SERVICE AND RELIABILITY

Generators for the age of variable power generation

Grid-support plants are subject to frequent starts and stops, and rapid load cycling. Improving the design of the plant's alternator so it can withstand additional stresses is fundamental to reliability. What are the design parameters to which special attention must be paid?

Timo Holopainen
Jari Jäppinen
Juhani Mantere
John Shibutani
Jan Westerlund
ABB Motors and Generators

Helsinki, Finland
timo.holopainen@fi.abb.com
jari.jäppinen@fi.abb.com
juhani.mantere@fi.abb.com
john.shibutani@fi.abb.com
jan.westerlund@fi.abb.com

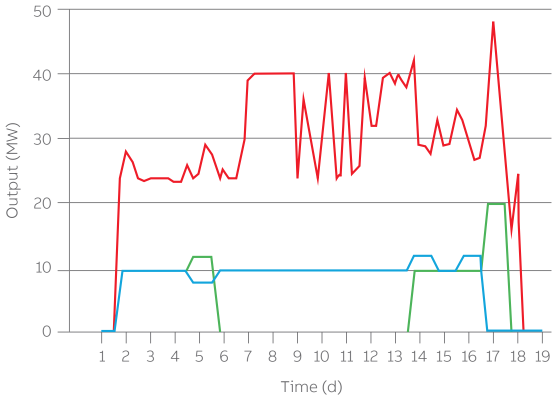
Mats.Östman
Wärtsilä Finland Oy
Helsinki, Finland

Joonas Helander
Former ABB employee

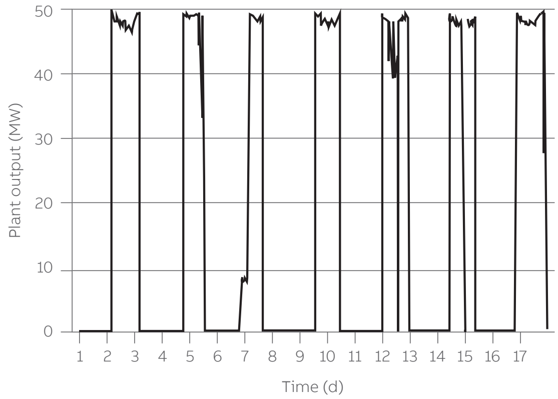
More and more renewable power generation sources are connecting to the power grid. The power output of many of these sources can be highly variable and their fluctuations have to be compensated for by flexible, grid-support plants. In contrast to traditional power generators, grid-support plants are subject to frequent starts and stops, and rapid load cycling. As is confirmed by studies of real-life loading cycles in grid-support duty, the key factor that must be taken into account in the design is the increased number of thermal and speed loading cycles. Improving the design of the alternator so it can withstand additional stresses is fundamental to the reliability →1.

Driven by legislation and the underlying climate concerns, renewable energy penetration is on the rise. The increased usage of renewable power generation, which in many cases is variable and without inertia, creates new challenges for the

It is expected that the thermal stresses are mainly generated in the windings and the core region of the alternator.



02



03

01

—
01 The alternators in grid support plants must be designed to accommodate the thermal and mechanical stresses caused by the need to ramp up and down in response to variable renewable generation on the grid. Shown Is power generation equipment with separate generating units at the Kiisa power plant in Estonia.

—
02 The measured balancing power of a combustion-engine-based plant over an 18-hour power production period.

—
03 Power production of a plant over one week in August 2013.

—
04 Generator loading profiles used in the thermal cycle analyses.

04a Repeated five-minute ramp-up from zero to full load for five minutes, then one-minute ramp-down to no-load, with five-minute standstill period.

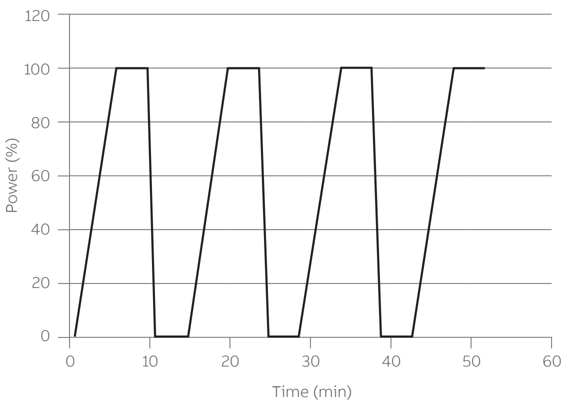
04b Rapid ramp-up in five minutes to full load staying at full load for two hours, followed by a rapid ramp down in one minute to no-load.

electrical grid, system control and the existing power generation facilities. More frequent starts and stops, and increased ramping and cycling capability is required from other power generation plants, all of which may impose additional costs and stress on the existing assets.

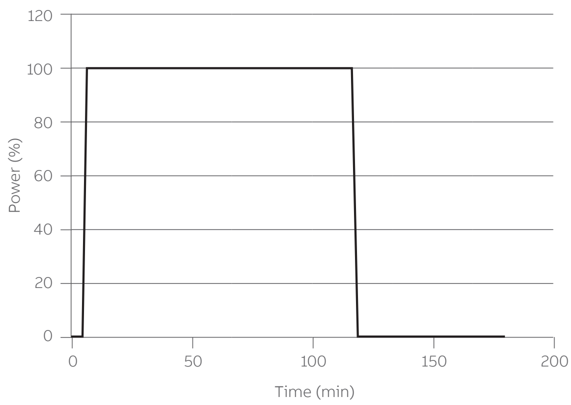
Power plant load cycles
Traditionally, alternators are operated at rated conditions and constant speed over long, uninterrupted periods. This has determined the design principles and dimensioning of alternator structural parts. Grid-balancing operation entails rapid alternation of operation and standstill periods – resulting in a much higher number of starts and stops →2.

In principle, the difference between the traditional and grid-balancing generator is the number of loading cycles and the steepness of the load change.

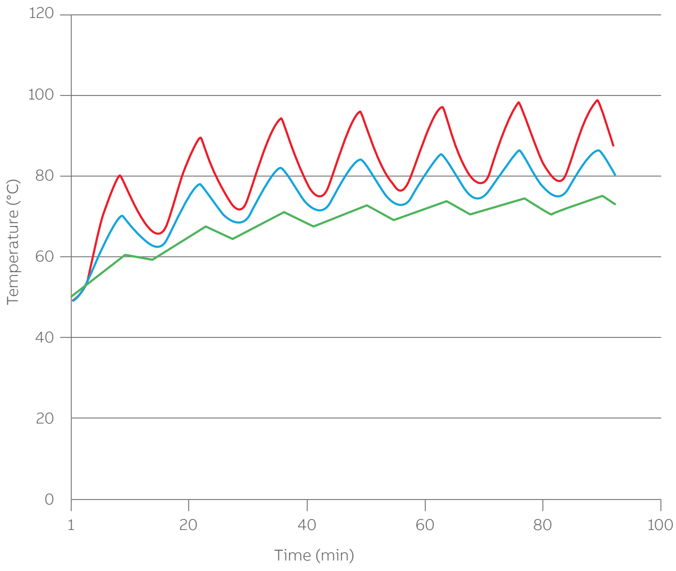
Modern generating sets can get from zero to full speed in 30 seconds and to full load in five minutes; stopping time from full load to standstill is one minute. The plant shown in →3 had nine starts and stops over a six-day period, averaging to 500 annually. In practice, the number of cycles can be even much higher.



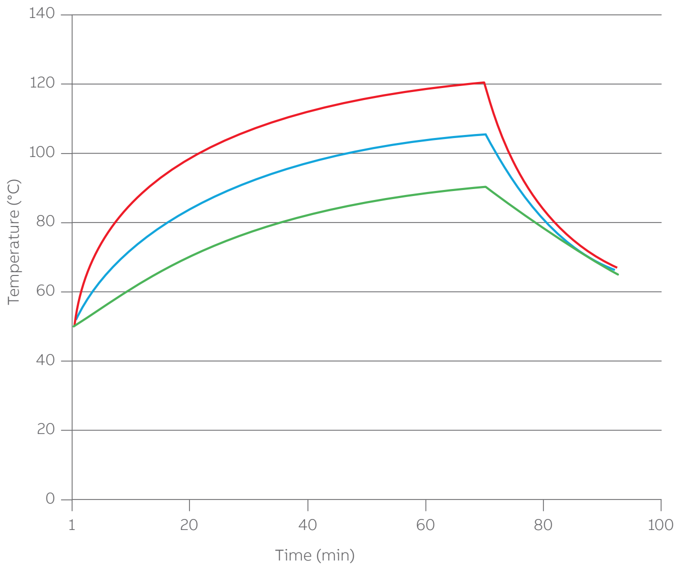
04a



04b



05a — Stator winding in slot — Stator core teeth — Average stator core yoke



05b — Stator winding in slot — Stator core teeth — Average stator core yoke

Loading profiles

In general, the warming and cooling of alternator parts is not even and their thermal time constants differ. This transient anisotropy is the main contributor to thermal stress and makes the analysis of thermal cycles demanding.

To analyze and simulate thermal behavior, two different load profiles – derived from the real site described above – were selected →4. These examples provide a maximum number of load/standstill cycles, which also gives a maximum number of thermal loading cycles for evaluation →4a, as well as a temperature gradient between the winding and core that is close to its maximum value →4b.

Analysis of the thermal cycles

It is expected that the thermal stresses are mainly generated in the windings and the core region of the alternator. The prediction of thermal stresses requires that the temperature distribution can be simulated. The thermal conductivity of copper is excellent and that of steel is good. Thus, the largest temperature gradients are in the electrical insulation layers between the copper-copper and copper-steel joint surfaces. The temperature difference between these parts defines thermal stress in an alternator.

A thermal network method was applied to predict the transient thermal behavior of the active parts of an alternator, such as the stator. In the case with several consecutive short loading/idle cycles, the temperature difference between the winding and core can vary by as much as 10 to 25 K during the load cycles →5a. Where there is a longer full-load period reaching close to maximum operating temperatures, the temperature difference between the winding and core can reach 30 K →5b.

As the stator coils are bonded to the slot walls due to the impregnation treatment and cannot move freely internal stresses are generated in the insulation layers, which can lead to cracking if appropriate measures are not taken.

The difference between the traditional and grid-balancing generator is the number of loading cycles and the steepness of the load change.

Analysis of the speed cycles

Usually, the origins of alternator vibrations are the reciprocating forces of the combustion engine. A four-stroke internal combustion engine creates excitation forces on full and half harmonics of the rotational speed. The generating unit is so complex that only numerical simulations can predict the vibration behavior with the required accuracy. The only way to reliably investigate the fatigue strength of the structural design is to perform a response analysis for the whole generating set. The vibration design of continuously operating alternators is based on the avoidance of main resonances. Due to the high number of starts and stops, fatigue design of grid-balancing application requires the analysis also for start and stop cases.

—
05 Predicted stator temperature of an alternator (20.8 MVA, 13.8 kV, 60 Hz and 514 rpm).

05a At maximum thermal cycle frequency, the temperature difference between the winding and core varies between ca. 10 K and 25 K, peaking after the first cycle.

05b At maximum thermal cycle amplitude, the temperature difference between the winding and core reaches a level of 30 K.

—
06 Example of the verification test results for winding insulation lifetime (Arrhenius equation fitted to collected test data using the least-square method.)

Implications for alternator design
Based on the thermal and speed-cycle analysis, as well as experience from other high cyclic generator and motor applications, there are several parts in the alternator that must be carefully considered when designing reliable alternators for grid balancing application.

Insulation and winding system
As discussed above, winding and insulation are detrimentally affected by thermal cycling. Experience has shown – and analysis has confirmed – that global vacuum pressure impregnation (VPI) gives outstanding characteristics to the whole stator and rotor (laminated steel core and windings).

—
The warming and cooling of alternator parts is not even and their thermal time constants differ. This is the main contributor to thermal stress and makes the analysis of thermal cycles demanding.

In the development process, the verification of the system by testing is always important. In a typical thermal cycling test procedure, several sets of test bars are heated in an oven to different temperatures and cycle times. The test bars are then exposed to mechanical stress on a vibration bench, to humidity and finally to voltage testing of conductor insulation and main insulation.

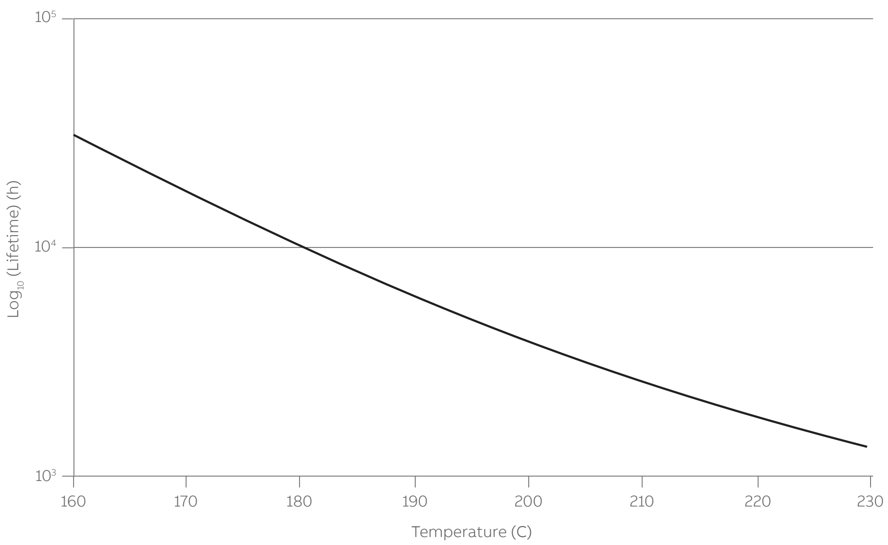
Test cycles are repeated until a certain number of test bars in each set fails voltage testing. The lifetime is then calculated from the test results of each set using the so-called Arrhenius rule →6. Successful tests have been recently performed for the impregnation system in use.

End windings
End windings, along with their support construction and connections, are exposed to thermal cycling and vibrations caused by acceleration, deceleration and frequent grid switching.

The vibration of stator end windings is of major concern in large electric machines. Particularly in two-pole machines the natural frequencies of winding ends tend to decrease to close to the twice-line frequency (100/120 Hz). Thus, in these machines special support structures are needed in order to increase the winding end stiffness and natural frequencies. However, in multi-pole alternators the winding ends are inherently short and the natural frequencies sufficiently high without any additional support structures.

In the development and design of the end winding construction a set of modern methods is used, including 3D finite element analysis (FEA). This method is used for the calculation of forces together with static and dynamic response →7.

The construction and design of the end winding support system with global VPI gives very good characteristics given existing forces and stresses. This means that the end-winding design of medium-speed grid-balancing alternators is robust and resilient against vibrations.



06

—
07 Examples of end-winding analyses.

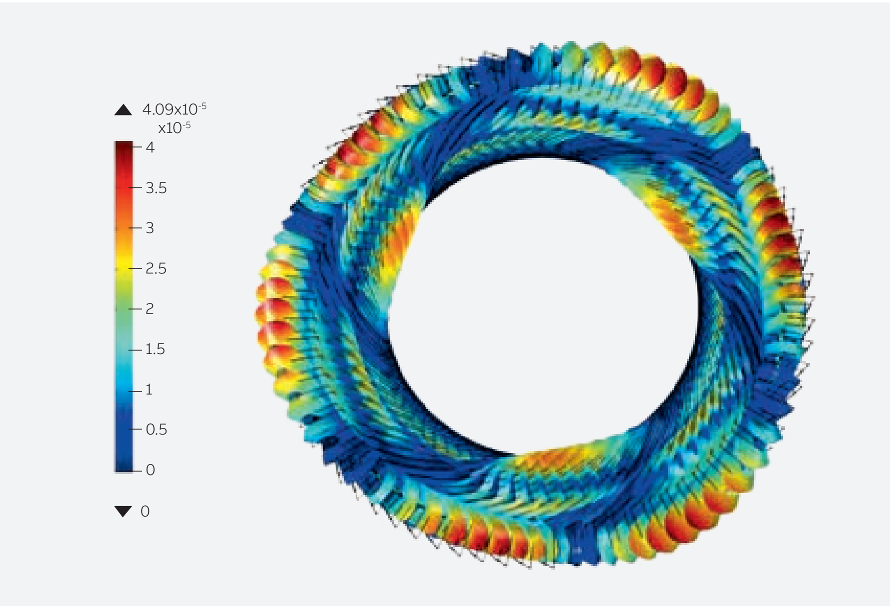
07a A mode shape.

07b The exerted magnetic force distribution at one instant.

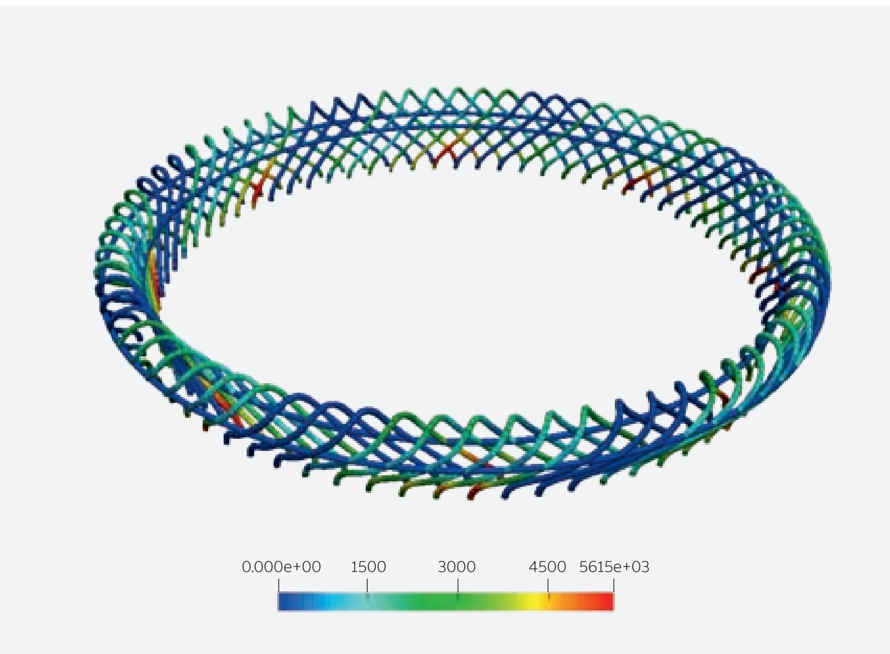
Operation at underexcitation (consuming reactive power) causes thermal stresses in the core-end region. In the case of medium-speed alternators (high pole number), this effect is less severe thanks to the smaller coil width and more favorable flux distribution at the end region.

Frame

The frame of the alternator is mounted on the common base frame together with the combustion engine. The design of the alternator frame is determined significantly by the vibration excitations of the engine transmitted to it by the base frame. This leads to a slightly more robust frame design compared to alternators mounted on a concrete foundation.



07a



07b

The alternator frame design is determined by fatigue resistance. Ability to design reliable alternators, and still have a cost-efficient frame structure, requires thorough knowledge of the dynamics of the whole generating set. A response analysis (numerical simulation) of the whole generating unit is the key to success here.

The fatigue stresses can be simulated during the start-up and shut-down periods. Based on the calculated stress histories, the fatigue life can be evaluated by conventional methods and the critical structural details can then be modified to resist the fatigue loads. Ultimately, this approach ensures that the alternator frame reaches the desired lifetime without any fatigue failures.

—
Global vacuum pressure impregnation gives outstanding characteristics to the whole stator and rotor.

Rotor and bearings

Regarding rotor design, medium-speed alternators are always sub-critical. This means that the first flexural critical speed of the rotor is above the rated rotational speed of the alternator. The rotor does not cross any flexural critical speeds during the cycling loading, thus giving freedom to rotor and bearing design. This is clear advantage over higher speed alternators (eg, two-pole design). The thermal cycles have effects on the rotor similar to those on the stator. The prevailing principle of rotor design is to retain the contact between the components over the temperature cycles – thus avoiding the resin mechanical fatigue. Moreover, the bearings are equipped with a jack-up system, enabling a very large number of starts without any wear.

Good design ensures long life

The age of variable renewable generation means that grid-balancing generators must endure a much larger number of thermal and speed cycles than traditional generating units. The design of the grid-balancing alternator requires particular attention for reliable operation. However, with an optimal design, alternators will be well able to withstand these new, greater stresses and deliver high reliability over very long lifetimes. ●