades. As such, the transient stability performance of conventional synchronous generators has likewise remained consistent [7]. Therefore, current system planning and protection practices have evolved to accommodate this "synchronous rotating machine response" of conventional units as a measure for designing the grid.

Now, even with today's system protection technologies, i.e. dual high-speed schemes and independent pole operated circuit breakers, some codes are imposing performance requirements that are well beyond the limitations of existing machine design [3-5]. As such, grid compliance has become a major concern for generation stakeholders, both owners and manufacturers, even for the most optimistic situations.

Typically, the LVRT criterion requires that conventional generation remain synchronized to the power system following a pre-defined fault condition in the form of a low voltage dip [3]. These conditions are simulated by applying a specific voltage-time characteristic profile at the point of interconnection and monitoring unit synchronism. Often unit stability must be evaluated at full load over a range of operating conditions, usually from over-excited (O.E.) to under-excited (U.E.) operation, and for the entire duration of the fault.

Frequency ride-through criterion (RoCoF) is the requirement to remain synchronized to the grid following an event that perturbs the grid frequency resulting in an average Hz/sec disturbance, as exemplified in Figure 2.

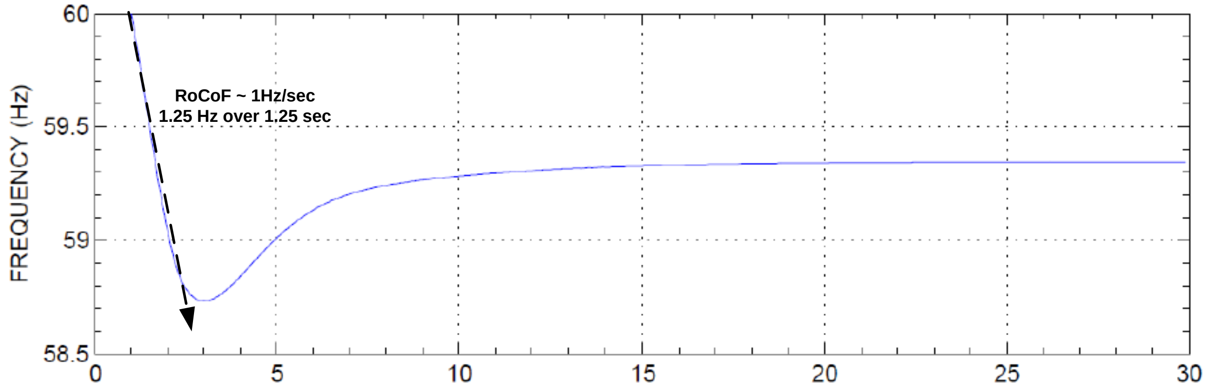


Figure 2. Example of RoCoF grid requirement profile.

This type of compliance event can be categorized by a rapid change in frequency from a loss of synchronous generation or load. If the system is small (such as an island grid) or if the loss of generation/load is large, then this event may affect the transient stability of the interconnected synchronous machines. Two such examples of this requirement include: 1) Northern Ireland, wherein all transmission connected conventional generation should meet a minimal functional specification RoCoF of 1.5 Hz/sec [9] and 2) Australia, wherein the minimum requirement is 1 Hz/sec for 1 second, while automatic access is granted for generators with capability of 4 Hz/sec for 0.25 seconds [12].

As with most grid codes, a performance requirement, such as LVRT or RoCoF, must typically be met by the generating facility. In these cases, failure to comply could result in harsh penalties [6]. Therefore, technical solutions in the form of performance upgrades should be available to generation stakeholders to help avoid a non-compliant situation. The following sections will present a few close-to-market solutions that can improve the LVRT and RoCoF capabilities for synchronous generators.

Parameters Affecting Transient Stability for Conventional Generation

The ability of a synchronous machine to maintain synchronism with the grid after a local fault is largely determined by the strength of the grid connection, initial loading, and the power factor of the generator. More specifically, the generating unit is most prone to instability when the following initial conditions are encountered:

- Rated power.
- Under-excited operation.
- Equivalent system reactance is high (i.e.weak grid strength).

These operating conditions are generally used as a conservative measure to calculate the worst case stability margin of a synchronous machine. The worst-case fault condition to determine this stability margin is from a three-phase bolted fault in the transmission grid, usually near the point of interconnection of the generating plant. The ability of a machine to successfully ride-through this type of event is measured by the Critical Clearing Time (CCT). The CCT of a unit is defined as the maximum fault period under which a unit remains in synchronism with the grid after the fault is isolated. Protective relaying in the grid is set to ensure a fault is isolated before exceeding the CCT of a unit, thus avoiding loss of synchronism.

Grid code regulations are in some cases demanding CCT durations irrespective of grid strength, standard protection practices, and existing machine designs. As such, the transient stability of a unit is challenged beyond its ability to recover from a fault. In this situation, the rotor angle of the synchronous generator would pull out of step with the grid and loss synchronism. Similarly, for RoCoF excursions, when the grid frequency drops rapidly, the relative phase angle between the synchronous generator and the grid increases causing the synchronous generator to decelerate. When this happens, the rotor angle of the synchronous generator may deviate significantly from the phase angle of the grid such that the synchronous generator may lose synchronism.

A benchmark single machine-infinite bus test system is displayed in Figure 3. This machine is representative of a typical 500 MVA class combined cycle power plant. The performance of this unit is given by Figure 4 which shows the corresponding CCT as determined at its rated operating conditions, O.E. (0.9 lagging), unity, and U.E. (0.95 leading), over a range of equivalent system impedances. It is clear that the lowest critical clearing time for a bolted fault at the high voltage interconnection bus (POI) occurs when the machine is under-excited and the grid strength is weak (X_s of 0.45 p.u. in this case). Figure 4 shows the CCT capability of the single machine-infinite bus test system for a range of operating conditions (grid strength and power factor). As an example, the test generator can ride through a 155 ms, 3-phase bolted fault when the machine is operating U.E. and the grid strength (X_s p.u,) is 0.2 p.u. CCT continues to decrease as X_s increases.

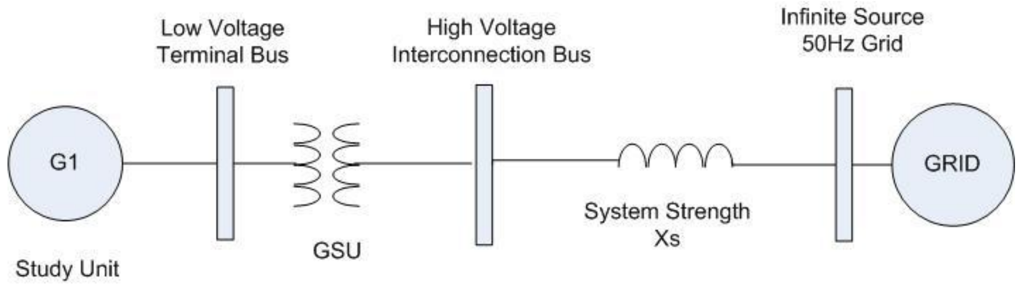


Figure 3. Single machine infinite bus test system.

Some emerging grid code requirements in different parts of the world are requiring critical clearing times of up to 300 ms for the entire reactive operating range of a unit. Comparing the performance characteristics of the 500 MVA class benchmark unit with a 300 ms CCT requirement, it becomes obvious that present-day synchronous machines may encounter compliance difficulties. If a unit is unable to comply with a particular grid code due to a limited transient stability margin, then equipment solutions presented in the next section may be considered for upgrading an existing or a new-construction unit.

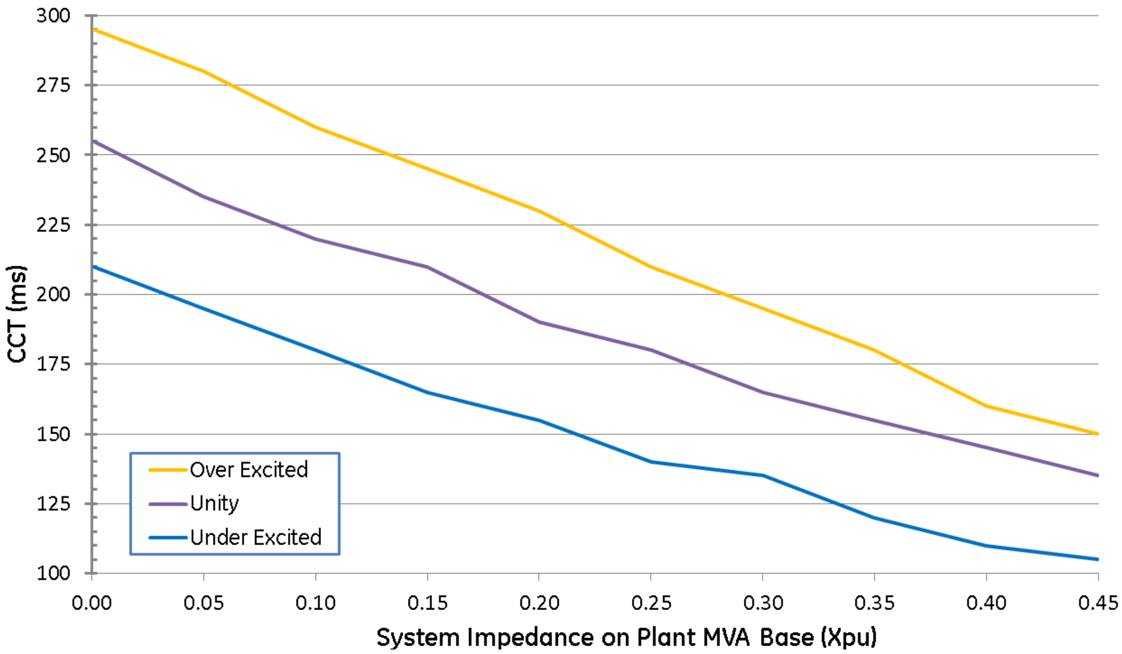


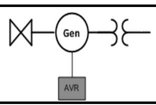
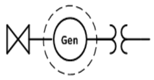
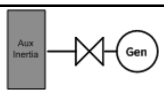
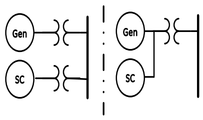
Figure 4. Base line plant performance (CCT vs. system strength at selected power factors).

Methods to Enhance the Fault Ride-Through Compliance of Conventional Generation

This section presents and evaluates several hardware methods, applied within the plant boundary for improving the transient stability of conventional synchronous generation. The CCT is used as a metric to compare the performance improvement of each method over the benchmark test-unit performance, shown earlier in Figure 4. The U.E. operation gives the most limiting stability margin and thus was used as the operational constraint for evaluating each upgrade method.

The described methods are close-to-market applications such that the performance ride-through benefits, for voltage and frequency events, are economically feasible and realistic in a short-term period relative to the time-period for constructing a new power plant. Table 1 summarizes each option evaluated for enhancing the CCT capability of synchronous generators and provides a simplified graphic representing hardware upgrade, general performance benefits, and the expected capital expenditure.

Table 1. Methods for increasing the CCT under LVRT grid conditions.

	Pictorial Representation	Configuration	Improvement	CCT	Cost
Higher field excitation ceiling		Increased power transformer and bridge for 2.5 - 3.0 pu excitation ceiling voltage	Increased field excitation voltage improves post fault power transfer	Very Low	Very Low
Generator Oversizing		Lower machine resistance and reactance	Lower initial internal rotor angle increase stability margin	Medium	Medium
Auxiliary Rotational Inertia		Increased power train mass through flywheel application or redesigned turbine shaft sections	Increased machine inertia constant defers angluar acceleration	Medium	N/A
Parallel Condenser Configurations		Connected as common terminal and GSU fed or common high side bus fed through separate GSU	VAr distribution provides lowered initial internal rotor angle, transient power exchange (braking), and better post fault power transfer	High	High

1. Higher Field Excitation Ceiling

This solution has been studied previously with similar performance benefits [10], as reported here. Upgrading to a higher excitation ceiling voltage helps to improve post fault voltage recovery, thus improving synchronizing torque following a voltage depression. Normal full field forcing is typically 1.6 p.u. to 2.5 p.u. while higher ceiling levels are upwards of 3.0 p.u.

Figure 5 presents the margin improvement in CCT of the benchmark test unit when ceiling voltage was increased from 1.6 p.u. to 2.5 p.u. The results show that this approach provides very limited incremental CCT benefit, although the benefits are largely independent of system strength.

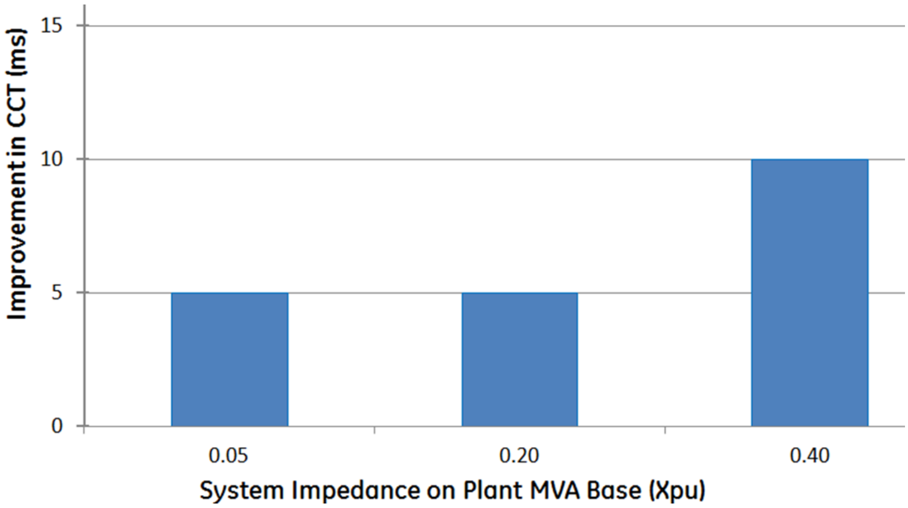


Figure 5. CCT performance improvement for higher excitation voltages.

2. Over-Sized Generator MVA Rating

The next method examines the benefits of installing a larger generator relative to the turbine capability. Increasing the MVA size of the generator reduces machine reactance and thereby increases the stability margin of the machine [11]. The performance improvement was evaluated by determining the factor of over-sizing required to incrementally improve the CCT margin of the test unit. The blue colored trace in Figure 6 shows the required increase in size of the generator for an incremental benefit in CCT. Note, that this benefit is relative to the benchmark test unit CCT of 155 ms while operating in an U.E. condition and at a grid impedance of 0.20 p.u. This method shows that the CCT can be increased by 140 ms with a 2.3 times increase in the generator MVA size. Over-sizing a unit may not lend itself practically to existing units but has potential for new-construction projects.

3. Additional Turbine-Generator Inertia

Another method examined for CCT improvement was to increase the rotational inertia of the turbine-generator shaft. Extra inertia could be in the form of an auxiliary flywheel added to the turbine shaft or by oversizing the shaft itself during the manufacturing process. This method would delay acceleration of the rotor during a fault or a low voltage condition and thus improve the transient stability margin. The incremental performance was evaluated by determining the inertia over-sizing factor required to incrementally improve the CCT margin of the test unit, shown in the black colored trace of Figure 6. Again, this performance is relative to the benchmark test unit CCT of 155 ms while operating in an U.E. condition and at grid impedance of 0.45 p.u. The results indicate that the CCT is increased by 140 ms with a 7 times increase in the turbine-generator inertia.

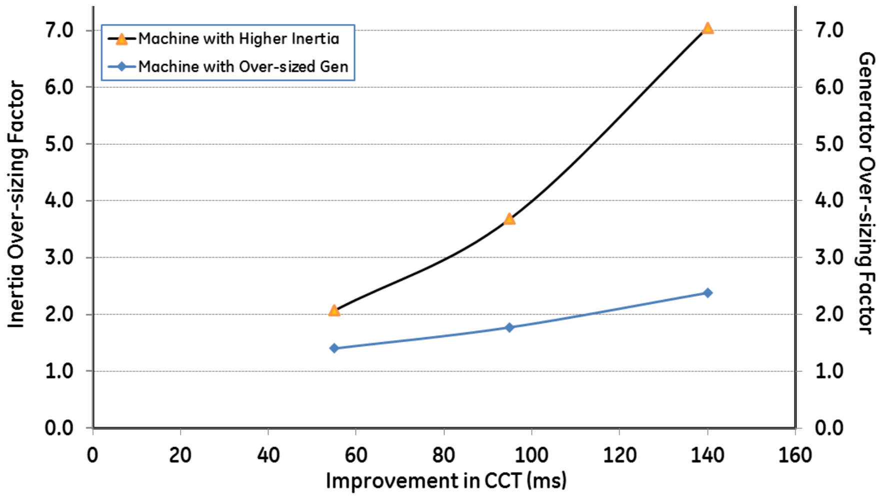


Figure 6 Improvement of CCT for higher generator MVA rating (blue curve, right scale) and turbine-generator inertia (black line, left scale).

Comparing the different over-sizing methods in **Figure 6**, it is obvious that for a given level of improvement in CCT, the turbine-generator inertia has to be increased many times more as compared with increasing the generator MVA. Additionally, when over-sizing shaft inertia of this magnitude, shaft torsional vibrations may present separate reliability design challenges. Given this analysis, it shows that on a factor-to-factor basis, oversizing a generator is a more practical solution than increasing the turbine generator inertia.

4. Parallel-Connected Synchronous Condensers

Another effective close-to-market method to improve performance of a generating unit is to connect a synchronous condenser in parallel (or shunt) with the synchronous generator. Two shunt configurations have been studied: (a) a separate step-up transformer to the high voltage bus of the generator GSU (referred in the paper as "parallel condenser") or (b) on the low voltage side of the generator GSU, thus sharing the same bus (referred in the paper as "common condenser").

Both of the shunt configurations allow the generating unit to operate in a more stable pre-disturbance power factor while the total plant output remains unchanged. This is accomplished with a plant level coordinated VAr sharing control scheme between the generating unit and the synchronous condenser. The control scheme allows the generating unit to be pushed closer to an O.E. state while the condenser is pushed to an U.E. state. As such, the plant operating condition remains unchanged, but the generating unit is inherently in a more stable pre-fault operating condition. During the faulted period, unit performance can be further improved with a common-condenser hardware configuration. This happens by an inherent transient power exchange from the generating unit to the synchronous condenser. The common-condenser configuration acts as a local power sink to the generating plant; thus the accelerating energy of the generating unit, during the fault, is transferred to the condenser, which limits the rotor angle swing of the generating unit. Additionally, a high-inertia condenser, one with an auxiliary flywheel, can absorb more transient energy from the generator unit and thereby achieve an even better transient response. After the fault clears, both generating unit and condenser are again managed by the plant level controller to restore voltage and the allocation of reactive power. The combined reactive capability of both machines allow for a faster voltage recovery and more stabilizing post fault operation.

Figure 7 displays the CCT performance for an U.E. operation of the reference 500 MVA class unit with the described shunt condenser hardware configuration upgrades. The condenser was sized to be 0.5 p.u. of the MVA base of the generating unit. Note that when a high-inertia ("high-H") synchronous condenser is connected on the same bus as the generator, it can help to increase the critical clearing time by 150 ms over a wide range of grid strengths. This high-inertia condenser was sized with a four-fold factor on the H constant of a standard design condenser.

Other factors to consider when implementing a parallel-condenser or common-condenser is the impact of higher short circuit currents on circuit breakers and bus connections as well as any impact on transformer loading, especially in the case of the common-condenser. Some equipment modifications may be required and cannot be generalized in this discussion. Additionally, the arrangements described above for the parallel-condenser could be applied to an existing in-service plant as well as a new-construction projects.

The hardware configurations and control concepts described herein have been filed with the United States Patent Office and are currently pending.

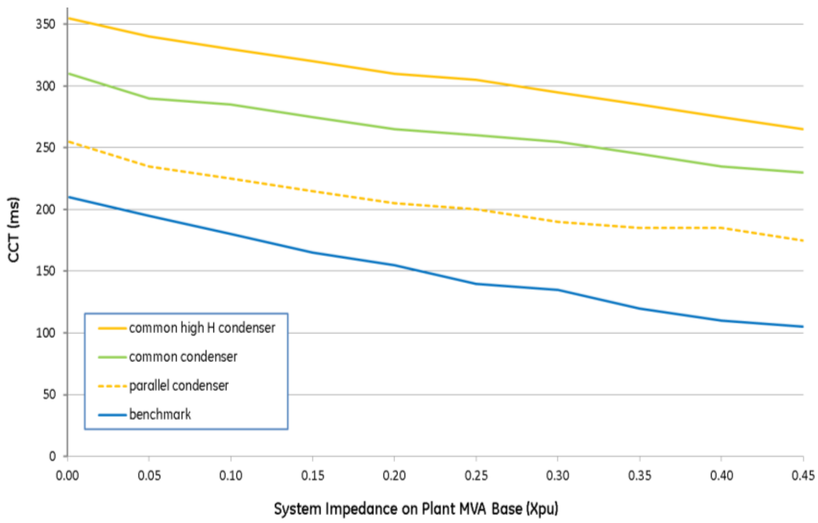


Figure 7. Synchronous condenser application performance (under-excited operation).

Methods to Enhance the RoCoF Compliance of Conventional Generation

As mentioned previously, some of the new interconnection grid codes require RoCoF compliance in addition to the LVRT requirement. This type of grid compliance requirement is currently mandated in Ireland [8, 9]. However, generators with higher RoCoF compliance capability can also generally

improve grid reliability especially in an islanded system, where a large loss of generation or import can challenge the frequency stability of the grid.
Table 2 displays the limiting RoCoF compliance of the base synchronous generator at -1.75 Hz/sec, when the unit is operating in an U.E. condition and the grid impedance is 0.2 p.u. To simulate this event, a frequency ramp was applied at the Infinite Source bus in Figure 3. The table also shows the limiting RoCoF compliance of the base unit with two other upgrades: 10% additional inertia (H) and a 10% larger generator MVA. Increasing the inertia and generator MVA were also shown as options for improving the LVRT compliance of the base machine.

Table 2. Improvement in RoCoF Compliance with the proposed solutions.

	Limiting ROCOF Compliance	Relative RoCoF Performance Compared to Base Machine
Generator Auxiliary Inertia (10% higher H p.u.)	1.5 Hz/sec	-14%
Base Machine	1.75 Hz/sec	0%
Oversized generator (+10% MVA)	2 Hz/sec	14%

The results indicate that an increase of 10% generator shaft inertia reduces the generating unit RoCoF down to -1.5 Hz/sec. This is because an increase in generator inertia results in a faster separation of the angle between the grid and the rotor under a frequency disturbance. On the other hand, a 10% increase in the generator MVA size can increase the RoCoF ride-through capability to 2 Hz/sec.

Shunt connected synchronous condenser is also a viable solution for in-service or new-construction generating units. Figure 8 compares the RoCoF capability of the benchmark unit with a common-condenser configuration and a parallel-condenser configuration. The results show that a common-bus condenser is the most effective strategy in improving the frequency ride-through capability. The same conclusion was obtained when measuring the effectiveness of different strategies in improving CCT of the test unit. This suggests that a single solution (common-bus condenser) can be used to improve both the LVRT as well as RoCoF compliance of the generator.

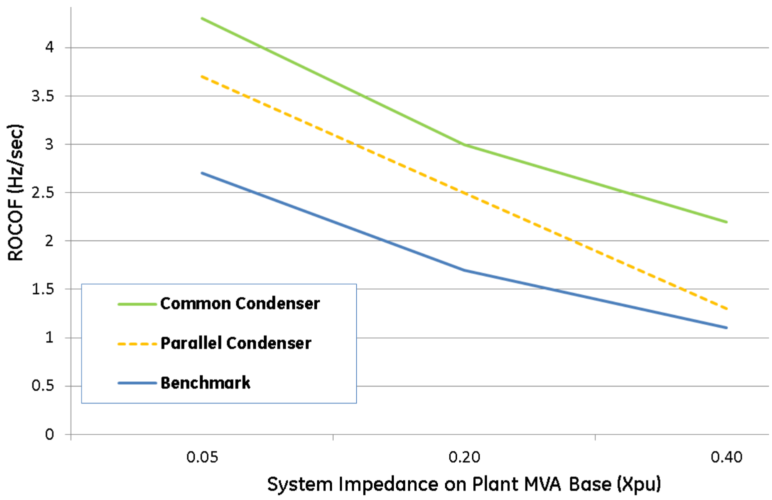


Figure 8. RoCoF capability with and without synchronous condenser.

Economic Considerations

The strategies described in this paper can increase the compliance limits of a synchronous generator, but they come at a cost to the plant owner. This section attempts to quantify the incremental benefits against the incremental capital expenditure of each solution. Note that additional capital expenditures in terms of reinforcing switchgear and bus work were not considered and are site-specific considerations.

Figure 9 shows the relative cost-benefit comparison for each upgrade strategy. The benefits are measured in terms of percentage improvement in CCT and the cost is measured in terms of the percentage increase over the base plant cost. For some solutions, a range of cost estimate is provided to capture the uncertainty in the estimate (indicated by a vertical bar). An ideal solution would be one that is both economic as well as technically practical. As such, a solution should be realized with a low capital cost but should provide sufficient performance benefits to meet a desired grid code.

The figure shows that a higher exciter ceiling voltage is an inexpensive solution, but provides marginal performance benefits. The more notable performance benefits come from oversizing a generator, which provides considerable improvement in CCT at relatively modest capital expenditure. However, the solution is not easily scalable outside product ranges. Paralleling the generator with a synchronous condenser (or high inertia condenser) can provide greater benefits and is a scalable solution, but comes at an incremental higher cost. Note that these solution options are additive and it is possible to pair different solutions to arrive at a different mix of costs and benefits.

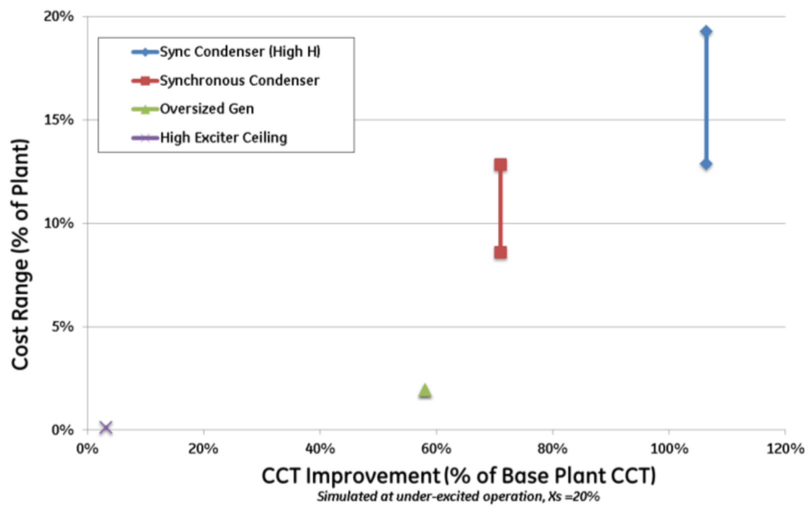


Figure 9. Relative cost versus CCT improvement for various upgrade solutions for synchronous generators.

Conclusions

As grid codes around the world evolve in response to higher levels of non-synchronous generation, compliance is becoming more challenging for traditional synchronous generation. While non-synchronous machines can use power electronics and other means to comply with grid codes, the same options are generally not available for conventional units. The legacy options to improve synchronous generators performance (higher excitation ceiling voltages, etc.) are no longer sufficient and this new reality requires a new set of LVRT and RoCoF solutions.

This paper performed a high-level technical and economic viability assessment of several close-to-market methods to improve LVRT and RoCoF performance of synchronous generators. The results indicate that generator over-sizing and paralleling the unit with a control-coordinated synchronous condenser are the most effective and practically feasible solutions. Additionally, these methods are not mutually exclusive and provide additive performance benefits when combined to improve both voltage and frequency ride through capabilities for grid code compliance.

Beyond strictly meeting the challenge of grid code compliance, these upgrades inherently improve the transient stability margin of a synchronous generating unit. As such, particular grid conditions may require an improvement in system stability for reliable operation. These situations are more commonly seen in high renewable penetration and weak grid areas, or a combination of both.

The more recent and continuing influx of renewable generation has the tendency to displace thermal generation and in many situations, the renewable generators are located in remote grid locations. This trend, especially exaggerated in island systems, can easily create weak and sensitive conditions that leave the grid vulnerable during voltage and frequency events. Typically, transmission upgrades have been used to address these challenges and reinforce the grid. The unit upgrades described within this analysis is applied within the plant boundary as a generation-based grid reinforcement solution to improve the generator response under sensitive grid conditions. Figure 10 highlights the synergistic effects of promoting generation-based grid reinforcements for solving grid compliance and grid reliability challenges. The benefits of shifting grid upgrades to a generation-based solution generally include lower cost, less permitting required for right of way access, and faster implementation times than transmission upgrades. The close-to-market solutions presented in this paper not only improve grid compliance, but can also address transient and frequency stability issues present in high renewable penetration and weak grid areas.

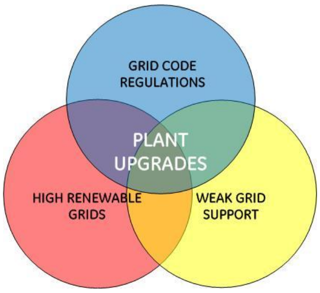


Figure 10. Synergistic application of unit upgrades for conventional generation.

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