Extended requirements on turbo-generators due to changed operational regimes

Matthias Baca and Ana Joswig

Kurzfassung

Erweiterte Anforderungen an Turbogeneratoren aufgrund eines veränderten Betriebsregimes

Weltweit ist ein ungewöhnlich schnell stattfindender Wechsel der Betriebsweise vom klassischen Grundlastkraftwerk zum höchst flexiblen Spitzenlastkraftwerk zu erkennen. Neben den geänderten Anforderungen an die Turbinen führen diese Randbedingungen dazu, dass sich Turbogeneratoren nicht mehr im thermisch eingeschwungenen stationären Zustand befinden. Die aktuellen, hoch volatilen Randbedingungen des elektrischen Verbundnetzes – bedingt durch die Einspeisung erneuerbarer Energien – spiegeln sich insbesondere sowohl durch die hohe Anzahl an Start-Stopp-Zyklen als auch durch häufig auftretende und steile Lastwechsel von Gas- und Dampfturbosätzen wider.

Aus dem täglichen Aufwärmen und Abkühlen (Start-Stopp-Zyklus) oder häufigen Ändern des Leistungspunktes (hohe Anzahl an steilen Lastgradienten, vermehrter Schwach- und Teillastbetrieb des Generators) resultieren auch neue Anforderungen an die Komponenten. Infolge der unterschiedlichen thermischen Ausdehnungskoeffizienten der verbauten Komponenten ergeben sich zyklische thermo-mechanisch getriebene Dehnungen, die zu einer beschleunigten Alterung der Komponenten im Generator führen können. Bleiben diese Belastungen bei Auslegung und Konstruktion der jeweiligen Komponenten unberücksichtigt, kann es zu unvorhergesehenen, langen und kostentensiven Stillstandszeiten kommen.

Der vorliegende Beitrag stellt aktuelle Analysen der neuen Betriebsweisen und deren Auswirkung auf die Turbogeneratoren, welche am häufigsten in gasbefeuerten Turbosätzen eingesetzt werden, vor und beschreibt Lösungsansätze für einen sicheren und kostenoptimierten Betrieb der Anlage mit Blick auf die aktuellen Entwicklungen des Energiemarktes.

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Introduction

The integration of renewable energy sources with preferential feed into the high-voltage transmission system results in fundamental changes in the load regime of the European grid.

Conventional power plants will be significantly displaced from the market or used as reserve capacity for when the renewable energy plants are unable to generate the total output required in the grid. In addition to grid operation requirements, the operating regime of the conventional power plants required to cover the supply gap is based especially on aspects of cost-effectiveness under consideration of the borderline implementation costs of the respective power plant.

Figure 1 shows an example how wind and solar energy contribute to the total generating capacity in the spring and winter over a period of one week in March and December 2014 [1]. During sunny weather in March, photovoltaics (solar – yellow) provide roughly ¼ of the required energy at midday, while hard coal power plants (HC – black) provide the regulating power reserve. With the change in weather over the weekend (Sat – Sun), wind power (gray) provides up to nearly 50 % of the power demand, and even nuclear power plants (Uranium – red) have to reduce their output. Most of the hard coal power plants are disconnected from the grid at this point. The situation for electric power generation is completely different in the selected week in December. No wind or solar energy are available from Tue to Sat due to the weather situation. The conventional coal- and gas-fired power plants now have to weigh in and close the supply gap.

The contribution to electric power production from renewable energy sources (especially wind power and photovoltaics) is increasing continuously in Germany. This gives rise to a large dependency on the weather and results in permanent fluctuations in the utilisation of conventional power plants, with the consequence of an extremely volatile operating mode at times. The number of start-up and shutdown cycles for peak load power plants increases significantly. Power plants remain in turning gear operation more frequently and for longer periods, complete shutdown times at 0 rpm are also increased. Load changes in operation are more frequent, and output gradients significantly steeper (e.g. due to unpredictable changes in weather and priority of renewable energy sources). Overall utilisation of the power plants is only partial or very low, oftentimes resulting in uneconomical operation. The evaluation of power plant operating data has revealed this special operating mode not only in Germany but also throughout Europe [11].

This energy market trend is highlighted by an evaluation of the operating mode of 32 power plant units in southwestern Europe. The evaluation shows the change from base load and lower medium load to peak load operation from 100 to 300 h/start to 10 to 70 h/start in many gas-fired power plants within only 4 years. Most new power plants are operated in peak load or upper medium load from the very first commissioning [2].

The conventional power plants contribute more and more to grid stabilization and power reserve. The new operational mode results in higher wear of the power plant components.

It is absolutely necessary to adjust the design and maintenance of the component such as generators in power plants to this changed operating mode.

New grid demands and evaluation of operating regimes

The operating modes of conventional power plants and their generators can differ greatly, even if the power plants are of the same type and output range.

The operating modes of 33 plants worldwide with generators of the same type (indirectly air cooled generators in the 300 MVA class) were analysed in a detailed investigation. The explored generators cover all operating modes from base-load to peak-load power plants (Figure 2).

In addition to a daily start/stop cycle, it is clearly evident that the generator was not in a steady-state thermal condition in load operation, as the power plant frequently changed between full, part and minimum load.

The frequent and steep active power gradients form a further important charac-

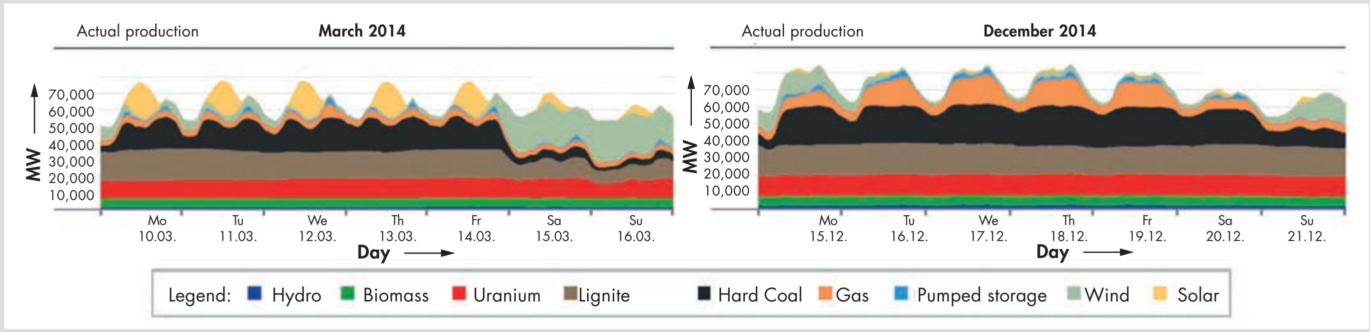

Fig. 1. Weather-dependent fluctuations in the contribution to electric power generation from wind and solar plants (Fraunhofer Institute for Solar Energy Systems (ISE) Freiburg, 2015-01-07).

teristic. These gradients are necessary to compensate the weather- and power demand related fluctuations. Reactive power input is similarly volatile. This provides the necessary voltage stabilisation in the grid, as renewable energy sources can generally only provide limited grid support.

Figure 3 shows a compact representation of the load points and gradients for one specific generator during entire operation lifetime. The left-hand image shows the relative frequency of the operating points in the capability curve. The broad scatter clearly reflects the operating modes described above:

- Operation in whole released capability range
- High share of reactive power for grid stabilisation
- Full use of under-excitation capability because of capacitive grid demand

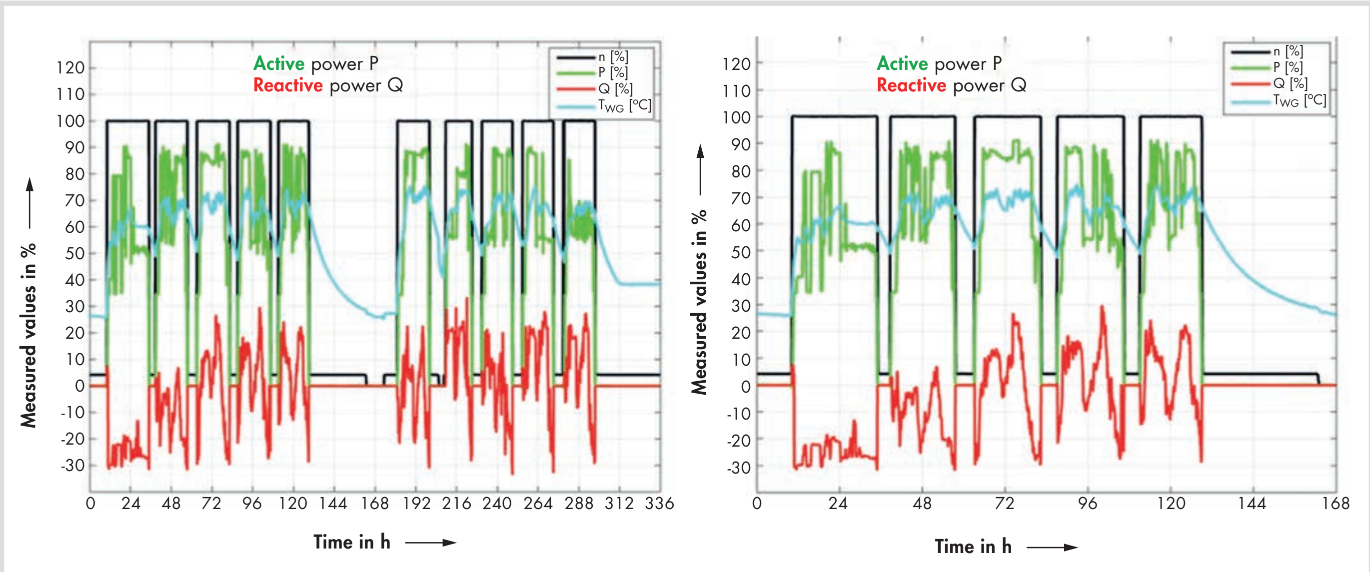

Fig. 2. Typical operating profile for a power plant in peak load operation (2 weeks period on the left, expanded view for 1st week on the right) [3]).

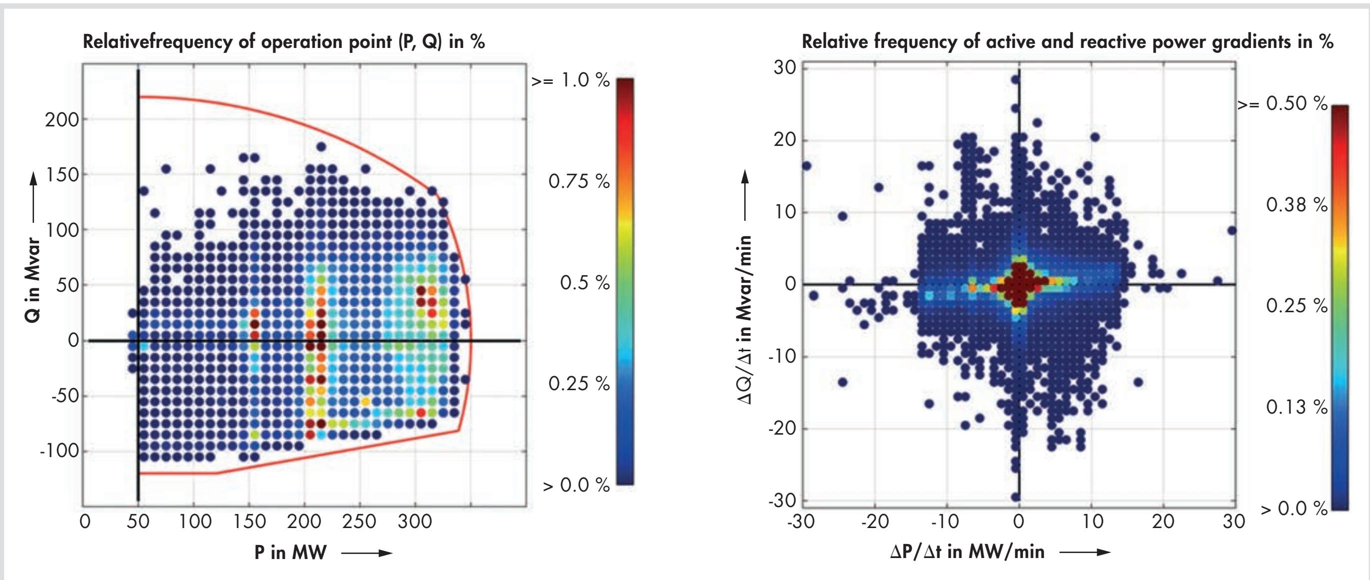

Fig. 3. Distribution of load points and load gradients for a generator with highly volatile utilisation [3].

Tab. 1. Effects of new grid demands on generators [3].

Increased requirements	Physical/technical challenges	Expected stress based on cooling method		
		Generator components	Indirectly cooled	Directly cooled
Fast active & reactive load changes	High thermo-mechanical stress at windings	Main bushings of stator winding	Mid	Low
		Carbon brushes and slip rings of static excitation	Low	Low
		Stator core end zones (stepped teeth)	Mid	Low
		Stator winding, especially overhangs	High	Low
		Rotor winding, especially end-turns covered by retaining rings	High	Mid
Load ramps up to 24 % of rated MW/min	Thermal cycling	Complete stator winding	High	Low
		Complete rotor winding	High	Low
Under excitation	High magnetic flux in end region	End teeth, clamping fingers, pressure plates	High	Mid
Overvoltage	High magnetic flux density	Stator winding in stepped core area	High	Low
		Dovetail bars at stator core back	High	High
		Rotor winding	High	Mid
		Stator core insulation	Low	Low

In addition to the load points, it is extremely important to examine in detail what are the gradients of the load changes.

The image on the right in Figure 3 shows the relative frequency of the generator load gradient, distinguished between active and reactive load gradients, over the entire operating period. The broad scatter out to higher amplitudes reflects the high demand from the grid for generator flexibility.

New grid demands and effects on generator components

The additional demands on power plants resulting from the volatile grid demand are known and are accounted for in the current specifications of the European Network Code. The relevant specifications for behaviour of the power generation units connected to the grid are especially defined in the Network Code "Requirements for Grid Connection applicable to all Generators" (NC RfG) [6]) and are further explained in a corresponding application guideline [7]. The determining requirements for the power plant/grid interface are significantly more stringent in comparison with the previously applicable regulations in NC RfG, and in part exceed the degree regarded as reasonable and necessary from the standpoint of the utilities.

Major impact on generator components:

- High number of start-stop cycles
- Operation in whole released capability range with fast load changes
- High share of reactive power for grid stabilization incl. under-excitation capability
- Wide grid frequency range
- Wide voltage range

The degree of the impact is strongly related to the cooling system of the components as illustrated in Table 1.

Every change in active or reactive power leads to a change of stator current, which in turn influences the copper losses and also the temperature in the stator winding. Due to different thermal expansion coefficients of the stator components (copper, insulation and steel), thermo-mechanical stresses will occur during every change of power. An evaluation of a generator fleet has shown that both relative load gradients and their occurrence will increase. It is expected that this trend will continue in the future (Figure 4).

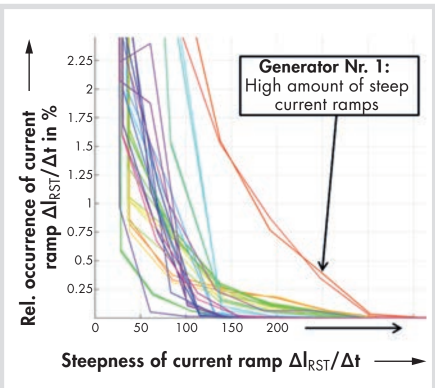

Fig. 4. Relative frequency and steepness of current ramps in stator for various units.

The generators have to withstand a "more exhausting" type of operation. These boundary conditions have to be considered in the future generator design.

In addition to the dynamic effects occurring during sudden load changes, the thermo-mechanical loads acting on the end winding structure also call for attention. Extensive finite element calculations are necessary to determine the detailed effects on the respective types of generators and end windings.

The extremely high degree of detail is necessary and requires superior modelling and calculation strategies (e.g. 3D FEM calculation) to determine the transiently occurring maximum stresses in various components, particularly the insulation system on a stator bar.

The stator winding insulation system has to be extremely robust and ensure, that local thermo-mechanical delamination effects have no negative influences on stator winding life time. Siemens GVPI Micalastic system fulfills this requirement by implemented Inner Corona Protection design (ICP) between copper strands and main insulation and by double layer Outer Corona Protection design (OCP) between main insulation and laminated core. Both interfaces are free of electrical stress, which avoids the occurrence of partial discharges (Figure 5).

Favourable designs for highly volatile grid operation will need additional mitigation for further stress reduction and therefore require water-cooled stator bars.

By these measures thermo mechanical stresses are decreased significantly and the consequential impact on lifetime consumption is minimised.

Further solutions and mitigations

Several measures can be employed to address the new operating conditions for generators which have been in service for many years as well as for new apparatus generators:

- Online and offline monitoring with lifetime consumption assessment
- Smarter inspection intervals, condition based maintenance

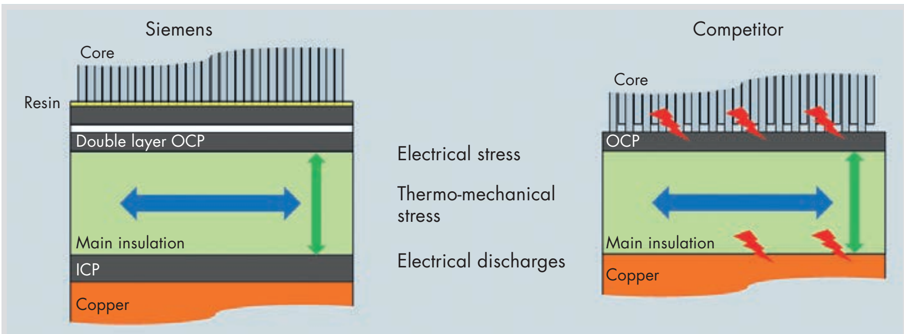

Fig. 5. Design of stress-resistant insulation system.

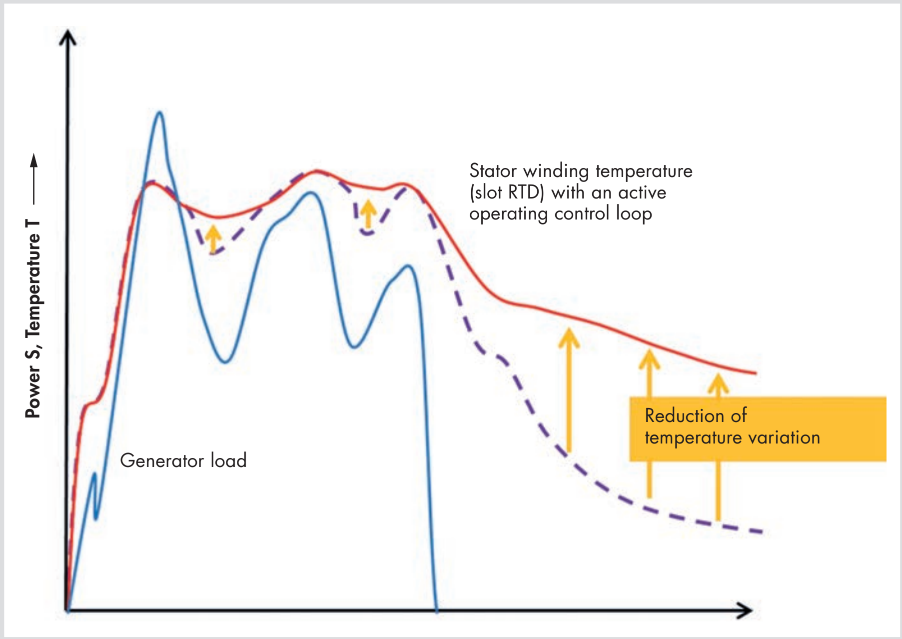

Fig. 6. Example of an active/intelligent temperature control in the power plant.

- Dynamic and active control of generator cooling system to reduce thermo-mechanical stress
- Improved design of components and use of special features
- Advanced strategic spare parts planning
- Specific generator design for flexible grid demands and extreme peak load operation.

Dynamic and active control of cooling gas temperature

The frequent load changes and start/stop cycles result in continuous thermo-mechanical stresses. Condition-oriented temperature control for the cold gas temperature in the generator is a means to counteract the actual cause of these thermo-mechanical stresses. The purpose of a cold gas temperature control of this type is to significantly reduce the temperature changes in the individual generator components due to load changes by controlling the cold gas temperature based on condition (e.g. as a function of apparent power output). Figure 6 shows a schematic RTD temperature of a non-regulated system (dashed line) which can be converted to a system with condition-oriented dynamic control through (solid line) the implementation of new hardware.

By its use during park load/turning gear operation, the cool-down times are extended and the most severe thermal shift which occurs between ambient and hot condition is greatly reduced if the plant is cycling within reasonable periods of time.

The development of an adaptive, dynamic control of the generator cooling system provides the following advantages:

- Improved thermal conditions of the generator as a thermo-mechanically sensitive system
- Seamless integration in the power plant as an overall system
- Individual solution possibilities for existing plants

Robust design of components

During the analysis of the operation data of the generators it could be seen that the power plants will be operating more and more for the grid support and stabilisation. To withstand the higher thermal strain due the higher magnetic flux on the stepped core end during under excitation an improvement of its design is essential. The steeper design of the core end as for the indirect cooled stator winding normally used can reduce the thermal stress in the core significantly during under excited operation. Yet at the same time it would increase the losses (radial field losses) and the temperature in the stator winding when the generator operates in the over excited mode.

To remain within allowed temperature limits in the generator components it is recommended to switch from indirect to direct water-cooled stator winding. This design solution causes also the temperature relief in the whole winding not only in the end region.

The direct water-cooled stator winding and steep stator core end region validated by long-term fleet experience is the best design solution to meet extended requirements.

Product life cycle philosophy and future targets

A condition-based maintenance, refurbishment and replacement strategy is the key success factor to maximise the customer value and to reduce the forced outage risk for existing generators. The first step should be an economic decision-making process which evaluates operation and maintenance costs versus risks of loss of availability and efficiency of the generator.

Siemens' vision: based on multiple information and evaluation routines the utility could start a detailed residual life assessment together with the OEM to prepare the decision for possible lifetime extension of the generator.

The future goal is to develop and built a monitoring system, that can be installed in the power plant to enable condition-based maintenance. This system should give a prediction on how the service life is reduced till now, which fatigue occurred, and at which point in time the generator should be serviced. The prediction is based on load characteristics in the past and on expected load scenarios in the future. Also

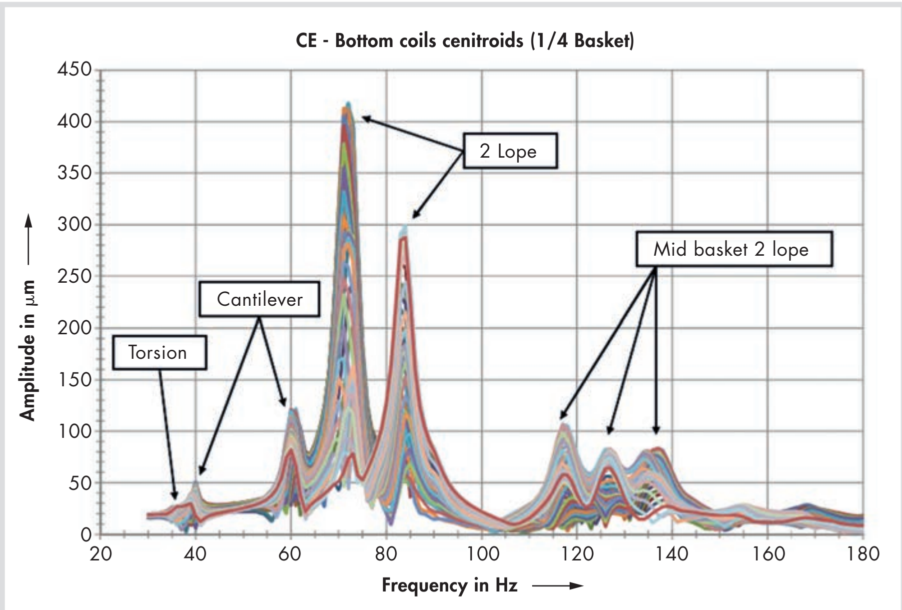

Fig. 7. Natural frequency spectrum of a stator end winding structure.

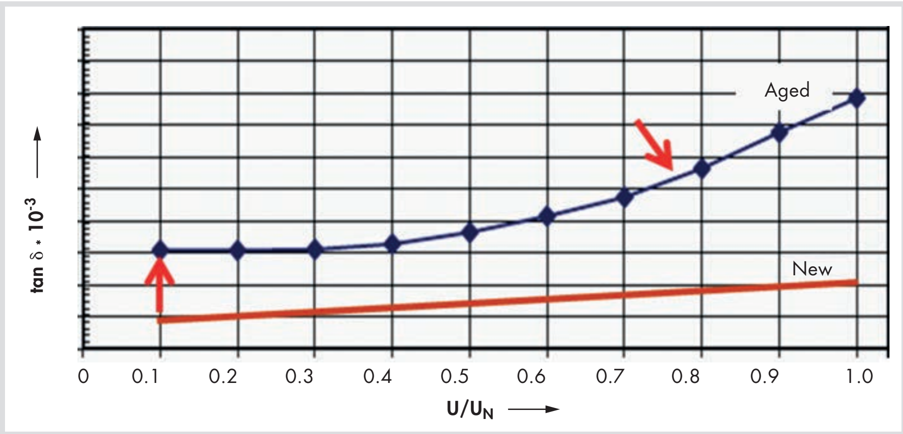

Fig. 8. Dissipation factor measurements of a new and an aged high voltage insulation system.

a risk prediction respectively risk rating for the generator components should be given by this system.

The necessary evaluation data will be obtained during operation as well as during regular inspections. For example the possible changes in structural dynamics of stator end windings can be assessed by experimental modal analysis. The natural frequency spectra (Figure 7) can be used for trending of on stator end winding's behaviour over time as well as comparison within a comparable fleet.

Fiber optic vibration measurement of stator end windings can be used to directly monitor online vibrations during operation. Such data can be correlated for further analysis with operating parameters such as currents, temperatures, power factor etc. The combination of thermal, mechanical and electrical loading may induce degradation of the high-voltage insulation system. Trending of such degradation over the lifetime of a generator can be performed i.e. by means of recurring dissipation factor and partial discharge measurements. Figure 8 shows the general difference between the dissipation factor curves of a new and an aged insulation system. The increase in dissipation factor at low voltage indicates increased losses of thermally aged resin system. The tip up at higher voltages indicates delamination voids within the main insulation, which are not present in new generators.

Conclusion

To summarise the changes in grid requirements and their impact on future generator design and service, it can be stated that:

- The new flexible grid demand has significant impact on the generator as an overall system with aging acceleration for individual components
- Changed requirements and remaining uncertainty for the future increase in flexibility must be considered in current generator development programmes

Accordingly mitigation measures have been evaluated and proposed:

- Thermo mechanical stresses on generator components require enhanced load dependent cooling technology, particularly at the stator winding
- Special generator design features such as water cooled stator windings or modified core end zone shapes help to adapt to flexible operation regimes
- Special online monitoring systems and offline maintenance tools are needed for economical inspection decision for generator components and as early warning systems for weak points
- A refurbishment and replacement strategy is needed too to reduce the forced outage risk for older generators

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