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Fault Ride Through Effects on Alternators Connected to the Grid

White Paper

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Abstract

A significant shift in environmental policies and energy deregulation in the last decade has led to the growth of renewable energy sources. Led by the development of wind farms throughout Europe, changes to 'Grid Codes' have been implemented requiring embedded generation schemes to stay connected during the presence of system faults (Fault Ride Through requirements). This is contrary to the traditional approach, whereby the power plants were not required to stay connected. Changes to the grid codes also include wider operating limits under steady state conditions (Voltage, power factor limits etc). These changes impose significant stresses on the genset and associated components such as the alternator. Genset manufacturers are posed with the problem of not just dealing with these new challenging operating conditions, but also variation in the grid code requirements across various network operators and countries.

This paper discusses the experience of Cummins Generator Technologies as an alternator manufacturer in addressing these challenges. For the purpose of this paper the authors perform a case study on the impact of the German grid code on the alternator design and performance and then attempt to provide a generalised view of the impact of grid codes on alternator sizing / selection.

I. Introduction

Traditionally, industrial countries have generated most of their electricity in large centralised facilities, such as fossil fuel (coal, gas), nuclear, large solar power plants or hydropower plants. Although these plants have excellent economies of scale, they usually transmit electricity over long distances and negatively affect the environment. More recently, a surge in the concerns over climate change has led to a modification of energy policies so as to facilitate energy to be produced and consumed in an eco-friendly manner. These changes have brought about an increase in what is now called distributed generation. Distributed generation also seems to fit in well with being able to accommodate a grid architecture with renewables. While distributed generation plants have low maintenance, low pollution and high efficiencies, they have a tendency to make the grid unstable. It is for this reason that a number of grid operators around the world have begun enforcing performance expectations on generating sets. These expectations – called 'Grid Codes' exist primarily to ensure stable & continuous operation of power systems. The most challenging aspect of grid codes is the Fault Ride Through / Low Voltage Ride Through requirements. Table 1 and Figure 1 summarise the key requirements of the German grid operator – E.ON [1] and will be the focus of this paper. Low Voltage Ride Through refers to an event when the voltage at the point of common coupling drops below a critical value.

Earlier, power plants could disconnect from the grid in the event of a LVRT; but grid codes require that power plants stay connected to the grid for period of time during a LVRT event – without going unstable. The situation is worsened because of the static requirements that grid codes demand.

Quantity E	xpectation
Voltage variation	+/- 10%
Frequency deviation	+/- 2%
Power Factor Range 0	.95 lead to 0.95 lag
Power delivered at above conditions	100% engine load
Fault ride through time	150 ms
PCC voltage during fault ride through	30% nominal

Table 1: German Grid Code

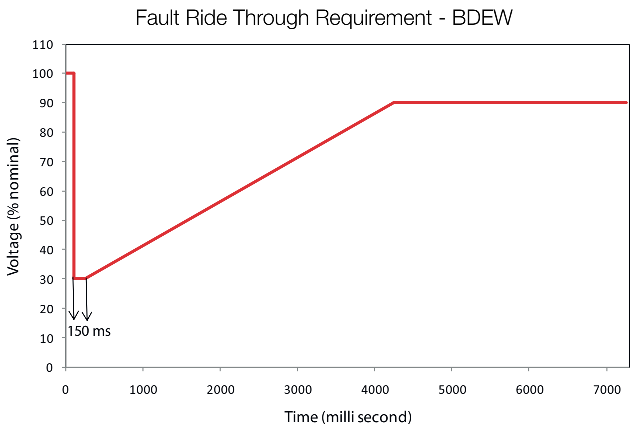


Figure 1: Low Voltage Ride Through – Germany

These include continuously operating the power plant, and hence the generating set at an underexcited power factor, while providing rated load at lower than nominal point of common coupling voltage. In this paper, the authors explain the effect of a LVRT on an engine driven alternator connected to the grid and hence explain the challenges that Cummins Generator Technologies as an alternator manufacturer has faced while designing alternators for such applications.

II. Fault Ride Through - Description

Figure 2 represents an engine driven genset directly connected to the grid without a transformer.
The performance of the genset under steady state grid code conditions has been discussed in detail by S. Narayanan et al [2] and so the focus of this paper will only be on the performance of the genset during a fault ride through Earlier, power plants could disconnect from the grid in the event of a LVRT; but grid codes require that power plants stay connected to the grid for period of time during a LVRT event – without going unstable. The situation is worsened because of the static requirements that grid codes demand.

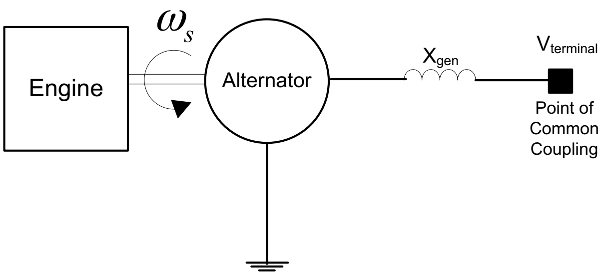


Figure 2: Engine Driven Genset

The E.ON code requires that a genset be capable of staying connected to the grid without losing stability for up to 150 ms in the event of a fault ride through and then smoothly transition back into its pre-fault operating point once the grid returns.
To be able to understand the challenges posed by a fault ride through condition to an alternator, a basic understanding of the fault ride through mechanism is needed. To illustrate the basic mechanism of fault ride through, the authors describe the fault ride through as two independent events – (A) a genset going into a fault and riding through and (B) the fault clearing and the grid coming back online.

A. Genset Going into a Fault and Riding Through

The behavior of a genset riding through a fault is a transient stability problem. Assume that before the fault occurs, the genset is operating at some steady-state condition. The engine is delivering some torque Tmech to the alternator that is supplying an electromagnetic torque Tem to some electrical load. For stable operation of the genset, the mechanical torque must equal the electromagnetic torque.
During a fault, the alternator is no longer supplying real power and this causes all the stored energy in the engine to accelerate the rotor and thereby increasing the risk of a pole-slip. It is during this phase that pole-slip must be avoided according to grid codes.

B. Fault Clearing and Grid Coming Back Online

The alternator that has accelerated during the fault ride through now gets connected to the grid that returns to pre-fault levels. This would mean that there is a likelihood of an out of phase synchronisation event. The difference in the alternator and grid voltages are determined by how much the alternator has accelerated by which is again a function of the alternator design and the fault clearing time. The extent of out of phase synchronisation needs to be minimised to reduce damage to the genset and to return to pre-fault operating points quickly and within the time frame recommended in the grid codes.

III. Fault Ride Through Effects on an Alternator

Section 2 described the phenomena of fault ride through and the events that the genset is exposed to during a fault ride through. In this section, the authors explain the effects of fault ride through on an alternator. The performance of alternator pre-fault ride through, during fault ride through and post fault ride through will be addressed separately so as to fully describe the impact on the alternator. It is assumed that the genset is operating at a worst case steady state operating condition as dictated by the E.ON code – i.e. 0.95 leading power-factor while supplying 100% load at 10% lower than nominal voltage [2].

A. Pre-fault Ride Through

Steady-state power delivered (Pe) delivered by the genset is given by (1) [3].

(1):

$$Pe = \frac{E_q V_T}{X_d} \sin\delta + \frac{V_T^2}{2} \frac{X_d - X_q}{X_q X_d} \sin 2\delta$$

The in (1) is the steady-state load angle of the alternator and defines the static & dynamic stability limits of the alternator according to (1) and (2) [3].

(2):

$$P_m - P_e = \frac{2HS_n}{\omega_s} \frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt}$$

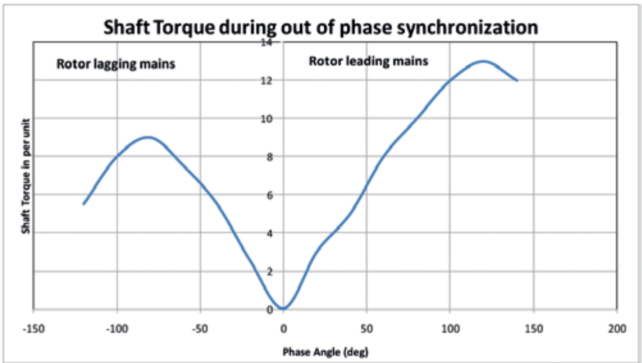
For a loading condition defined in the preceding part of this section, the steady-state load angle tends to be high – due to the leading power factor operation and lower point of common coupling voltage condition. Under this operation, the stator is operating at anelevated temperature (thermally stressed); there is reduced electromagnetic coupling between the rotor and stator due to the under-excited condition.

B. Fault Ride Through

The terminal voltage (Vterminal from Figure 2) of the genset drops to 30% of its nominal value. This reduces the real power delivered by the alternator by 70%. As the mechanical time constants are much bigger comparedto the electrical time constants, the engine is supplying 100% of the genset kilowatts. The excess kinetic energy stored in the shaft of the genset accelerates the rotor. The amount ofacceleration is determined by (2). It is during this operating regime that the grid codes require the genset does not run away into a poleslip scenario but remain stable for a smooth connection back to the grid. Acceleration of the rotor induces high currents in the dampers; longer the duration of the fault ride through, higher the thermal stresses on the damper bars. A fault ride through also induces huge short-circuit like current transients on the stator windings. These currents lead to large electromagnetic forces on the windings thereby stressing them and impacting insulation life.

C. Fault Clears, Grid Returns

The genset that has accelerated during the fault is now connected to the grid after the fault hasbeen cleared. The voltage of the alternator and the grid do not match and this leads to an out of phase synchronisation. Energy is exchanged between the alternator and the grid as one tries to pull the other back into synchronism. An outof phase synchronization involves large currenttransients on the stator, large torque transientson the shaft, and heating of damper bars. Figure 3 shows the plot of shaft torques (in per unit) for synchronisation at different phase angles on a test machine. Figure 4 shows pictures of the shaft (around the key area) of the same test machine damaged due to the large torque transients that occur during an out of phase synchronisation event. The phase angle at which the out of phase synchronisation happens depends on how far the rotor has accelerated from its initial position and how long the fault lasted.



The shaft torque in Figure 3 refers to the torque calculated using (3)

$$T_{shaft} = T_{em}\frac{J_{drive}}{J_{alternator} + J_{drive}}$$

Figure 3: Shaft Torque during out of Phase Synchronisation

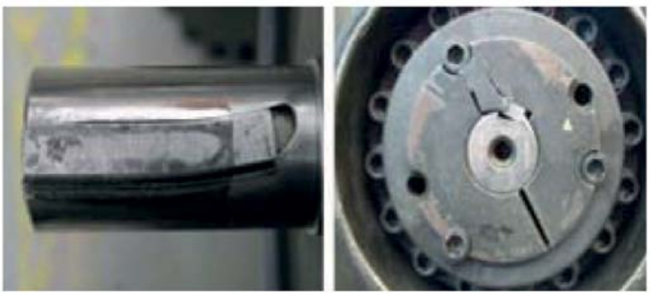


Figure 4: Damaged Key Due to Torque Transients

IV. Design of Alternator - Fault Ride Through Applications

Design of the genset for a grid code compliance / fault ride through application involves design of alternator and the engine individually and as a system for optimum performance. This section describes the lessons learnt by Cummins Generator Technologies while analysing alternator designs for grid code compliance / fault ride through applications. Design for a grid code compliance application involves:

A. Design for compliance

B. Design for robustness

A. Design for Compliance

Grid codes impose performance expectations during steady-state conditions and during a fault ride through.

(a) (1) suggests that the best way to maintain static stability is to keep the steady state load angle low by tuning the reactances (Xd, Xq). Xd should be lowered as necessary to stay well within static stability limit [2].

(b) Fault ride through requirements state that the genset must not pole slip up to the maximum fault clearing time stated by the grid codes – 150 ms for Germany. Pole slip is caused by excessive acceleration and a high steady state load angle of the alternator; pole slip can therefore be avoided by designing an alternator with a low Xd to ensure a low enough steady state load angle, a high inertia constant (rotor inertia / machine kVA) to reduce acceleration during transients and the sub-transient reactances (X"d, X"q) and hence sub-transient saliency to tune the electrical time constants.

These changes involves significant modifications to the electrical machine design; for example, an optimal tuning of the reactance involves either a derate or designing the machine with a bigger air gap. Any change to the machine design (like air gap increase) will affect the overall performance of the machine (say efficiency) and so care needs to be taken to ensure overall performance does not take a hit. There is also a limit on how much inertia can be added to any alternator.

B. Design for Robustness

To operate a genset in a grid code compliant application means to expose the alternator to huge forces and stresses – both thermomechanically and electrically. The various causes of stresses in the alternator are:

(a) Thermal stresses on the stator windings– caused by over-current conditions (reduced voltage under steady-state operation): danger to the lifetime of the insulation – alternator needs to be de-rated

(b) Mechanical stresses – the huge current transients induce large electromagnetic forces on the stator windings which cause displacement / vibration of the windings.

Figure 5 captures the 3 components of the electromagnetic force in an electrical machine and what causes them - Current transients are a function of the sub-transient and transient reactances of the alternator and hence by may be modified to reduce the fault currents and hence winding forces to acceptable levels.

Additionally, mechanical reinforcement of the windings can be ensured by designing a suitable bracing and picking the right impregnation for the windings to minimise vibrations / winding displacement.

(c) Thermal stresses on the damper bars – due to the huge currents induced during long fault ride through scenarios and the simultaneous electromagnetic forces that act on them due to large current transients

(d) Mechanical stresses on the shaft – out of phase synchronisation can exert immense forces on the shaft and without the right ratio of alternator to engine inertias, these torques can cause significant damage to the engine.

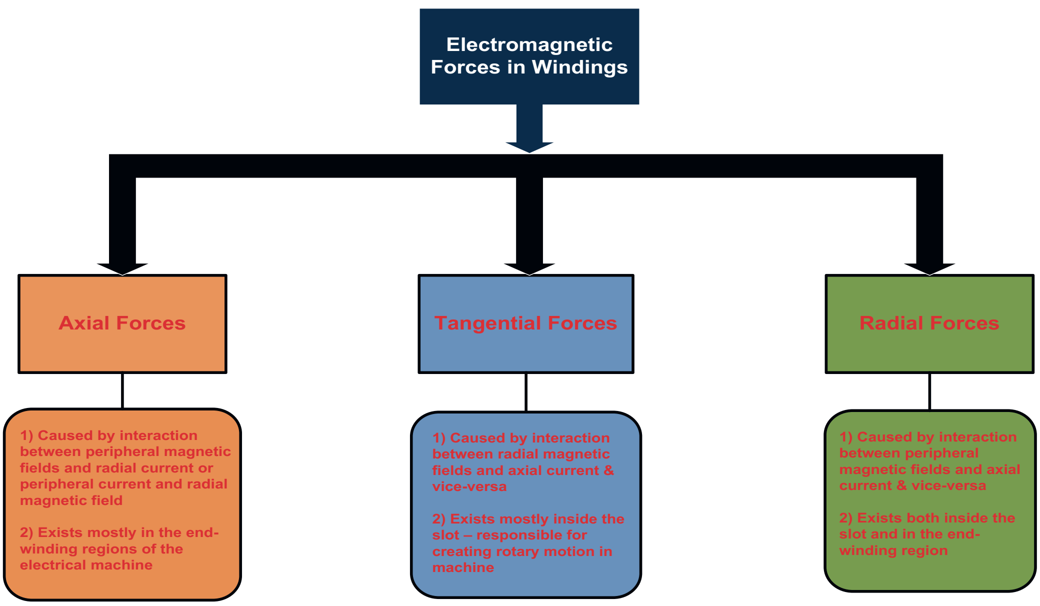


Figure 5: Electromagnetic Force Components in Alternator Windings

Conclusion

Figure 6 [4] compares the magnitudes of various forces on generator windings and reinforces the need to understand these forces while designing a robust alternator that is also grid code compliant. S.Narayanan et al [2] have shown that for an alternator to satisfy the steady state requirements of the German grid code, the short-circuit ratio of the alternator needs to be at least 0.45 which puts the value of Xd (main d-axis reactance) at around 2.28 pu. If the same machine had to be then optimized to satisfy fault ride through requirements, a further reduction in Xd is required followed by an increase in the inertia and sub-transient reactances of the machine to ensure robustness and grid code compliance. A high sub-transient reactance to reduce forces on windings also means reduced fault current levels and low starting torques. Modifying winding stiffness to minimize displacements involves re-configuring the windings to eliminate failure modes, modifying bracing and hence potentially modifying alternator packaging. The paper only includes alternator design with the German grid code as an example. There exist however, grid codes in other countries, some of which are more stringent than the German grid codes; this would mean a different alternator sizes for the grids in different countries. Unreasonable requirements such as voltage being depressed for a prolonged time after fault clearing, or overly long fault clearance times, in combination with abnormal operation conditions such as operation on overload or under excitation, might lead to fault ride through conditions that may not be met by commercially viable equipment. There is a need, therefore, for sound engineering judgment as to which conditions should apply any given network. Designing for absolute extremes or unlikely operation conditions is neither economical nor practical. Transmission and distribution operators should therefore set reasonable rules for fault ride through capabilities. An alternator that is meant to be used in a standby generating set should by nature be compact – hence smaller air gap (high power density) and reduced mass (for easy transportation). The introduction of grid code compliance and the proliferation of distributed generation would mean that these alternators that were traditionally used only in standby gensets will now have to become bigger and more robust to be allowed to connect to the grids.

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