Critical parameters of a synchronous alternator for a grid code compliant generating set

White Paper

Sridhar Narayanan

Abstract

Liberalisation of energy market combined with growing energy demand has led to an exponential growth in the number of embedded power plants. Unlike grids made up of large power plants, grids made of many smaller grids tend to be unstable. To minimise the impact of the unstable grids on the consumer, transmission and distribution system operators worldwide are coming up regulations – Grid Codes that specify performance expectations on power plants and therefore on the generating set and their associated components that make up the power plant. These codes are broadly categorized as static and dynamic. Static codes refer to expectations on steady state conditions and Dynamic codes – the expectations on transient stability and fault ride through capability. Achieving grid code compliance means that the power plant owners and the manufacturers of the components have to work together and individually. The focus of this paper is to broadly describe the effects of grid codes on design of engine driven generating sets and thereby define the scope of changes within the alternator. The authors specifically focus on key design features of the alternator that can be optimised to help the power plants achieve compliance. The design features that will be discussed have been established as the most significant influencers with power system simulations; some of them helping with achieving static grid codes and some of them with dynamic grid codes.

I. Introduction

The global electricity demand is growing at a rate of 2.4% every year[1] and the fastest way to address this demand is embedded generation – ad hoc power plants consisting of engine driven generating sets (Figure 1). Along with renewable, these embedded generation units make up a significant portion of the modern grids. Though there are environmental and economical benefits, distributed generation makes the grid less stable. In order to ensure continuity of power supply, electricity transmission and distribution system operators all over the world, with Europe in the lead are enforcing regulations – grid codes – that define performance expectations on power plants. Table 1 summarises the key aspects of a grid code document for Germany – voltage, power factor, frequency under steady state conditions and the required 'connection period' during a fault ride through. The grid codes can broadly be classified as static – steady state operating conditions and dynamic – transient operating conditions. Designing power plants and associated components to comply with grid codes is challenging, especially for generating sets smaller than 5 MW. Sections II, III and IV have been structured around trying to explain to the readers the nature of the challenge and its impact on the design of alternators for grid code compliant generating sets.

Figure 1: A Typical Power Plant made of smaller Gensets.

S.No	Quantity	Expectation
Static Grid Code		
1	Voltage variation	+/- 10%
2	Power Factor Range	0.95 lead to 0.95 lag
Dynamic Grid Code		
3	Voltage and fault ride through time	30% for 150 ms

Table 1: Grid Codes Germany

II. Grid Codes - Challenges

The grid conditions mentioned in Table 1 mean that the alternator is exposed to thermal and electrical stresses. Combined with the need to comply with the codes, these requirements challenge the generating set components in numerous ways. This section explains the challenges for the alternator in particular. Consider a generating set connected to the grid through a reactance as in Figure 2a.

STEADY STATE CONDITION

Under steady state condition, the grid codes demand the alternator to supply the nameplate kVA for a wide range of voltage, power factor and frequency conditions. While the requirements from the lagging power factor condition is not so demanding, the leading power factor operating conditions expose the alternator stator to higher currents, higher mechanical stresses due to the stator currents and also reduces the electromagnetic coupling between the stator and the rotor. The weak electromagnetic coupling means the generating set is mechanically stressed and is close to its operating margin under steady state conditions.
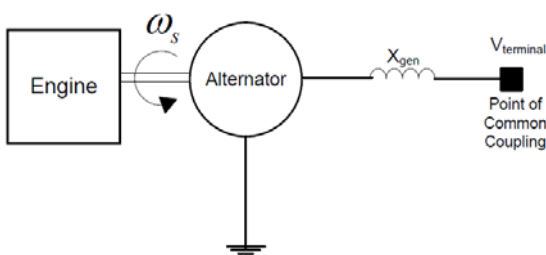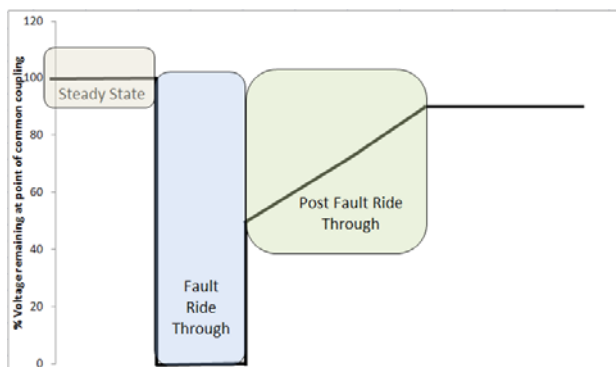

Figure 2a: Generating Set Connected to Grid

Figure 2b: Voltage Profile: Fault Ride Through Event

FAULT RIDE THROUGH

Figure 2b is a representation of the voltage profile of the 'grid' during a fault ride through event. The voltage at the point of common coupling drops to a very low value and the active load on the generating set also drops. The kinetic energy in the shaft accelerates the rotor while the generating sets works really hard to not pole slip (rotor magnetic field trying to catch up with stator magnetic field - stresses the rotor) for the duration of the fault as required by the grid codes. The acceleration of the shaft and the rotor stresses the alternator mechanically; while the low voltage at the alternator terminal induces short-circuit level currents in the stator windings which expose them to thermal and mechanical stresses.

POST FAULT RIDE THROUGH

The grid starts to recover depending on the local condition and the alternator that had previously accelerated is now attempting to connect to the grid with a different frequency and phase than the grid. This is similar to a game of 'tug of war' with the grid and alternator attempting to regulate each other's phase and frequency. This results in huge mechanical forces on the alternator. Figure 3 is the simulation result of calculation of forces on the alternator windings during a fault condition and Figure 4 shows the impact of the 'tug of war' on an alternator shaft (in-house test result).
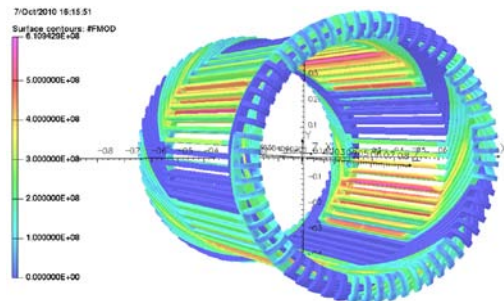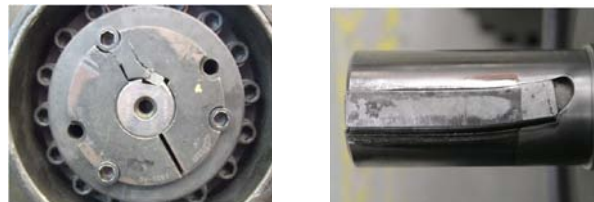

Figure 3: Distribution of Electromagnetic Forces on Alternator Windings

III. Study Methodology

The requirements as described in the previous section would imply that an alternator design to support grid code compliant generating sets would involve more than just complying robustness and durability. There is a need to understand the factors influencing both compliance and robustness the critical parameters. This section describes the methodology adopted by Cummins Generator Technologies' Engineers to determine these critical parameters.

Cybergen[2] is a tool that was developed at Cummins Generator Technologies to study the effect of transients on alternators. Figure 5 is a schematic of the tool.
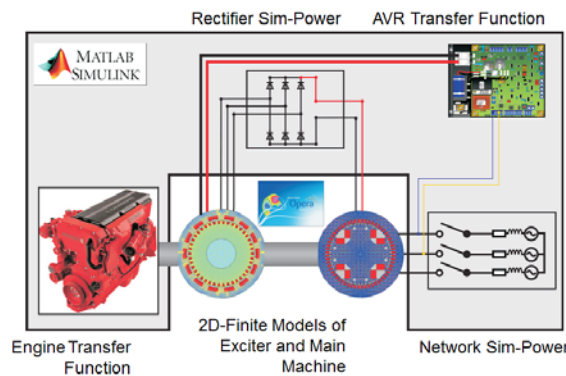

Figure 5: Schematic of Cybergen

Cybergen combines the detailed finite element models of alternators with mathematical models of the engine, controls and the application thereby running accurate simulations of the alternator in an application. Both mechanical and electromagnetic performance of the alternator can be evaluated. Combined with test data, the tool was used to define the critical alternator characteristics / parameters that impact design for grid code compliance.

IV. Critical Parameters

Using the tool described in Section III, simulations of the generating set connected to the grid were run at various operating points. To summarise the results of the simulation, this section will be split into Static Grid Codes, Fault Ride Through and Robustness – the three key requirements to be satisfied.

STATIC GRID CODES

The key issues related to designing alternators for static grid code compliance are:

(i) Thermal:

Due to the leading and lagging power-factor conditions and the huge voltage range, the rotor and stator windings of the alternator are exposed to high currents and therefore high temperatures. It is crucial to understand the temperature rise in various scenarios. The current and losses in the rotor and stator and the effectiveness of cooling in the alternator are what influence the temperature rise.

(ii) Mechanical:

The currents in the windings of an alternator induce an electromagnetic force which causes the windings to vibrate at twice the fundamental frequency of the supply. It is therefore essential to consider these vibrations while designing the windings of an alternator. Care should be taken to avoid resonance. The geometry of the windings – overall length, mass, insulation material have a significant impact on the mechanical performance of the alternator.

(iii) Electro-Magnetic:

It is important that the generating set remains stable for all operating points within the boundary specified by the grid codes. As the mechanism behind static stability of alternators have been discussed in numerous publications and most recently in [3], suffice to say that the alternator must be designed with the correct value of synchronous reactances – X_d and X_q. These parameters affect the 'load angle' of the generating set. The higher the load angle, the closer the set is to stability limits.

FAULT RIDE THROUGH

Even though the dynamic grid codes involve much more than fault ride through, the design of the alternator itself is focussed on the fault ride through. Achieving dynamic grid code compliance would involve the generating set packagers, engine manufacturers, alternator manufacturers and control systems specialists working together to integrate a 'grid code compliant genset'. The fault ride through requirements in grid codes state that the generating set stay connected to the grids for a specified duration of fault on the grid (150ms-250ms). The acceleration of the rotor described in the previous section during a fault ride through would mean it would be difficult to maintain the stability of the alternator under dynamic conditions. Some of the key factors influencing the behaviour of the alternator during a fault ride through are:

(i) Initial conditions:

The steady state load angle of the generating set is one of the most significant contributing factors to determining dynamic stability. As the rotor accelerates, care must be taken so that the 'dynamic load angle' does not reach a critical value. Smaller the steady state load angle, longer it takes for the rotor to accelerate to this angle and therefore the generating set can stay connected stably for longer.

(ii) Inertia of the alternator:

The laws of physics state that heavier a body, smaller its acceleration for a given force. So the inertia (mass and diameter of the rotor) is fundamental to solving the problem of dynamic stability. However, there are practical limits on the amount of mass that can be added to the rotor and how much the diameter of the rotor can be increased by.

(iii) Back-Swing:

Back-Swing is the phenomena where the alternator slows down for a few tens of milliseconds after the fault before it starts to accelerate again. This buys the generating set additional time. The factors affecting Back-Swing are the subtransient reactances – X''_d, X''_q and their ratio (subtransient saliency).

ROBUSTNESS

The stresses in the various components of the alternator need to be studied in order to design a robust alternator for grid code compliance.

(i) Stator Windings:

The mechanical and thermal stresses caused by the increased current levels in the stator windings need to be minimised. The vibration signature of the alternator must also be studied so 'resonant modes' can be avoided. Figure VI shows simulation results of a study conducted to determine the normal modes of vibration of the stator windings.
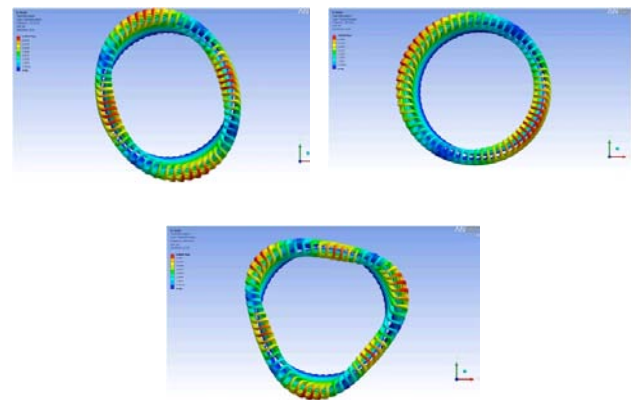

Figure 6: Normal Modes of Vibration

Conclusion

Studies on whether additional bracing would be required to protect the windings are also required.

(ii) Damper cage:

The long-fault ride through scenarios means the damper cage gets hot and is also exposed to mechanical stresses. Numerous tests and simulations are required before designing the damper cage or evaluating the suitability of the existing damper cage.

(iii) Shaft:

Figure 4 showed the extent of damage a failed synchronisation event could do to the shaft. If the masses of the alternator and the engine are not matched correctly, then some of this torque could be transmitted to the engine as well. So it is essential to understand the nature of torque transients that occur in the alternator. Designing the shaft to accommodate these transients would ensure a robust shaft design.

(iv) Rectifiers:

Low leading power factors and huge current in-rush can lead to a high negative voltage on the rectifiers commonly used in the rotor electrical circuit thereby damaging it. Understanding the magnitudes of these voltages is key to designing measures to protect them.

While distributed generation is a quick solution to the ever growing electricity demand, the conditions imposed by grid codes pose great challenges to the design of generating sets for distributed power generation. It might appear that using permanent magnet machines with full power converters may be a straight forward solution, but high initial costs and effects of having too many permanent magnet machines on the grid stability need to be understood. Modern tools, as the ones described in this paper can be used to make design recommendations, but practical considerations and time to implement versus time to enforcement of codes make the implementation of these changes even harder. With that in mind, the grid codes have transformed what seemed to be a stable concept - 'synchronous alternators' into an exciting area where numerous innovations are possible. Furthermore, with the uncertainty in the rare earth metal prices, wound field synchronous alternators could well become the preferred electrical machine type for use in grids.

References

[1] Source: International Atomic Energy Agency

[2] Neil L.Brown, Alex Michaelides "Cybergen: Modelling the Design Challenges for Small Embedded Synchronous Alternators Connected to Increasingly Unstable Networks" Proceedings of Power Electronics Machines and Drives 2010, UK.

[3] Sridhar Narayanan et al "An analytical tool to check for static grid code compliance of generating sets" Proceedings of the 45th Universities Power Engineering Conference, 2010, UK.

[4] Sridhar Narayanan et al "Fault Ride through effects on alternators connected to the grid" Proceedings of Powergen Asia 2011, Kuala Lumpur.

[5] J.Machowski, J.W.Bialek, J.R.Bumby, "Power System Dynamics, Stability and Control", 2nd Ed. John Wiley & Sons Ltd.

[6] J.M.Fogarty "Connections between alternator specifications and fundamental design principles", Proceedings of the International Electrical Machines and Drives Conference, 2001.

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