LOW VOLTAGE RIDE THROUGH CAPABILITY OF GAS ENGINE DRIVEN UNITS

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ABSTRACT

Recent developments in European grid code regulations demand the inclusion of decentralized generation (DG) into their requirements. Gas-engine-driven generators, as a part of Europe's DG, need to comply with these requirements; and therefore procedures to receive admission are formed. Simulation stands for the most economical way to achieve this, however the simulation models need to be validated beforehand with the help of actual low-voltage-ride-through tests. This paper highlights the crucial steps of the validation procedure and questions the common practice of stability analysis and its applicability on gas-engine-driven units. Furthermore, events and operating conditions that may be critical and have not been considered so far for stability investigation are highlighted.

INTRODUCTION

The penetration of decentralized generation in Europe's power generation mix increased in the last years and will be further increasing. Requirements for these power plants to stay connected during faults and support the grid (fault-ride-through requirements) have been established, but are still varying between European countries. ENTSO-E tends to harmonize them in the future.

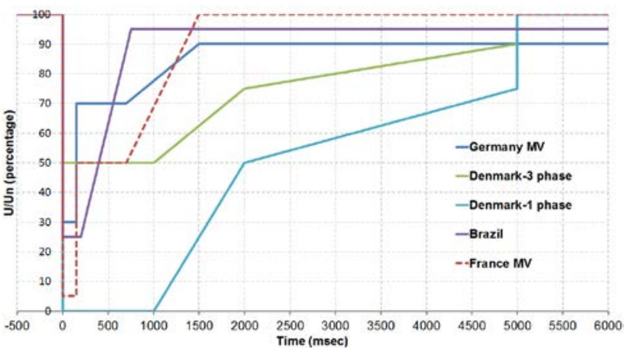

Fig. 1: Overview of selected dynamic grid codes currently applicable

Considering a generator during fault, typically an imbalance between mechanical power from the engine and electrical power fed to the grid emerges, leading to acceleration or deceleration of the rotor and possible loss of synchronism. Two basic effects can occur: The first and obvious is the acceleration of the rotor due to reduced electrical torque during the voltage drop. However, in some cases a deceleration in the first few cycles of the fault can be observed ("backswing"). This is mainly due to the high initial subtransient fault current with superposed DC-transient and resulting I²R losses of the grid.

To proof compliance with these fault-ride-through (FRT) requirements included in national grid codes, there is an aim to establish guidelines in determining the FRT-behavior of generating units. Regarding these guidelines, Germany has taken the leading role - and the "Fördergesellschaft Windenergie" (FGW), a development association for renewables, has issued several technical regulations (TR's) that describe procedures to, among others, determine the electrical properties and certify power generating units. Primarily aiming on decentralized, renewable generation out of wind energy, the guidelines have been adopted for photovoltaic and combined heat and power plants (CHP) as well. Power plant operators need to comply with these requirements to receive admission.

According to the TR's, compliance can either be verified by measurements on the power generating system or by studies with a certified dynamic simulation model. However, due to economic factors, i.e. costs for the test setup and time effort, the simulation is preferred in most cases. Irrespective of the method, the results of a compliance-test need to get approved by an independent certification body.

MEASUREMENT

To test the FRT behavior of a power generating unit, an appropriate test setup is installed (Fig. 2). A series connected reactance (Z_1) is activated by opening the circuit breaker CB_1 and used to limit the grid's short circuit current. After activation of the series reactance, transient effects need to decay. The ratio of fault reactance (Z_2) to series reactance (Z_1) determines the level of voltage dip. The fault is activated after the system has reached steady-state via circuit breaker CB_2, which also determines the fault duration.

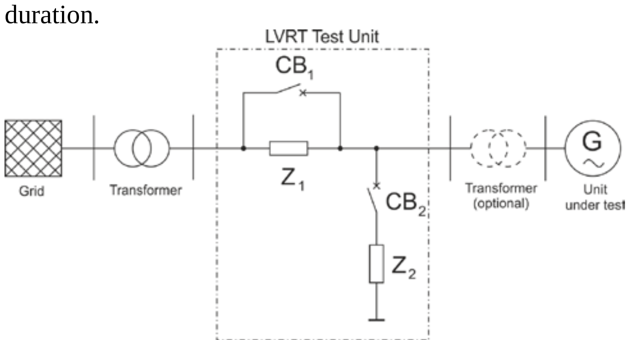

Fig. 2: Single line diagram of a setup to measure effects of a fault-ride-through on a generating unit

Tested scenarios are based on a worst-case assumption: under-excited operation with a power factor of 0.95, where fully- and partly-loaded cases are tested. The condition for the generating unit to successfully pass a test according to the TR's is to stay connected to the grid and provide 95% of pre-fault active power within 5 seconds after the fault.

SIMULATION

Requirements

Main objective of the simulation is to represent the electrical characteristics of the power generating unit, compared to the measurement, with a specified accuracy. Hence, the behavior of the electrical key variables 'active power', 'reactive power' and 'reactive current' during the simulation is analyzed.
The main criterion for the model validation is the accuracy, which is calculated following the procedure in the technical regulation to classify and evaluate deviations between measured and simulated quantities.
The gas engine is commonly modeled such that the driving power is assumed to stay constant during the event. Modeled components are the synchronous generator and the corresponding excitation system, the FRT-test unit represented by reactances and circuit breakers, and the grid connection characterized by short circuit capacity and voltage level. One or several transformers may be included as well, depending on the voltage level of the generator related to the grid and/or the test unit.
As the model's level of detail is not specified in these requirements, either electromagnetic transient (EMT) models or – conventional for stability studies – transient stability models (RMS-models) with certain simplifications can be used.

Generator representation

A crucial element to model the system properly is the generator. The machine's flux and stator voltage equations without simplifications (EMT-model) are the basis for the representation in simulation. For detailed information see [1] and [3].
Accurate reflection of the fault behaviour is essential. In case of a nearby short circuit, which causes the most excessive voltage dip, the generator's fault current in each phase consists of two distinct components:

- A fundamental frequency component, which decays initially very rapidly and pursues relatively slowly to a steady-state value
- An unidirectional direct current (DC)-offset which decays exponentially

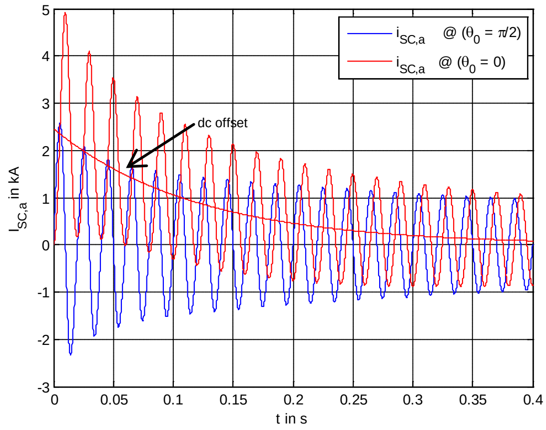

Fig. 3: Short circuit current in phase a with a relative rotor position of a) $\vartheta_0 = 0$ and b) $\vartheta_0 = \pi/2$

The magnitude of the DC component depends on the rotor position related to the respective phase during an incidence; it is at maximum at ϑ_0= 0 or ϑ_0= π, respectively. At ϑ_0= π/2 or ϑ_0= 3π/4, the DC offset remains 0 and the fault current in the corresponding phase is characterized by the fundamental frequency component. The magnitude of the DC offset current (e.g. in phase a) is given by

$$i_{DC,a} = \frac{\hat{u}_a}{2}\left(\frac{1}{X_d^{"}} + \frac{1}{X_q^{"}}\right) e^{-t/T_A} \cos \vartheta_0 \qquad (1)$$

where T_A is the armature time constant.
Within comprehensive stability studies, there is a need to reduce the order of the overall system and ease computation. Therefore, stator flux transients are neglected and the DC offset in the generator fault current disappears (Fig. 3), as well as its related effects to the dynamic performance of the generator.
The machine's stator voltage equations get simplified (stator flux transients neglected) and the approximation that the magnetizing voltage is equal to the magnetising flux is taken. This model is typically used when simulation framework refers to RMS-models.
However, observing a fault in the dq-frame using the exact EMT model, the phase currents I_d and I_q contain fundamental frequency components, which correspond to the DC offset in the phase currents. The resulting air-gap torque consists of a fundamental frequency oscillatory component that reduces the mean speed of the rotor. The second, unidirectional component of the air-gap torque can be quite high and it reduces the acceleration of the rotor as well. The overall effect of these two components initially causes retardation of the rotor. Analyses of this backswing-effect have been already conducted in the 70's in [9] and [10].
As the magnitude of the torque components are dependent on the resistive losses of rotor and stator, the scale of the machine and the X/R-ratio of the grid have a significant influence on this effect.

In most cases this backswing-behavior is, if present, mainly beneficial. The primary retardation of the machines' rotor is opposing the critical acceleration during fault. Nevertheless, in special cases this effect might be too strong and therefore contribute to instability.

Validation of simulation model

The necessary tests for validation according to Germany's requirements include a combination of load cases (full and part load). For each load case various residual voltages and two-/ three-phase tests are carried out.

Fig. 4 shows an exemplary FRT test carried out according to Germany's technical requirements. Though model validation does merely demand electrical variables to be observed, the purpose of this paper is stability consideration; therefore active power and rotor speed are shown.

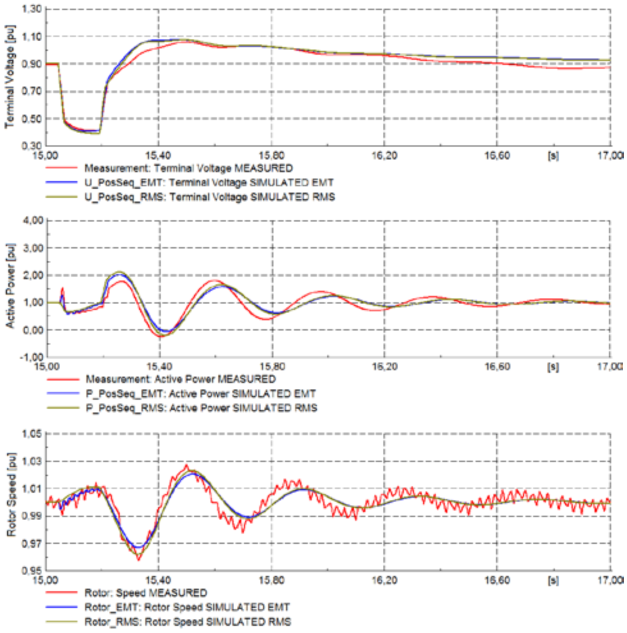

Fig. 4: Fault-ride-through of a 5.5 MVA / 10.5 kV gas-engine-driven generator; voltage dip for 150 ms

The unit under test is a 5.5 MVA synchronous generator connected to a MV system. In course of the validation procedure, a comparison between measurement and simulation is carried out to quantify the deviation of the model. Common practice is to use the simulation results of RMS simulation; EMT simulation results are shown for association. Examined electrical parameters are active power, reactive power and reactive current. For each of these quantities, the measured signal is taken as a reference and divided into three sections and subsections, which are evaluated separately. Permitted deviations are stated for each quantity and transient /steady-state sections in the TR's.

Both RMS and EMT simulations show a good match with the measurement. Therefore, the approach to neglect backswing effects is appropriate for this generator type; RMS simulation can be used. As the simulation model's deviations lie within acceptable tolerances throughout the test cases, it can be regarded as validated according to the TR's and can also be used for stability assessment.

Scaling of validated model

To investigate the consequences of the backswing effect on smaller engines, the validated model is modified and scaled to a typical 780 kVA unit, connected to LV. The test setup is basically not altered and the voltage dip is generated by the FRT test unit. Simply a unit transformer (MV/LV) is added connecting the LV-generator. This significantly changes the X/R ratio of the grid connection and leads to an increase of I^2R-losses during the fault.

A demanding case to be observed is defined in the ENTSO-E draft network code requirements [4]. It defines a voltage dip down to 5% on the point of common connection (PCC) for 150 ms. The operating conditions of the generator are set half-loaded with a constant driving power and over-excitation at a power factor of 0.9. This is selected to clearly demonstrate the effect of the backswing.

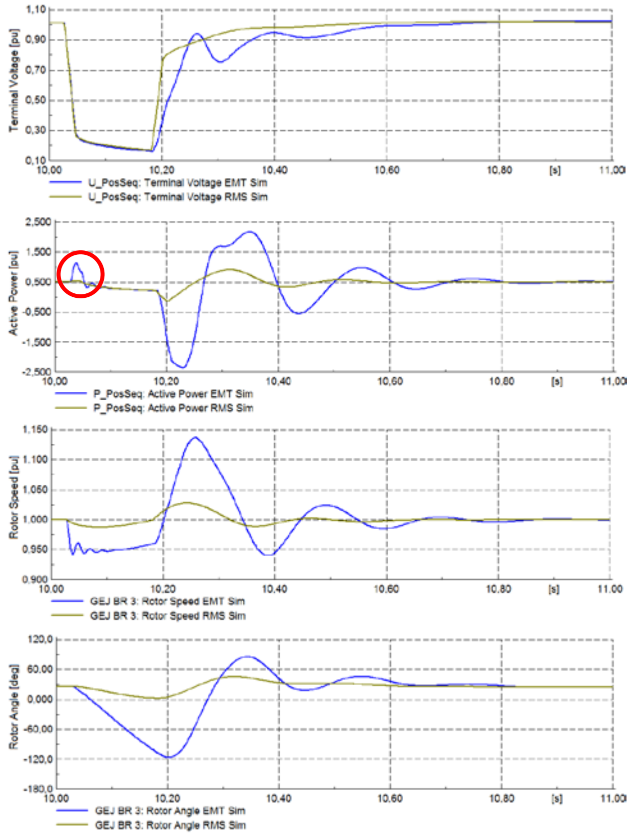

Fig. 5: RMS-/EMT simulation of a fault-ride-through: 0.78 MVA / 0.4 kV gas-engine-driven generator; voltage dip for 150ms

Within stability observation, the active power characteristic in Fig. 5 is especially relevant. The backswing effect is clearly visible through a positive peak, which is highlighted in the EMT-simulation results, right after the voltage collapses. A retardation of the rotor due to high I^2R-losses in the LV-system is apparent in both RMS- and EMT-simulation results; however it is much stronger within the EMT simulation with the DC transients not neglected.

The consequences of neglecting the stator flux transients within the RMS simulation in this case are huge deviations in all observed variables, which would make model validation according to TR only possible if an EMT model is used.

The backswing causes strong retardation of the rotor, visible in the undermost diagram, where the minimum rotor angle reaches -120°. Larger rotor angle displacements affect the air-gap torque transferred from the grid to the generating unit and lead to prolonged oscillations in the generated power after the fault is cleared. Furthermore, a risk of pole slip in the negative direction would increase correspondingly. This risk has to be considered, therefore an overexcited and partly-loaded operating case should be included in worst-case observations.

Since model validation according to TR and especially unit stability assessment can only be performed accurately within EMT simulations, the backswing effect should not be largely neglected anymore. Important parameters as scale of the generator and inertia have to be taken into account before selecting the simulation model.

CONCLUSION

In this paper information on European grid code requirements for CHP power plants is given. Specific procedures aiming certification of power generating units according to German requirements are stated.

Simulation is emphasized as an economical answer, so generator modeling is explained within the framework of conventional stability investigation.

The backswing effect, which is usually neglected, can influence generator stability in two ways: in the first case, the backswing retards the acceleration of the unit with no major impact on the minimum rotor angle reached. This situation enhances stability of the unit and longer critical clearing times can be reached. That is why consequences of the backswing-phenomena are usually identified as beneficial.

The second case occurs if the backswing effect is so strong that it causes the rotor angle to swift into negative values.

It is a fact that gas-engine driven generators are usually small in size, compared to other common prime mover – generator combinations (hydro, thermal or wind). This implies that X/R ratios of these generators are low; consequently the resistive losses have bigger influence. Additionally, the inertia of the mechanical system is relatively low. These peculiarities have great influence on generator stability and increase the consequences of backswing-effects. The risk of negative pole slip or, at least higher mechanical stress and prolonging of rotor oscillations must be considered. Consequently, the use of RMS-models for validation according to German TR's is not always sufficient; EMT simulations are needed in cases with smaller units.

In view of the backswing effect, a worst case scenario for an engine to ride-through a fault may be reconsidered: an under-excited, fully-loaded operating condition of the generator stands for a worst-case scenario if the rotors' acceleration is critical. In contrast, an over-excited, partly-loaded operation that reduces the rotor angle at the initial point of the fault is critical for the backswing effect. Nevertheless, further investigations to quantify the effect of inertia, power factor, loading and short circuit power of the grid on the backswing should be carried out.

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