ABB White Paper

# Power Generation
# Designing Generators for Reliability in the Age of Variable Power Generation

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**John Shibutani**
Head of R&D, Generators
john.shibutani@fi.abb.com

**Jan Westerlund**
R&D Manager
jan.westerlund@fi.abb.com

**Jari Jäppinen**
Technology Manager
jari.jappinen@fi.abb.com

**Joonas Helander**
Senior R&D Engineer
joonas.helander@fi.abb.com

**Juhani Mantere**
Senior Technology Specialist
Juhani.mantere@fi.abb.com

**Timo Holopainen**
Prinicipal R&D Engineer
timo.holopainen@fi.abb.com

**Mats Östman**
Senior Development Manager, Electrical & Automation
Wärtsilä Finland Oy
mats.ostman@wartsila.com

**Abstract**
The variability of renewable power means that flexible grid-support plants are increasingly needed to balance power fluctuations. Together with the current development towards real-time energy markets, this evolution implies changed operational profiles for generators. In this new environment generators have to cater for frequent starts and stops, and rapid load cycling.

A typical set of requirements could include multiple starts and stops per day, rapid readiness for synchronization, and continuous load cycling. This involves the need to ramp up from standstill to full load in a few minutes and ramp down from full load to stop in even less time.

Generator designs have to be modified to ensure that these tough new requirements are met. Based on experience with alternators and motors in applications with similar operating profiles, the key factor that must be taken into account is the increased number of thermal and speed loading cycles. This is confirmed by studies of real-life loading cycles in grid support duty.

Thermal and speed cycles create stresses at various points in the alternator structure, and a number of methods for managing these stresses effectively are described. In particular, the thermal cycles must be considered in insulation design, and the speed cycles in fatigue design. In addition, the implications for the design of major components – stator core, winding, frame, rotor, and bearings, as well as the cooling arrangements – are considered in detail.

The age of variable generation means that generators are subject to even greater stresses than before, but with the right designs they can deliver high reliability over very long lifetimes.

# Part 1. Changing Power Market

Many regions in United States and elsewhere are on the way of launching aggressive renewable energy deployment schemes. Those can either be in the form of legislated demands (Renewable Portfolio Standards = RPSs) that within some specified time, utilities are required to sell a specified percentage or amount of renewable electricity. Or in the form of investment, tax or feed-in related support schemes.
For example, thirtyseven states and Washington, D.C. have adopted RPSs that increase the amount of wind, solar, biomass, and other renewable resources in their energy portfolios. The increased usage of renewable generation which in many cases is variable and without Inertia creates new challenges for the electrical grid, system control and the existing generation.

The trend of increasingly variable available load is a visible attribute of power systems with an increasing penetration of renewable energy based on wind and solar power generation. As the amount of wind and solar energy increases, decreasing minimum available loads and increasing load ramps require more frequent starts and stops and increased ramping and cycling capability, all of which may impose additional costs and stress on the dispatchable generation assets.

Moreover, the electrical markets are also rapidly developing, moving ever closer to realtime. For example, in March 2014, a real time electricity market with 5 minutes price settlement and delivery was introduced in the Southwestern USA by Southwest Power Pool (SPP) with other regions moving in the same direction. In order to capture the opportunity with the rapidly changing market signals generators may choose to balance their position in terms of load, starting/stopping and ancillary services sold many times even within the same hour.

Indeed, the term “to run 24/7” may take on a whole new meaning. Not anymore will it signify a full week continuous running, rather it will take on the meaning of 24 start in 7 days or even hours. When new thermal generation is added to the system it is very important that this new generation pattern is factored into the equipment design. The design of the alternator is no exception.

# Part 2. Balancing Power Plants Load Cycles

**Figure 1. Power plant with separate generating units.**

Most of the traditional alternators are operated on rated conditions with constant speed and long uninterrupted periods. This operation profile has naturally determined the design principles and dimensioning of structural parts of alternators. The grid-balancing operation entails alternating operation and standstill periods with much higher number of starts and stops. In principle, the difference between the traditional and grid-balancing generator is the number of loading cycles and the steepness of the load change.

There are two types of loading cycles: thermal cycle and rotational speed cycle. The thermal cycle induces thermal stresses due to the uneven temperature distribution and due to the different thermal expansion factors of applied materials. The rotational speed cycle, i.e. the starts and stops, generate transient vibrations due to the structural resonances excited by higher order harmonics.

The main aim of this paper is to present the specific features of grid-balancing alternator design. First, the typical load profiles of these alternators are described. After this, the simulation methods used for the analysis of thermal and speed cycle effects are described. Finally, the implications on the alternator design are shortly reviewed before concluding remarks.

# Part 3. Loading Profile

### 3.1 Plant

The loading profile of a plant provides a framework for the loading profile of a separate grid-balancing generator. In practice, there is a large variation between the loading profiles of different plants. The current design profiles have been developed and validated against the actual operation of generation systems supporting the electric grid.

A measured power balancing curve gives an example of how conventional generating asset can be used to supply the needed flexibility to an electrical system. Figure 2 shows the measured balancing power of a combustion engine based plant in Texas. The plant produces varied power between 20 and 50 MW during the 18 hour period. It can be clearly seen that the actual demand of power regulation of power is fast and recurring.

Figure 3 shows a measured power balancing curve for a six day period. In this example the 10 hour production periods (at 50 MW) are followed by the 10 hour stand still periods. The total number of starts and stops is 9 during 6 days recording period (August 25 - 31, 2013). This equals to an annual 500 starts and stops.

In practice, the number of cycles can be much higher, as with electric systems consisting of a large share of intermittent renewable power generation or after electricity markets have moved even closer to the real-time trading.

The main function of a grid-balancing plant is to produce active power to the network. In addition, the plant is needed to balance the reactive power with similar fast changing behavior [2].


**Figure 2. Power production of a Texas plant during 18 hours running period. The dark red line shows the plant total output. The blue and green lines show the respective ancillary services provided by the installation.**

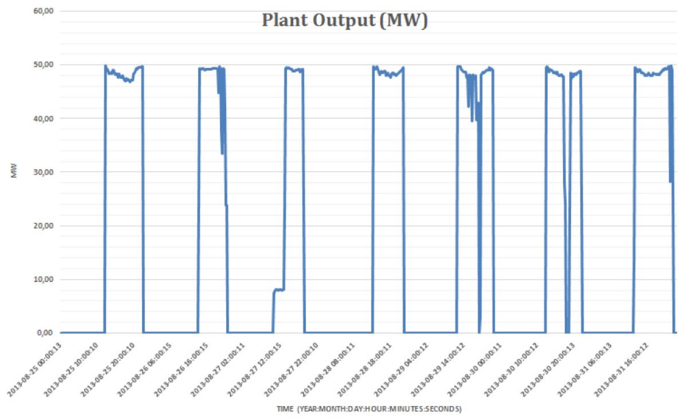



**Figure 3. Power production of a Texas plant during one week in August 2013.**

### 3.2 Generating Unit

Power production of a plant must be distributed to the separate generating units. The number of operating units determines roughly the total power. The speed of the power regulation is dependent on the required time for starts and stops and the ramping capability of the generation unit. Modern generating sets enable a start to full speed in 30 seconds and the full load is reached in five minutes. The stopping time from full load to stand still is one minute. Figure 4 shows an example of a possible starting, loading and unloading sequence of a combustion engine [3, 4].

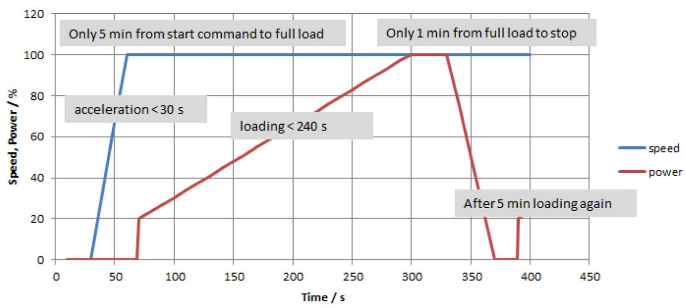



**Figure 4. Example of starting, loading and unloading sequence of a combustion engine.**

# Part 4. Thermal Load Cycles

**4.1 Loading Profile**
In general, an alternator warms up under operation and cools down in stand still. The heat is generated by dissipative losses and transmitted from the active parts by cooling circuit propelled by fans. In principle, the dissipative heat generation can be determined and the steady-state temperatures calculated based on the material characteristics and heat transfer functions. The main questions of thermal cycles are related to the transient behavior. In general, the warming and cooling of alternator parts is not even and the thermal time constants differ. This makes the analysis of thermal cycles more demanding.

To analyze and simulate the thermal behavior, two different load profiles were selected and defined (Figure 5). These profiles are derived from the load cycles described in Figures 2 and 3.

The first load profile involves consecutive rapid load cycles of five minutes ramp-up from zero to full load, followed by five minutes at full load and then one minute ramp-down from full load to no-load. This cycle is then repeated after a five minutes stand still period. This profile provides maximum number of load / stand still cycles, which also gives maximum number of thermal loading cycles for evaluation.

The second load profile consists of a 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 (cooling down period). In this load profile the temperature gradient between the winding and core is reaching close to its maximum value.

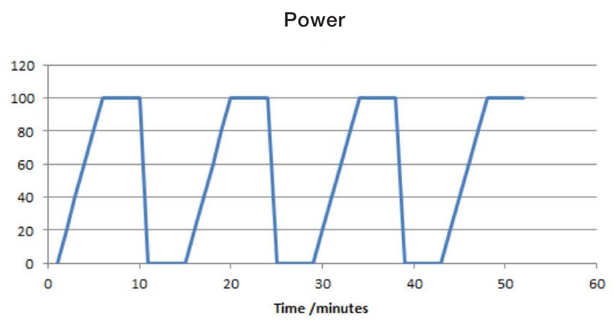
These extreme profiles (i.e. maximum number or maximum amplitude of thermal cycles) are used to investigate the effects of temperature cycles.

**4.2 Thermal Cycle**
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 of steel is good. Thus, the largest temperature gradients are located in the electrical insulation layers between the copper-copper and copper-steel joint surfaces. This means that the main factor behind the thermal stresses is the temperature of different parts.

A well-suited approach to predict the transient behavior of the active parts of an alternator is the thermal network method. In this method, the main parts of the stator and rotor are divided into nodes with thermal capacitances and thermal resistances between the nodes. The load dependent loss components, derived from the separate numerical calculations, are fed as input for the corresponding nodes in the network. The system of differential equations can be formulated in matrix form and solved by any time-step method. Figure 6 shows an example of a thermal network model for a part of an alternator.

As an example of thermal network simulations, Figure 7 show results for an alternator with rated values 20.8 MVA, 13.8 kV, 60 Hz and 514 rpm.

In the first case (several consecutive short loading / idle – cycles) temperature difference between the winding and core varies between ca. 10 K and 25 K during the load cycles, approaching the maximum level of variation fairly quickly, roughly already after the first cycle. The maximum temperature of the winding approaches 100 °C according to its time constant. After 90 min it has nearly reached its final, balanced temperature. In the second case (longer full load period reaching close to maximum operating temperatures) temperature difference between the winding and core reaches a level of 30 K, major part of the gradient increase takes place already during the first 15 minutes. At the end of the loading period the winding temperature has nearly reached its final, balanced value, which in this simulated case will be 125 °C.



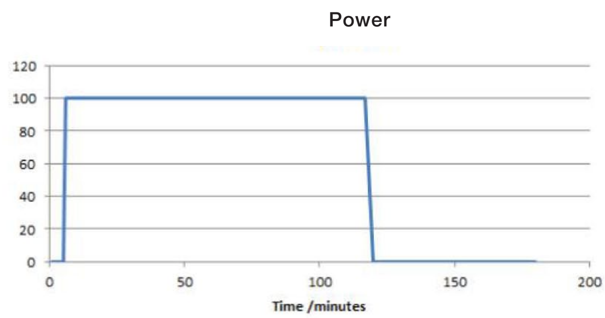




**Figure 5. Generator loading profiles used in the thermal cycle analysis.**

### 4.3 Thermal Stresses

The mechanical loading due to the thermal cycles are composed of two different physical sources. The internal forces are generated by a) uneven temperature distribution between parts, or b) different thermal expansion factors of parts. Both of these sources must be included to the evaluation of thermal stresses. In the example case (Figure 7), the largest temperature difference between the copper and iron is around 30 K, and the thermal expansion factors of steel and copper are typically $12 \times 10^{-6}$ and $16.6 \times 10^{-6}$ 1/K, respectively.

Temperature difference and high temperature gives rise to increased stresses mainly on the winding insulation layer. If the windings could freely move in the slot, the thermal effects would expand the copper coils longitudinally. In practice, the coils are bonded to the slot walls due to impregnation treatment. Thus, instead of expansion of copper coils, internal stresses are generated in the insulation layers. These internal stresses can be minimized by adjusting the stiffness/flexibility of structural members of different material.

If the generated shear stress is too high, cracks are induced in the insulation layer. The most vulnerable location for the cracking is the insulation layer close to the slot end [4].

The influence of temperature rise rate is investigated by numerical FE analyses in the reference [5].

Actually in the global VPI system the curing temperature (treatment in oven) is typically 160 °C, which means that at this temperature there is no differential elongation stress in the insulation. Thus, at high operating temperatures, the differential stress is resulting mainly from the thermal gradient from copper to iron.

### 4.4 Thermal Aging

Average operating temperature is the most important factor concerning the thermal aging. The main parameters determining the aging are the temperature and the spend time. This is particularly valid for the thermal aging of winding insulation. It is significant, that the average winding temperature of grid-balancing alternator does not exceed the corresponding temperature of continuously operating alternator at rated load. The expended time in elevated temperatures is naturally smaller due to the loading profile of variable power generation. Thus, the thermal aging of grid-balancing alternator is smaller than that of continuously operating alternators.

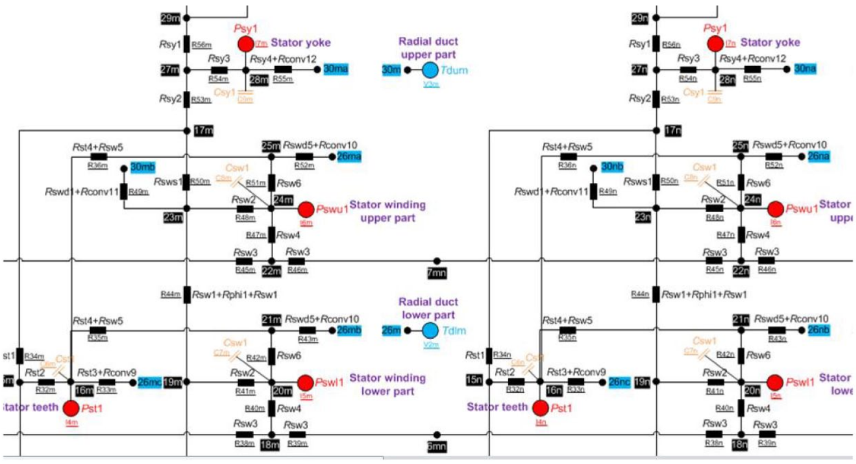



Figure 6. One part of a thermal network used for the simulation of alternator temperatures.

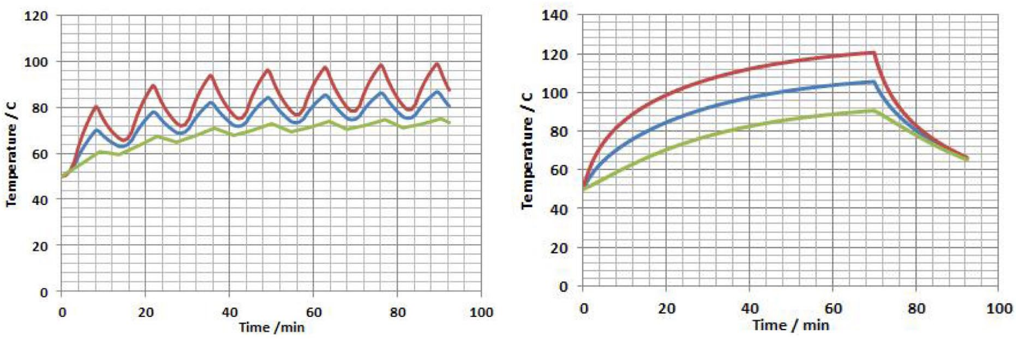



Figure 7. Stator temperature of an alternator with maximum frequency (left) and maximum amplitude of thermal cycles (right).
Red = stator winding in slot, blue = stator core teeth, green = stator core yoke (aver.) Similar analysis are made for rotor temperatures.

# Part 5. Analysis of Speed Cycles

### 5.1 Generator Vibrations
This paper is limited to the designs consisting of an alternator and a combustion engine, which are mounted on a common base frame. This generating set is resiliently mounted on a plant floor. Thus, all the possible vibrations induced by the system remain internal and are not transferred to the surroundings.

Typical rotational speeds are clearly below 1000 rpm. Thus, the unbalance excitation forces from the rotor can be easily limited to a low level. In addition, the appearance of the twice-line vibrations is limited naturally by the high number of poles. It can be concluded that the vibrations originating from the alternator design or manufacturing are fairly small.

Usually, the origins of alternator vibrations are the reciprocating forces of the combustion engine. A 4-stroke internal combustion engine creates excitation forces on full and half harmonics of the rotational speed. These excitation forces are transferred as structureborn vibrations via the common base frame. The vibration design of continuously operating alternators is based on the avoidance of main resonances. In practice, the resonances are avoided by designing the base frame and the alternator in a manner that natural frequencies of the structure are far enough away from the main excitation frequencies. The required margins are dependent on the several details, such as the amplitude of excitation and damping ratio of the corresponding natural modes.

It can be mentioned, that the resilient mounting of the generating unit gives an excellent boundary condition for the vibration design, because the effects of different plant floors can be neglected. This is a great advantage compared to the vibration design of directly mounted machinery. The vibration modelling of these stiff mounted machines require the modelling of the foundation or large margin between the main excitation and natural frequencies.

### 5.2 Response Analysis
The generating unit is so complex that only the numerical simulations can predict the vibration behavior with required accuracy. The only way to reliably investigate fatigue strength is to perform a response analysis for the whole generating set.

The fatigue design requires the response analysis for start and stop cases. A conservative approach is to assume steady-state condition on the resonance speed. A more accurate approach is based on the simulation of transient crossing of resonances. Based on the steady-state or transient deflection shapes of the frame the stress state in critical locations is calculated and the fatigue strength can be evaluated.

### 5.3 Starts and Stops
The rotor design of a multipole, medium speed alternator is always rigid meaning that the first critical speed of the rotor is clearly above the rotational speed. This is a clear advantage for alternators with a large number of starts and stops, because there is no need to cross any rotor critical speed.

The resonance vibrations during the starts and stops are to be evaluated together with the much higher number of lower stress cycles of constant speed operation.

It is clear that the design of reliable alternators requires that these resonance phenomena are included to the fatigue design.

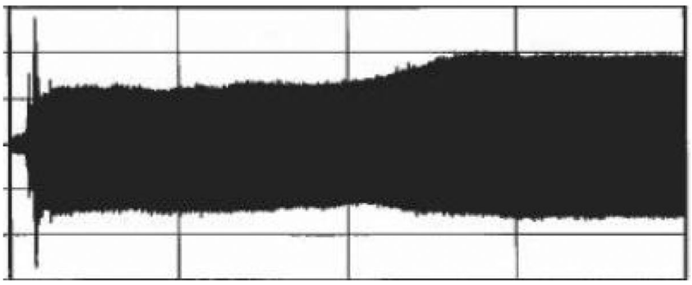


**Figure 8. Measured stress of a critical location close to a weld toe of an alternator frame. On the left can be seen the starting transient of rotational speed. In the middle and right the increase of load can be seen.**

### 5.4 End Winding Vibrations
The vibration of stator end windings is a major concern in large electric machines. Particularly, in two-pole machines the natural frequencies of winding ends tend to decrease 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 (e.g. 12 or 14 poles) alternators the winding ends are inherently short and the natural frequencies sufficiently high without any additional support structures. This means that the end winding design of grid-balancing alternators is robust and resilient against vibrations.

# Part 6. Experience of Similar Applications

Fortunately, there are specific applications with similar loading profile than needed in gridbalancing generators. In marine applications, a set of generating units are used to provide power to the ship network. Very often, due to the changing power demand for propulsion and auxiliary systems, these units are facing repeated starts and stops. The experience of these marine alternators can be used, and is actually vital, for successful design of grid-balancing alternators.

Another source of major experience is based on motor applications. As is well known, the synchronous motor and alternator designs are very similar. The main difference is the direction of the power flow: from shaft to grid or vice versa. Thus, the experience from these motors increases knowhow for grid-balancing alternators. For example, in metals industry, the rolling mill motors are facing very fast and frequent load changes including frequent over load cycles. In overload cycles, the windings are exposed to very high thermal stresses due to the temperature rise rates. Further, it is also typical that electric propulsion motors are operated according to cyclic profiles.

Summing-up, the alternators and motors in these reference applications are similar to the grid-balancing alternators when the size, construction and insulation system is considered. It can be added that the experience from these reference applications show very high track-record in reliability. Further, in some cases it has been possible to witness clear superiority of the current design and insulation system over the older designs and technologies.

# Part 7. Implications to Alternator Design

Alternators in new operation environment have to be designed to take into account all the new stress factors to be faced. Design of the main components of the alternator is discussed in this chapter, considering the design methods, the verification by testing and the experience gathered in similar operation conditions.

### 7.1 Insulation and Winding System

As discussed earlier, the winding construction and insulation system is affected by the thermal cycles with connection / disconnection to the grid. A thorough consideration of these loading factors is essential in the design and manufacturing process. Verification by testing is important, especially for the insulation system, and experience from other similar applications is utilized.

Global vacuum pressure impregnation (VPI) system was developed and implemented in manufacturing already in late 70'ies. Although basically the VPI system has remained the same, there has been gradual development and improvement in design, materials and in manufacturing process including implementation of the system for bigger sizes. Experience has shown that global VPI gives outstanding characteristics to the whole stator (laminated steel core and windings). Global VPI system has been successfully implemented also to the rotor (laminated pole core and field winding).

In the development process, the verification of the system by testing has been important. Test procedures for the validation and certification of the system are specified in standards such as IEEE 1310-2012 [6] and IEC 60034-18-31 [7]. In a typical thermal cycling test procedure, several sets of test bars are heated in oven to different temperatures and cycle times. Test bars are 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 certain number of test bars in each set has failed in voltage testing. The life time is then calculated from the test results of each set using the so-called Arrhenius rule (Figures 9 and 10). Successful tests have been recently performed for the impregnation system in use.

In Metals industry, the rolling mill motors are facing very fast and frequent load changes including frequent over load cycles. In overload cycles, the windings are exposed to even higher thermal stresses, especially when the ramp rates of temperature rise are considered.

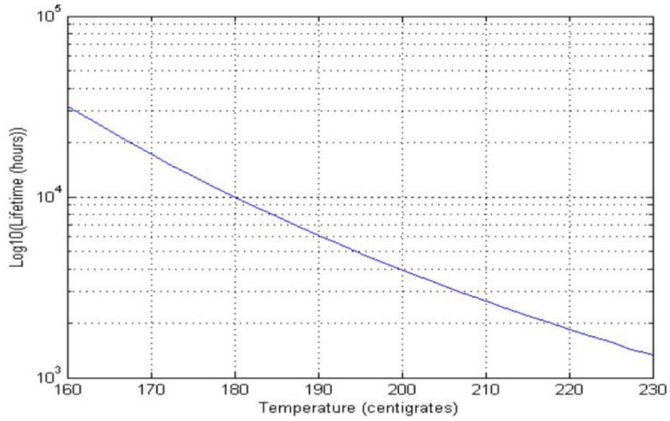



**Figure 9. Example of the verification test results for the winding insulation life time (Arrhenius equation fitted to collected test data using the least square method).**


**Figure 10. 1 Aged test bars (steel covers rusted due to moisture handling) | 2 Test bars in moisture chamber | 3 Test bars on vibration bench**

## 7.2 End Windings

End windings with their support construction and connections are also exposed to thermal cycling and vibrations caused by acceleration, decelerations and frequent switch-on / switch-off to the grid. Especially, the in-rush currents in the case of unsuccessful synchronization can cause high forces in the end windings. This is, however, a clearly lower stress factor for end windings than it is in many motor applications, in which repeated direct-on-line starts expose the end winding support and connections to high forces resulting from inrush currents. In principle, the design and construction of the end winding support is the same. In addition, the dimensioning of end windings of medium speed alternators (pole number is typically 8 or higher) is easier than e.g. the end winding if 2-pole machines due to the shorter overhang.

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. Figure 11 shows two examples of analysis results. In the development work, the validation of the calculation models by testing and measurements has an important role.

The construction and design of the end winding support system with global VPI gives very good characteristics in view of existing forces and stresses and has proofed to be outstanding in contrast to the older technology which was based on (often too) heavy and rigid support system.

The operation at under-excitation (consuming reactive power) causes, in addition to the thermal stresses from the winding currents, thermal stresses in the core-end region (coreend heating effect). In case of medium speed alternators (pole number high), core-end heating effect is less severe thanks to the smaller coil width and more favorable flux distribution at the end region.

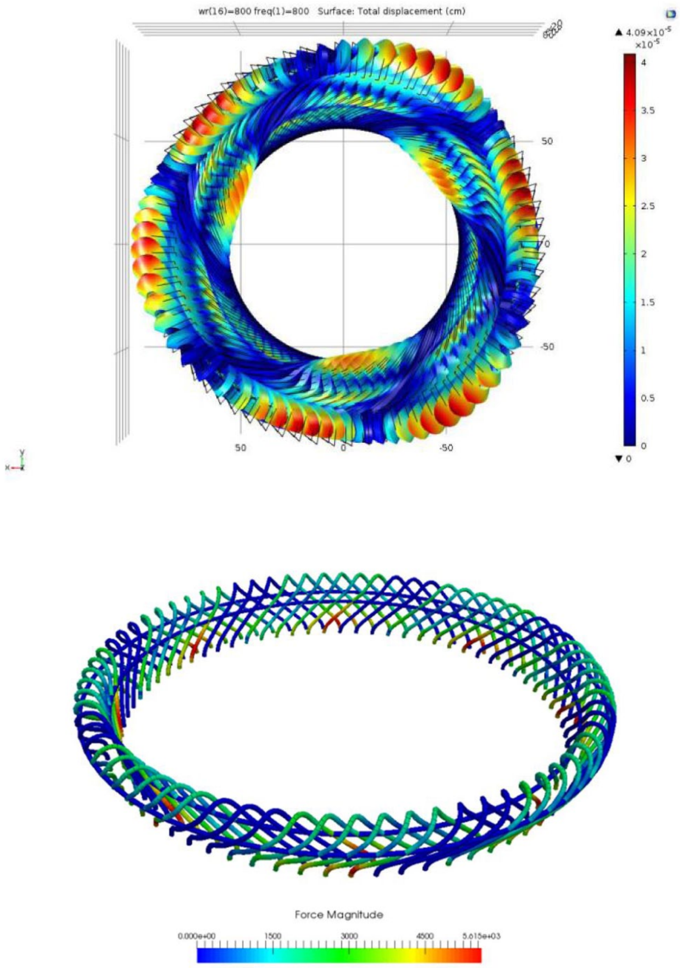



**Figure 11. Examples of end winding analyses: on the left is a mode shape, and on the right the exerted magnetic force distribution on a time instant.**

### 7.3 Frame

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

The frame design is determined by the 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. The response analysis of the whole generating unit is the key for success.

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. Based on this, the critical structural details can be modified to resist the fatigue loads. Ultimately, this approach ensures that the alternator frame reaches the desired lifetime without any fatigue failures.

### 7.4 Rotor and Bearings

The first flexural critical speed of the rotor is above the rated rotational speed of the alternator. Thus, the rotor design is subcritical. This means that the rotor does not cross any flexural critical speeds during the cycling loading. The operation below the critical speed gives freedom to rotor and bearing design.

The thermal cycles have similar effects on the rotor as they have on the stator. The prevailing principle of rotor design is to retain the contact between the components over the temperature cycles, and thus, the mechanical fatigue of resin is avoided.

The bearings are equipped with a jack-up system enabling very large number of starts without any wear.

### 7.5 Cooling System

Efficient cooling system is important to ensure safe operation temperatures and uniform temperature distribution in all operation modes. In the alternators under study the air circulation is symmetrical. Cold cooling air is drawn in to the winding end compartment and in to the rotor by the shaft mounted fans. From rotor the air is blown evenly through the air ducts in the stator core to the cooling air outlet arrangement. Efficient filters are typically used to ensure cleanliness of cooling air.

Blowing of cooling air with separate motor driven fans is an alternative, which gives possibility to reduce cooling effect during low load operation or idle periods to decrease temperature variations.

In the development and design of the air circulation computational fluid dynamics (CFD) tools are regularly used in addition to thermal field computation with both 2D and 3D FE tools. In Figure 13 some examples of thermal simulation are illustrated.

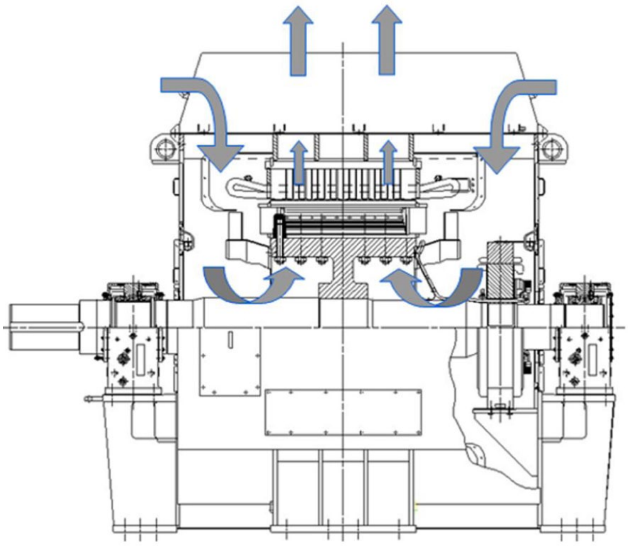


Figure 12. Principle of cooling air circulation in an alternator.

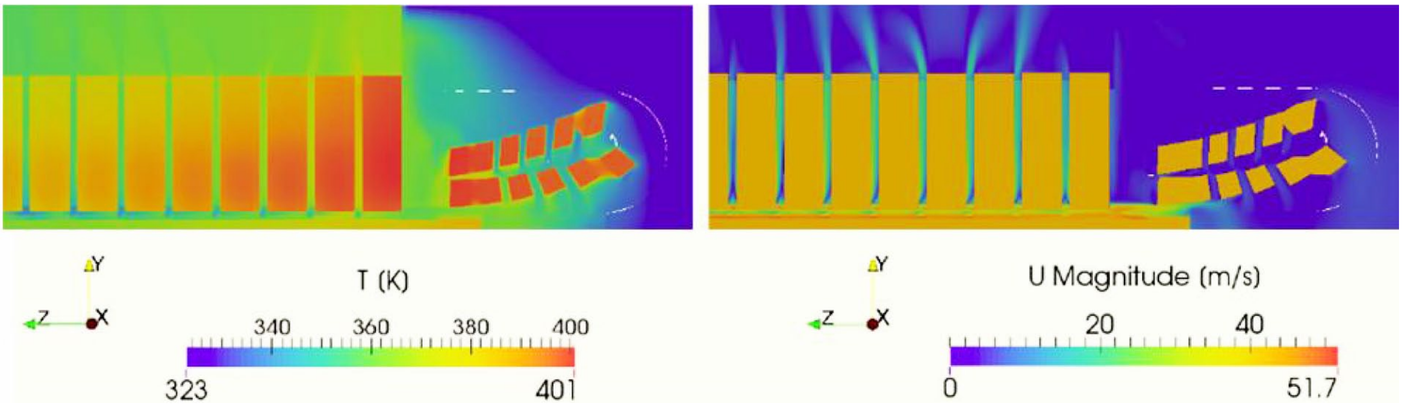



Figure 13. Illustration of thermal simulations: on left the temperature distribution, on right the air flow velocity.

# Part 8. Conclusions

The demand of grid-balancing generators is expected to increase. A power plant with several generating units fulfills the essential requirement of flexible and fast power adjustment. In practice, this means that the generators must endure much larger number of temperature and speed cycles than the traditional generating units. Though, there are ample of experience from marine generator and metals motor applications with similar load profile, the grid-balancing alternator design requires special attention for reliable operation. This paper describes the available experience, the analysis methods and the design principles needed for the manufacturing of robust alternators. The age of variable generation means that generators are subject to even greater stresses than before, but with the right designs they can deliver high reliability over very long lifetimes.

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# Contact

**John Shibutani**
Head of R&D, Generators
john.shibutani@fi.abb.com

**ABB Oy, Motors and Generators**
P.O. Box 186
FI-00381 Helsinki
Finland

**http://new.abb.com/motors-generators/generators**

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