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Note:

This is a translation of the RSK statement entitled “Netzstabilität“ - Rückwirkungen von Stabilitätsproblemen im deutschen Stromnetz auf elektrische und leittechnische Einrichtungen von Kernkraftwerken und Sicherstellung der notwendigen elektrischen Energieversorgung dieser Anlagen aus dem Netz”

In case of discrepancies between the English translation and the German original, the original shall prevail.



**RSK Statement  
(453<sup>rd</sup> meeting on 13 December 2012)**

**Grid stability:**

**Impact of stability problems in the German power grid on electrical and I&C installations  
of nuclear power plants  
and securing the required electrical power supply for these plants from the grid**

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## 1 Summary

In view of the permanent shutdown of eight German nuclear power plants and the changes in the electricity grid due to the increasing share of renewable energy sources, there is growing debate among experts and in the media about securing the electricity supply and possible problems with the stability of the electricity grids in Germany. In terms of the safety of German nuclear power plants, the RSK therefore saw a need for consultations with respect to operating and decommissioned plants regarding the repercussions of possible grid stability problems on the electrical and instrumentation and control (I&S) installations of German nuclear power plants and any safety systems that may be affected.

The Committee on ELECTRICAL INSTALLATIONS (*ELEKTRISCHE EINRICHTUNGEN* - EE), which was tasked by the RSK with providing advice, adopted a draft of this statement at its 223<sup>rd</sup> meeting on 21 November 2012 and submitted it to the RSK for approval at its 453<sup>rd</sup> meeting. The basis for this was prepared by the ad hoc GRID working group (AG *NETZ*) set up by the EE committee for this purpose.

During the consultations, aspects were identified - based on relevant safety assessments - which, in the opinion of the RSK, require further investigation. Specific recommendations were formulated in each case.

The assessments are based on the defence-in-depth concept, the requirements of the non-mandatory guidance instruments, in particular, the relevant KTA safety standards for safety system equipment. With regard to the consideration of international nuclear regulations or conventional regulations for the operation of electricity grids, conflicts of goals may arise because these may not be consistent with the legal situation of the German licensing and supervisory procedure or may not sufficiently take into account the requirements of the electrical and I&C installations of nuclear power plants.

The statement in hand assesses the technical effects to be considered as a result of potential stability problems, such as voltage and frequency deviations, on the one hand with regard to their influence on the reliability of safety-relevant electrical and I&C installations in nuclear power plants, and on the other hand with regard to ensuring the necessary electrical power supply to these plants from the German electricity grid.

The deliberations conducted by the RSK on the consequences of the accident at the Fukushima nuclear power plant in Japan concerning the internal power supply provided by emergency power systems and plant-internal accident management measures are not the subject of this statement but were dealt with in connection with the final deliberations on the RSK's safety review (RSK-SÜ).

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## Repercussions of stability problems on the reliability of safety-relevant electrical and I&C installations in nuclear power plants

As regards longer-term under- or overvoltages, the RSK concludes that deviations that may occur within the range still permitted by the German Transmission Code TC-2007 do not have an impermissible effect on the electrical and I&C installations of a nuclear power plant due to the component design, the compensation options offered by the intervention of the generator voltage regulator or corresponding voltage stepping by the generator, auxiliary power or offsite system transformers, due to automatic measures or appropriate manual measures or – in the case of I&C equipment – decoupling via the DC systems. However, to the RSK's knowledge, not all plants are equipped with an automatic warning system that alerts the control room personnel to an overvoltage or undervoltage in the auxiliary power supply and prompts them to take manual actions. It is therefore recommended that such a warning system for overvoltage and undervoltage be installed in all plants. In addition, the resulting measures should be specified in the plants' operating manuals. /E-1/.

At European level, a binding European grid code in the form of an EU directive is currently being developed under the leadership of the European Network of Transmission System Operators for Electricity (ENTSO-E). The provisions of such a grid code also have an impact on the operation and safety of nuclear power plants, e.g. in the form of specifying permissible operating ranges for voltage, frequency, power and operating time in the event of deviations of these parameters from the nominal values. Due to the fundamental importance of this interface definition, the RSK recommends that the BMU urge grid operators to take into account the safety-related designs and operating conditions of German nuclear power plants when drafting the ENTSO-E grid code. /E-2/.

In the opinion of the RSK, it can be assumed that, due to the protective measures implemented, short-term frequency deviations within the range permitted by TC-2007 (47.5 Hz to 51.5 Hz) do not jeopardise the safety of nuclear power plants. This assessment was also based on findings from investigations carried out in all German nuclear power plants following the so-called "Forsmark event".

Unlike in the case of operation during undervoltage or overvoltage, there is no way to counteract frequencies that deviate from nominal conditions for a plant operating in grid-synchronous mode without grid disconnection in the case of longer-term frequency deviations. For plants that are shut down, no protective measures are generally provided for operation at high frequencies, whereas for plants in power operation, load rejection to auxiliary power is carried out in order to be able to continue supplying the plant in island mode independently of the grid.

It is not possible to give a generic answer to the question of the extent to which prolonged operation of continuous drives or control drives at frequencies above the nominal value (50 Hz) in all plants - regardless of the mode of operation - may lead to the unintentional activation of overload protection devices. In the opinion of the RSK, prolonged operation at frequencies above the nominal frequency but within the requirements of TC-2007 requires separate, plant-specific consideration, taking into account the respective tripping characteristics of the protection devices. /E-3/.

Operation at underfrequency up to the actuation of the emergency diesel generators is covered by appropriate

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design and operating experience.

Ensuring the necessary electrical power supply (not uninterruptible three-phase power supply) from the grid

Based on the current design concept of German nuclear power plants and previous operating experience, a loss of off-site power (failure of the plant's auxiliary power supply with actuation of the emergency diesel generators) cannot be ruled out during the operating life of a plant. The frequency of a loss of off-site power has an impact on the results of probabilistic safety analyses (PSA). According to the nuclear regulations, it must be ensured that emergency diesel generators can operate for 72 hours in the event of a loss of offsite power. For emergency situations involving a hypothetical failure of the emergency diesel generators, it is assumed – on the basis of the RSK assessments following the Chernobyl accident in 1988 - that a secure grid supply can be restored within two hours.

Due to the increasing share of renewable energies in the electricity supply and the limitation of power reserves following the permanent shutdown of eight nuclear power plants, the available information indicates that a further increase in voltage and frequency fluctuations within the limits specified by TC-2007 (below and above the nominal values) is to be expected in the near future. This requires more frequent intervention by transmission system operators to maintain grid stability. Such interventions generally increase the potential for grid disturbances, as interventions can also fail. In addition, natural hazards can affect grid infrastructure and additional generation capacities, thereby exacerbating problems with the grid.

The grid problems mentioned above increase the potential for major transients in the power grid, which could lead to the failure of parts or the entire grid if the grid operators are unable to take countermeasures in such situations in a timely manner or if these measures are no longer sufficient due to the occurrence of multiple failures. According to the RSK, the reserves available for preventing and controlling disturbances – in the form of short-term available control energy – have become significantly smaller, meaning that without countermeasures, grid stability could become even lower in the future. Furthermore, such reserves often cannot be made available where they are needed at that particular moment.

Information provided by transmission system operators on measures to be taken following a grid failure indicates that the procedures required for grid restoration have been planned and documented in advance so that, in the event of a large-scale grid failure, nuclear power plants can be given priority and promptly supplied with energy for their auxiliary power demands. In Germany, there are no regulatory requirements regarding the priority restoration of the energy supply to nuclear power plants from the grid system, particularly after large-scale grid disruptions. The current regulations are based on agreements between the respective plants and the assigned transmission system operators from a time when energy generation and energy transport were still located under the umbrella of a joint corporate structure. In the opinion of the RSK, it should be ensured on a plant-specific basis that there are contractual agreements between the nuclear power plant operators and the transmission system operators regarding the priority supply of nuclear power plants and that these agreements will continue to apply in future to low-power and shutdown operation and to the post-operation of the plants. /E-4/.

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During the consultations, it was established that both an increase in the frequency of losses of offsite power and their duration have a noticeable influence on the core damage frequency determined in the probabilistic safety analysis (PSA). It can therefore be deduced that a reduction in the required duration of the running of emergency diesels by change-over at the earliest possible stage – i.e. restoration of the plant's auxiliary power supply from the external grid – has a significant impact on reducing the core damage frequency.

It is recommended that further developments in recent findings regarding the “frequency of failure of all offsite supply options” and the “duration of grid failure” be monitored closely in order to assess the impact on PSA results and, if necessary, derive corresponding measures. /E-5/.

For the prolonged operation of emergency diesel generators in plants that are no longer intended for power operation, it must be taken into account that these plants have less stringent requirements for the operation of emergency core cooling and residual-heat removal systems in the event of a loss of offsite power. This leads to a reduction in the diesel load in the event of a loss of offsite power. Prolonged operation of the emergency diesel generators below a minimum load of approx. 30% (manufacturer-dependent specification) has a negative effect on the operating behaviour and reliability of the diesel generators, as the combustion processes in the engine are not optimal when operating in this load range and coking in the combustion chamber may occur. Furthermore, when operating in the minimum load range, the load on the bearings is higher than in the upper load range, which leads to correspondingly higher wear. As a result, individual affected plants have already planned measures to increase the diesel load (using options for manually switching consumers to individual emergency diesel generators) in conjunction with the manual disconnection of emergency diesel generators that are then no longer required. Accordingly, it should be checked for all plants in post-operation to what extent low-load operation of the emergency diesel generators for at least 72 hours may have an adverse effect on the reliability of the generators and to what extent suitable precautions against such long-term operation are necessary /E-6/.

The RSK concludes that, from today's perspective and taking into account the recommendations made by the RSK in this statement, neither national nor international operating experience indicates any fundamental changes in the electrotechnical design of German nuclear power plants with regard to their ability to supply their own auxiliary power or to supply safety-critical consumers in the event of the grid disturbances considered here (voltage and frequency deviations). Measures to improve the reliability of electrical and I&C systems based on the investigations conducted by VGB following the ‘Forsmark event’ are not affected by this.

## **2 Cause of the statement**

In view of the permanent shutdown of eight German nuclear power plants and the changes in the electricity grid due to the increasing share of renewable energy sources, there is growing debate among experts and in the media about securing the electricity supply and possible problems with the stability of the electricity grids in Germany. In its report entitled ‘Effects of the nuclear power plant moratorium on transmission grids and supply security’ dated 26 May 2011 [2], the Federal Network Agency, which is responsible for production and distribution control in the German electricity grid, highlights potential future problems in the event of increased

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electricity demand or supply bottlenecks [1].

In terms of the safety of German nuclear power plants, the RSK sees a need for consultations (resolution of the 438<sup>th</sup> RSK meeting on 9 June 2011) with respect to operating and decommissioned plants regarding the repercussions of possible grid stability problems on the electrical and instrumentation and control (I&C) installations of German nuclear power plants and any safety systems that may be affected [1].

The technical implications to be considered as a result of potential stability problems are:

- prolonged under- or overvoltage at the grid connection, possibly combined with frequency deviations,
- prolonged frequency deviations,
- short-term low-frequency transients in the grid voltage, and
- new forms of grid instability (e.g. grid failures in the millisecond range).

Within the framework of this statement, these effects are assessed with regard to their influence on the reliability of the safety-relevant electrical and I&C installations of nuclear power plants and with regard to ensuring the necessary electrical power supply for these plants from the grid.

The deliberations conducted by the RSK on the consequences of the accident at the Fukushima nuclear power plant in Japan concerning the internal power supply provided by emergency power systems and plant-internal accident management measures are not the subject of this statement but were dealt with in connection with the final deliberations on the RSK's safety review (RSK-SÜ).

### **3 Course of the discussions**

A series of questions was initially formulated on the subject of the consultation at the 441<sup>st</sup> RSK meeting. The RSK Committee on ELECTRICAL INSTALLATIONS (*ELEKTRISCHE EINRICHTUNGEN* - EE) was tasked with addressing these issues on the basis of a consultation concept adopted by the RSK [1], corresponding presentations by the Federal Network Agency and the transmission system operators, an evaluation by GRS of national and international experience with grid disturbances and losses of offsite power, and a review of the relevant literature.

The EE committee adopted a draft of this statement at its 223<sup>rd</sup> meeting on 21 November 2012 and submitted it to the RSK for approval at its 453<sup>rd</sup> meeting on 13 December 2012. The basis for this was prepared by the ad hoc GRID working group (AG *NETZ*) set up by the EE committee for this purpose [37]. The RSK discussed and adopted this statement at its 453<sup>rd</sup> meeting.

During the consultations, aspects were identified on the basis of relevant safety assessments which, in the opinion of the RSK, require further investigation. Specific recommendations were formulated in each case.

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## 4 Assessment criteria

The fundamental basis for the assessments is the defence-in-depth safety concept [3] and, in particular, its technical implementation as described in Chapter 6.1 of this statement on uninterrupted three-phase power supply. In this context, all relevant requirements of the statutory provisions and non-mandatory guidance instruments are also taken into account (in particular [4], [5], [6]). For safety system installations, these are in particular the relevant KTA Safety Standards ([7], [8], [9], [10], [11], [12], [13]). If, in the opinion of the RSK, further requirements or clarifications are considered expedient for the safety of nuclear power plants, corresponding recommendations will be made.

The above-mentioned national regulations do not contain any requirements on the part of nuclear power plants with regard to the grids. However, conventional regulations (e.g. [14], [15], [16], [17]) governing the operation of electricity grids specify boundary conditions for the grid connection of nuclear power plants; these were used as a basis for the assessment in this statement.

With regard to the consideration of conventional regulations governing the operation of electricity grids, conflicts of interest may arise from the fact that, in practice, the responsibility of the nuclear licensing and supervisory authority ends at the interface between the plant and the grid. Further requirements for the grid, e.g. for priority power supply in the event of grid disruptions, are currently regulated by bilateral agreements between nuclear power plant operators and transmission system operators and are taken into account accordingly in the following considerations.

In order to establish a concrete link between the current requirements of nuclear power plants and the stability problems in the grid, plant-specific investigations were carried out using the example of a "PWR, 1300 MW, convoy"-type nuclear power plant (reference plant) [37].

## 5 Repercussions of grid stability problems on electrical and I&C installations in a nuclear power plant

### 5.1 Causes of grid stability problems

Stability problems can arise from local, regional or supraregional imbalances between electricity production and electricity consumption by consumers. They can also arise from insufficient frequency control due to a lack of base load supply from frequency- and voltage-stabilising power plants. With the current state of the art, wind turbines and photovoltaic systems are generally not equipped to generate sufficient reactive power, which causes problems with voltage control ([18], [19], [20], [21]). In addition, electricity production from photovoltaic and wind power plants is difficult to plan and predict, which requires high reserve capacity due to a lack of energy storage in the grid. Frequency deviations that exceed or fall below the specified limits immediately lead to the shutdown of consumers or production capacities in the affected area as otherwise considerable damage to electrical equipment could occur. Significant influences arise in particular from the supraregional utilisation of high-voltage power lines and the locally varying balance between active and reactive power.

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## **5.2 Plant design to counter voltage deviations (overvoltage, undervoltage) in the grid**

The requirements for the interface to the extra-high-voltage grid are defined in the grid connection agreements for German power generation plants, including nuclear power plants. These are based on the former Grid Code (currently Transmission Code 2007 [15]).

Transmission Code 2007 (hereinafter referred to as TC-2007) specifies i.a. the voltage range at the grid connection within which power generation plants must be able to operate, even if only for a limited period of time. With regard to the maximum voltage level, the tolerances for the nominal voltage are approximately minus 10% and plus 15%. According to the RSK, longer-term operation (i.e. for periods of more than ten to 30 minutes, depending on the voltage situation) of power generation plants outside this voltage window is therefore not to be expected as either the grid operator's measures to stabilise the grid will take effect (see Chapter 6.3) [19] or the power plant operator is no longer obliged to keep the plant available for electricity generation [15]. However, this does not preclude the occurrence of transient disturbances, which may cause voltages outside the specified tolerance range for a limited period of time. Such deviations must always be countered by plant-specific protective measures.

## **5.3 Effects on electrical and I&C equipment in the event of prolonged under- or overvoltage at the grid connection and their safety significance**

With regard to longer-term voltage deviations, it should first be noted that these can be compensated for in the plants by appropriate tap changes (technical term for this control process) of the generator or offsite grid transformers or by voltage tracking by the generator voltage regulator. In some cases, tap changers are also available on the auxiliary power transformers. Depending on the transformer type and plant, the possible adjustment range of the transformers is approximately  $\pm 10$  to 16% of the nominal value. Within the specified adjustment range, longer-term deviations would therefore not affect the consumers of the unit and emergency power systems of a nuclear power plant. Nevertheless, the basic effects of under- or overvoltage on electrical consumers will be described below insofar as they are considered relevant to their operation.

Undervoltages have an adverse effect on the starting behaviour of asynchronous motors used to drive work machines or in actuators for operating valves. If the torque required to start a motor can no longer be applied due to low voltage, the motor locks up and is shut down by its overcurrent protection devices to prevent further damage.

Undervoltages also have a negative effect on the pulling-in and holding capacity of AC-powered contactors and relays. However, based on previous experience, the starting and holding voltages guaranteed by manufacturers for contactors and relays are generally well below the above-mentioned minimum voltage of  $U_N - 10\%$ .

Overvoltages, on the other hand, lead to increased excitation of transformers and correspondingly higher thermal stress on the iron core. This is particularly important for machine transformers, which are already

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operating at high capacity during normal operation. Machine transformers are therefore protected by an adapted U/f protection system and are switched off as a precautionary measure if a preset limit value is exceeded.

In electric drives, the power consumption or motor current increases with increasing voltage due to saturation effects. During prolonged operation under such conditions, the shutdown thresholds of the motors' overcurrent protection devices may be reached, causing the drives to shut down for protection.

Due to immediate voltage tracking by the generator voltage regulator or prompt voltage stepping of the generator/offsite system transformer, deviations from the nominal voltage within the operating range specified by TC-2007 [15] do not have an impermissible effect on the function of the electrical components.

The rectifiers used in the emergency power system of nuclear power plants to supply the DC voltage level or to trickle charge the batteries also used to supply this level are switched off by their protective devices if the input voltage falls below 80% or exceeds 115%. When the operating voltage returns to the nominal range, the devices are automatically switched back on. However, if the nominal range of the operating voltage is not reached again, the batteries begin to discharge as trickle charging is no longer possible due to the unavailability of the rectifiers. However, this is signalled in the control room of the reference plant so that the personnel can take appropriate action. Since the power supply to I&C installations via batteries is decoupled from the three-phase current side and since the inverters and switching power supplies with the connected consumers (including I&C installations, if applicable) are decoupled from the three-phase supply in a similar way via the DC voltage level, longer-term voltage deviations at the grid connection point of a plant have no effect on the I&C installations, regardless of the possibility of stepping mentioned above.

In its assessment, the RSK concludes that longer-term under- or overvoltages in the area specified by TC-2007 [15] do not have an impermissible effect on the electrical and I&C installations of a nuclear power plant due to the component design, the compensation options provided by the intervention of the generator voltage regulator or corresponding stepping of the generator, auxiliary power or offsite system transformers, automatic measures or appropriate manual measures following corresponding hazard warnings or, in the case of I&C installations, decoupling via the direct current systems. The measures are implemented differently in the various plants.

However, to the RSK's knowledge, not all plants are equipped with an automatic warning system that alerts the control room personnel - possibly already prior to automatic measures - to an overvoltage or undervoltage in the auxiliary power supply and prompts them to take manual actions. In the reference plant under consideration, when a voltage of 110% is reached in auxiliary power mode, the generator switch is opened without prior warning after 5 seconds and turbine trip occurs if the generator voltage regulator is unable to intervene successfully during this time. The RSK therefore recommends that such a warning system for overvoltage and undervoltage be installed in all plants, especially since a comparable warning already exists in the reference plant in the event of undervoltage (95%). In addition, the resulting measures should be specified in the plants' operating manuals /E-1/.

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At European level, a binding European grid code in the form of an EU directive is currently being developed under the leadership of ENTSO-E. The provisions of such a grid code also have an impact on the operation and safety of nuclear power plants, e.g. in the form of specifying permissible operating ranges for voltage, frequency, power and operating time in the event of deviations of these parameters from the nominal values. Due to the fundamental importance of this interface definition, the RSK recommends that the BMU urge grid operators to take into account the safety-related designs and operating conditions of German nuclear power plants when drafting the ENTSO-E grid code /E-2/.

#### **5.4 Plant design to counter frequency deviations (overfrequency, underfrequency) in the grid**

Essentially, the frequency range permitted for the reliable operation of nuclear power plants is based on the frequency bands specified in TC-2007 [15] or, in reduced form, in the plant-specific grid connection agreements. The lower limit specified there is 47.5 Hz (corresponding to nominal frequency -5%). Although, from the transmission system operators' point of view, continuous operation below 49 Hz does not appear to be possible, the gradation of protective measures implemented in German nuclear power plants still shows design margins for the reliable operation of electrical and I&C equipment down to a drop to 47.5 Hz.

The upper limit for reliable operation of electrical components can be specified as 52.5 Hz (corresponding to nominal frequency +5%), with individual protective measures initiated by both the grid operator and the power plant operator to exclude the operating range for values greater than 51.5 Hz as the grid frequency increases.

In addition to the benchmark values for the permissible operating range at different frequencies, TC-2007 [15] also contains time specifications for the continued operation of a plant at frequencies deviating from nominal values, graded according to the significance of the deviations.

In the opinion of the RSK, it can be assumed that, due to the protective measures implemented, short-term frequency deviations within the range permitted by TC-2007 [15] (47.5 Hz to 51.5 Hz) will not jeopardise the safety of nuclear power plants (see Chapter 4.2 of the Annex).

#### **5.5 Effects on electrical and I&C installations in the event of prolonged frequency deviations**

This includes in particular frequency deviations which, due to their magnitude, have not yet resulted in the separation of the plant from the grid or the shutdown of components, but during which a prolonged deviation within the just permissible range could occur.

In contrast to the operating mode in the event of under- or overvoltage, it is not possible for a plant operating in grid-synchronous mode without grid disconnection to counteract frequencies that deviate from nominal conditions. For plants that are shut down, no protective measures are generally provided for operation at high frequencies. For plants in power operation, the grid is then disconnected by load rejection to auxiliary power

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so that the plant can continue to be supplied independent of the grid in island operation mode.

An increased voltage-frequency ratio leads to higher excitation of a transformer with corresponding thermal stress on the iron core. This means that even a low frequency can lead to higher excitation. This is particularly important for generator transformers, which are already operating at high capacity during normal operation. Generator transformers are therefore monitored by appropriately adjusted overexcitation protection (U/f protection).

An increase in the grid frequency is associated with higher power consumption by drives. In particular, during longer operating times just below the response threshold of overcurrent protection devices, this can lead to unintentional tripping of the protection devices if the response threshold of the overcurrent protection devices is reached due to the tripping characteristics of the protection devices. This applies in particular to continuous drives of working machines as well as to control drives for valves. In the investigations following the Forsmark event, only transient loads with an increased frequency of up to 120% and a duration of approx. 30 s were taken into account, but no operation at higher frequencies beyond this time.

It is not possible to give a generic answer to the question of the extent to which prolonged operation of continuous drives or control drives at frequencies above the nominal value (50 Hz) in all plants - regardless of the mode of operation - may lead to the unintentional activation of overload protection devices. This requires knowledge of the types used and the setting values of the component-related protective devices, the system-level protection limits, and the duration and level of the overfrequency. In the opinion of the RSK, prolonged operation at frequencies above the nominal frequency but within the requirements of TC-2007 requires separate, plant-specific consideration, taking into account the respective tripping characteristics of the protection devices /E-3/.

The frequently used thermal protection devices (bimetals) in electric drives are components whose functionality is independent of the frequency deviations discussed here. The extent to which this result can be applied to other protection devices, such as digital protection devices, has not been investigated.

I&C equipment is also unaffected by the frequency deviations discussed here as it is decoupled via the DC systems in terms of its power supply.

Operation at underfrequency up to the activation of the emergency diesel generators is covered by appropriate design and operating experience.

## **5.6 Process-related event sequences in NPPs in the event of impermissible voltage/frequency deviations in the grid, depending on the operating state (power operation or low-power and shutdown operation) and the duration of the deviations**

German nuclear power plants are designed for operation within a specific voltage range in terms of systems technology, i.e. at a level that is higher than that of electrical component design. Operation at frequencies

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deviating from nominal conditions was also taken into account in the design, but from a systems technology perspective, this was more in terms of transient conditions such as underfrequency excitation as the excitation criterion for diesel start-up or temporary overfrequencies in the plant as a result of load rejection to auxiliary power. Accordingly, the plants are equipped with monitoring and protection devices which, under certain boundary conditions, are intended to ensure compliance with the benchmark values for voltage and frequency on which the design is based.

With particular regard to the aforementioned boundary conditions, the aspect is addressed of the extent to which the monitoring and protection devices in question are capable of counteracting impermissible deviations in voltage and frequency at the grid connection point (without taking into account individual phase-related faults on the grid side, such as short circuits or interruptions), regardless of the operating status of the plant. In addition, the fundamental process-related effects of deviations in voltage and frequency from the nominal conditions are also described.

From the perspective of process engineering components, under- or overvoltages affect their operation (only) in that, when protective limits are reached at the system level, measures are initiated with the aim of restoring a reliable power supply to consumers or transferring the plant as a whole to a safe state. As long as the corresponding actuation criteria for undervoltage or overvoltage are not reached, process engineering components (ventilators or pumps) and systems with the corresponding design (e.g. with regard to start-up behaviour with the required start-up torque or the higher power consumption of motors in the event of overvoltage) practically do not 'notice' undervoltage or overvoltage in the network. This applies regardless of the operating state of the plant.

In terms of process engineering, however, deviations from the nominal frequency would have an impact, particularly on electric drives. Increasing frequency would lead to higher speeds, which would mean, for example, a higher delivery rate or volume flow, a greater delivery head or pressure increase, and higher power demand for pumps and ventilators. The consequences would include, for example, a pressure increase in closed systems and a higher coolant throughput in the reactor core of PWR plants.

Frequencies below the nominal value, on the other hand, would result in reduced speeds of electric drives. Lower core throughput would result in a poorer DNB ratio in PWR plants, extended drive running times could lead to problems with running-time-monitored actuators, and reduced pump delivery rates and delivery heights would be associated with reduced feed rates.

At this point, only examples of the process engineering effects of plant operation with a frequency deviating from the nominal value can be given. Whether and to what extent such deviations would have an impact in a specific case cannot be assessed in general terms as this would require detailed knowledge of the respective component and system design. This knowledge was not available. Accordingly, no specific process-related and plant-specific statements were derived.

The following section uses the reference plant as an example to illustrate which protective measures are effective at the system level when voltage and/or frequency reach specified limits and thus assume impermissible levels.

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In the reference plant, load rejection to auxiliary power is staggered according to protection limits at high frequencies, with turbine trip additionally required if necessary. Load rejection to auxiliary power acts as a barrier against overfrequency from the grid by disconnecting the plant from the grid at 51.5 Hz.

When the plant is at standstill, there is no longer any corresponding protection at high frequencies; the plant is dependent on measures taken by grid operators to limit overfrequency. However, since in such a situation other generating plants will be disconnected from the grid and/or additional load will be connected (e.g. commissioning of pumps at pumped storage plants), operation at overfrequency is limited to a period of < 30 minutes when the operating range specified in TC-2007 [15] is under load. It should also be noted that a decrease in the number of units feeding into the grid will quickly lead to a reduction in the grid frequency.

At frequencies below the nominal value, the plant is disconnected from the grid with load rejection to auxiliary power, also staggered according to protection limits, followed by a switchover to the standby power supply if necessary and, if this is not successful, the start-up of the emergency diesel generators. When the plant is at standstill, the same measures are taken except for load rejection.

In power operation, load shedding is again the first important barrier against continued operation at an impermissible frequency. The second important barrier is the separation from auxiliary power supply and the start-up of the emergency diesel generators. This ensures the self-sufficient supply of safety-critical equipment, regardless of the operating conditions in the grid, both for power operation and for plant standstill.

In the event of high voltage in the reference plant, turbine trip, switchover to the standby grid as need be and a temporary cut-off of rectifiers will be triggered, staggered according to protection limits. With the exception of turbine trip, the same measures are triggered when the plant is shut down.

It is clear that the measures mentioned are only partially effective against long-term overvoltage from the grid. On the one hand, long-term high voltage from the grid can be counteracted within the adjustment range of the generator, auxiliary power or standby transformers. However, there are no other automatically effective measures, which means that transient overvoltages from the grid reach the plant largely unhindered. Independence from the main and standby grids is not always guaranteed due to the interconnections between the grid levels. This can impair the effectiveness of a standby grid switchover. In addition, the availability of one of the two grid connections of the plants may also be restricted due to maintenance measures during the overall maintenance inspection and refuelling outage.

The measures taken in the event of low voltage during power operation are similar to those taken in the event of high voltage in the reference plant, with the difference that no turbine trip is triggered and the emergency diesel generators are started after the standby grid switchover with the voltage still being low.

Provided that the standby grid connection is available when the plant is shut down, the same measures are also carried out in this plant state. Since the undervoltage criterion causes the disconnection of the emergency power supply facilities from the auxiliary power supply facilities and start-up of the emergency diesel generators, the self-sufficient supply of safety-critical equipment (including the previously cut-off rectifiers) is ensured without restriction at low voltage at the grid connections, regardless of the operating conditions in the grid,

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both for power operation and for plant shutdown. The duration of the emergency power supply depends on the availability of the grid, but in principle is not limited in time provided that sufficient quantities of fuel and lubricants are available.

### **5.7 Protective devices in a nuclear power plant that may be triggered by grid instabilities**

The protective devices were illustrated using a reference plant (Convoy type) as an example. Other plants have similar devices, but there may be differences in terms of the staggering and scope of the devices. For example, not all plants have automatic switching devices that switch to the standby grid in the event of high voltage or high frequency. However, the basic design and mode of operation of the devices described are identical to those of the reference plant.

The majority of the protective devices are assigned to unit protection, where their task is to ensure that the plant operates within the permissible limits for voltage and frequency. In the safety system, minimum limits for voltage and frequency are used to start the emergency diesel generators and ensure reliable operation of the consumers if there is a deviation from the permissible operating range for safety-critical equipment. In this case, the emergency diesel generators take over the supply to the connected consumers. Further limit values serve to protect components and ensure the reliable operation of the associated components within the specified limits.

Some of the protective actions for unit protection described above are only effective if the power plant is in power operation. Monitoring by generator or turbine protection is inevitably unavailable when the turbine shaft is stationary. Here, the only barriers are the automatic switchover systems for auxiliary power supply - which trigger a switchover from the main to the standby grid when necessary if the main and standby grid connections are available - and the diesel startup criteria, which cause the emergency power system's power supply to be disconnected from the auxiliary power supply in the event of undervoltage/underfrequency.

Of the specified limit values, only the limit values for starting the emergency diesel generators and the protective limit values for the rectifiers are assigned to the safety system with the procedures specified for each plant in the event of possible changes in voltage or frequency. The remaining limit values are implemented in the operational area. However, due to their fundamental importance for safe and reliable plant operation in accordance with the defence-in-depth concept, some of these limits are also multi-channel and self-monitoring. In the opinion of the RSK, these protective limits must not be changed outside the nuclear regulatory procedure (i.e. only under the operator's own responsibility). Such changes require a comprehensive review. This requirement is also already the subject of Recommendation 2 of Information Notice (*Weiterleitungsnachricht* - WLN) 2006/07 on the Forsmark event [22].

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## **5.8 Effects of stability problems in the German grid on the electrical and I&C systems of a nuclear power plant against the background of the investigations conducted by VGB following the Forsmark event in 2006 and the resulting improvement measures**

Transients in grid voltage and frequency were examined in the conceptual considerations on the interaction between the grid and power plants and in the investigations conducted by VGB following the Forsmark event [23]. Possible scenarios for major disruptions were considered.

Further scenarios involving transients that could arise from the expected future grid situation with greater utilisation of the voltage and frequency tolerance bands and which would not be covered are not currently apparent. However, it can be assumed that the voltage and frequency tolerance bands will have to be utilised more frequently and possibly for longer periods than before.

## **6 Ensuring the necessary electrical power supply (non-interruptible three-phase power supply) from the German power grid**

### **6.1 Structure and safety significance of the non-uninterruptible three-phase power supply of a nuclear power plant**

In accordance with the defence-in-depth concept [3], the non-interruptible three-phase power supply of a nuclear power plant is based on

- Level 1: auxiliary power supply with available main grid connection,
- Level 2: in the event of a main grid failure, load rejection of the turbine generator to auxiliary power (only during power operation) and, if necessary, switchover to the standby grid connection and, if necessary, short-term (< 10 hours [4]) supply from emergency diesel generators.
- Level 3: long-term power supply via emergency diesel generators (> 10 hours [4]) as part of the safety system,
- Level 4: supply protected against external hazards from emergency power facilities, third grid connection via cable, and emergency measures.

Based on the current design concept of German nuclear power plants and previous operating experience, a loss of off-site power (failure of the plant's auxiliary power supply, requiring the use of emergency diesel generators) cannot be ruled out during the operating life of a plant. The frequency of a loss of offsite power has an impact on the results of probabilistic safety analyses (PSA). According to the nuclear regulations, the operation of emergency diesel generators must be ensured for 72 hours in the event of a loss of offsite power, as specified in the design [8]. For emergency situations involving the postulated failure of emergency diesel generators, it is assumed, based on the RSK assessments following the Chernobyl accident in 1988 [24], that

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a secure grid supply can be restored within two hours. It should be noted in the discussions that individual aspects are already the subject of other consultation topics (from the follow-up to the RSK safety review after Fukushima (RSK-SÜ) [25], [26]), e.g. emergency measures in the event of a station blackout, improvement of the third grid connection.

## **6.2 Lessons learned from stability problems in the German electricity grid**

The following findings are based on information from [18], [19], [20], [21], [27]. Due to the increasing share of renewable energies in the electricity supply and the limitation of power reserves following the permanent shutdown of eight nuclear power plants, a further increase in the range of voltage and frequency fluctuations within the limits specified by TC-2007 [15] (below and above the nominal values) is to be expected in the near future. In the absence of feed-in from photovoltaic systems and low feed-in from wind turbines, there are fewer power reserves available than in previous years to control short-term disturbances in the interconnected grid. In addition, trading activities on the electricity exchange also exacerbate the problem (so-called „hourly jumps“). On the other hand, high feed-in from plants in accordance with the Renewable Energies Act (*Erneuerbare Energien Gesetz - EEG*) [28] can lead to line overloads, requiring intervention in the grids. Such a situation last arose in the period from 28 to 29 March 2012 in the 50Hertz Transmission control area. Here, particularly after the grid operator shut down two 380 kV lines due to overload, power adjustments of up to 4925 MW had to be ordered in accordance with the Energy Industry Act, supplemented by switching pumped storage plants from turbine to pump operation [27].

During normal operation of the plants, the aforementioned influences lead to greater utilisation of the operating range specified by TC-2007 [15]. This can result in both underfrequency and undervoltage as a consequence of insufficient power generation or provision of reactive power, as well as overfrequency and overvoltage as a consequence of an oversupply of active and reactive power in the grid. The amplitude of the deviations from the nominal data directly influences grid stability. At 49.8 Hz, the measures of the five-stage plan of the former *Deutsche Verbundgesellschaft* (DVG), an association of German power utilities, [29] may begin with a reduction in load. Accordingly, in the event of overcapacity in the grid, pumped storage plants, for example, must be switched from turbine to pump operation, thereby becoming consumers, or generation capacities must be reduced.

Both power shortages and power surpluses contribute to grid instability and increase the potential for major transients, including the failure of parts of or the entire grid if grid operators are unable to take countermeasures in such situations in a timely manner or if multiple faults occur (such as weather-related faults caused by lightning strikes or line contacts due to galloping). The need for more frequent interventions generally increases the potential for grid disturbances, as interventions can also fail. In addition, natural phenomena can affect grid infrastructure and generation capacities, thereby exacerbating grid problems.

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### **6.3 Expectations regarding changes in grid operation and their impact on grid stability and the operation of nuclear power plants**

In this context, the main question is what changes can be expected in grid operation as a result of the increasing importance of fluctuating electricity generation (overproduction depending on the time of day, utilisation of transmission systems, n-1 criterion and reserves).

Maintaining the balance between supply and demand for energy from the interconnected grid requires significantly more frequent regulatory intervention by grid operators than in the past when basic load operation was more static and involved several large plants that were distributed across a wide area.

Continuous operation at frequencies below 49 Hz was ruled out by the grid operators, as this would pose a European problem that could no longer be addressed by providing additional capacity from the European interconnected grid. According to the grid operators, failures of powerful plants or grid operation components are still manageable as the transmission system continues to operate using the (n-1) criterion. If necessary, reserve capacity can be provided by power stations held in reserve on the basis of corresponding contracts with German and European partners of the grid operators ([19], [20], [21]).

Changes in load flow in the transmission system resulting from planned measures can be largely taken into account by grid operators due to the associated lead time. In contrast, fluctuations caused by changing feed-in capacities from renewable energy sources are difficult to plan and predict. Appropriate and suitable forecasts should be used to incorporate longer-term fluctuations into the planning of energy supply and consumption.

The presentations by the transmission system operators ([19], [20], [21]) and document [30] indicate that grid expansion is essential for the further connection of renewable energy plants if restrictions on feed-in from such plants in the event of imminent line overload and further measures under the DVG's five-step plan [29] are to be avoided in future. Grid operators expect this situation to ease in the next two to three years, provided that progress is made in grid expansion and new conventional power plants are successfully commissioned during this period.

According to the RSK's knowledge, reserves for preventing and controlling disruptions – in the form of short-term call-up operating reserve – have decreased significantly, meaning that without countermeasures, grid stability will become even less stable in the future. Furthermore, such reserves can often no longer be provided where they are needed at the time.

### **6.4 Reliability of a plant-specific allocation of conventional power plants (hydroelectric power plants, gas turbines) for the priority supply of nuclear power plants**

The question of reliability arises because the priority supply to a nuclear power plant to prevent or end an

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emergency power situation must be provided via the grid. Grid disturbances of the type in question here do not follow a specific pattern resulting in an identical end state from which grid restoration could take place and which could then be exercised accordingly to function reliably when needed. For this reason, transmission system operators assume certain scenarios in the event of a partial or complete grid failure, which they then use as the basis for the necessary grid restoration strategy. Features of these scenarios and the derived courses of action include determining the extent of the disruption, creating defined basic conditions for grid restoration, clear communication with the partners involved, and coordination of grid leadership during restoration.

In addition to the necessary resources in the form of resilient partner grids or black-start-capable plants, the success of grid restoration depends on the availability of up-to-date information on the grid status and available technical resources to those involved in the process, as well as flawless communication and coordination, even under difficult conditions.

The measures required for the selected grid restoration strategy are set out in writing in the form of instructions within grid restoration plans or concepts. In addition, control systems support the central or group control centres responsible for grid control. In addition, annual simulator training courses are used to train the personnel responsible in controlling the respective scenarios. According to [20], these simulator training courses are not only conducted within the organisation itself but also involve neighbouring national and international transmission system operators.

However, the aforementioned simulator training courses do not replicate dynamic grid conditions but only the processes in the specified scenarios. Dynamic simulations or tests are only carried out in individual cases for specific circumstances, e.g. for motor or transformer connections to investigate the switch-on behaviour with corresponding surges in current.

Regardless of the pre-planned procedures that have been incorporated into the grid restoration plans, practical start-up tests of nuclear power plants have also been carried out in the past, using designated black-start-capable facilities, and have been completed successfully.

Since all German nuclear power plants are connected to the extra-high voltage grid and it is these plants that are used to restore the grid in case of need, fewer switching operations are required to connect a black-start-capable plant to a nuclear power plant due to the supra-regional nature of this grid compared to the subordinate grids. On the one hand, this increases the reliability of the processes, but on the other hand, it makes grid restoration more difficult if extra-high voltage lines are destroyed by external influences.

[21] and [29] clearly showed that the procedures required for grid restoration have been planned and documented in advance so that, in the event of a large-scale grid failure, nuclear power plants can be given priority and be promptly supplied with energy for their auxiliary power demand.

In [21], particular reference is made to the following provision in the grid restoration concept:

*“When restoring the grid, priority will be given to securing the nuclear power plants’ auxiliary power supply from the extra-high voltage grid as soon as possible (within one to two hours). This*

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*securing of the nuclear power plants' auxiliary power supply is incorporated into the grid restoration concept and included in all strategies that have been developed."*

The same conclusion was reached in [24] in 1988. At that time, the operators (at that time, plant and grid operators were still united in one company) had stated that following a large-scale grid failure caused by an electrical fault, the nuclear power plants would be supplied with auxiliary power from the grid again within one to two hours. From the perspective of the transmission system operators, this situation remains unchanged today and is guaranteed by the precautions taken by the grid operators.

However, from the point of view of the RSK, the binding nature of these statements is open to question based on current knowledge. In Germany, there are no regulatory requirements regarding the priority restoration of energy supply to nuclear power plants from the interconnected grid, particularly after large-scale grid failures. The current regulations are based on the continuation of agreements between the respective plants and the assigned transmission system operators from a time when electricity generation and transmission were still under the umbrella of a common corporate structure. However, following the legally mandated separation of transmission system operators from power plant operators, these regulations were adapted to the changed conditions (e.g. TC-2007 [15]).

In the opinion of the RSK, it should be ensured on a plant-specific basis that contractual agreements exist between nuclear power plant operators and transmission system operators regarding the priority supply of nuclear power plants and that these agreements will continue to apply in future to the low-power and shutdown operation phases of the plants /E-4/.

The reliability of such a priority auxiliary power supply for nuclear power plants in various grid failure scenarios cannot be quantified or evaluated in detail here because the application of grid restoration concepts has not yet been tested for all affected plants, there is no practical experience with such worst-case scenarios, and the results and scope of relevant simulator training are not known. With regard to the practical testing of measures to ensure auxiliary power supply for a nuclear power plant, realistic tests are not possible, also in view of the current tense grid situation, because the corresponding tests for preparation and implementation require major disconnections and such measures would currently place too much additional strain on the grid [19].

## **6.5 Influences on the safety requirements for power supply by plant-internal emergency power supply facilities**

### **6.5.1 Safety significance of a loss of offsite power with regard to grid instabilities under different operating conditions of a plant**

This assessment focuses in particular on the consideration of boundary conditions that may arise in different operating states, e.g. operation of the emergency diesel generators at minimum power only, lack of a fallback level for load rejection, possible unavailability of a grid connection or emergency power supply in test status. Findings from GRS investigations ([31], [32], [33]) on grid failures, load rejection and losses of offsite power between 1980 and 2011 as well as international operating experience with large-scale grid failures and losses

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of offsite power at nuclear power plants have also been considered.

The occurrence of grid instabilities that would result in a loss of offsite power in the event of a plant standstill would have a different effect compared to the same grid instabilities during power operation. When a plant is not in power operation, there is initially no fallback option of “load rejection to auxiliary power” and thus no possibility for the plant to continue to supply itself via its own unit generator in the event of a grid disconnection following a corresponding underfrequency excitation. In addition, during overall maintenance inspection and refuelling outages, one of a plant's two grid connections may also be unavailable due to maintenance work. However, this latter aspect only applies to a limited extent to the eight plants shut down under the 13<sup>th</sup> amendment to the Atomic Energy Act, as inspection activities are no longer carried out on a tight schedule. Furthermore, in the event of a large-scale grid failure, it cannot be assumed that while the main grid connection at the 380 kV level may no longer be able to provide the required quality of voltage and frequency, the standby grid connection (220 kV or 110 kV), on the other hand, will be fully available within the specified limits for voltage and frequency – it is only within these limits that the automatic switching systems implemented in German plants for switching between the main and standby grid connections will function at all.

According to the results of various plant-related PSA, the failure probability of the emergency power supply in power and in low-power and shutdown operation is largely determined by the operational failure of the emergency diesel generators as a result of a common cause failure (CCF) or by the prior failure of the batteries due to a CCF. For this reason, batteries from different manufacturers or of different types are used in the plants wherever possible. In addition, according to the results of the RSK-SÜ [25], emergency diesel generators from different manufacturers or of different types are also used in the emergency power system in all plants still in operation (e.g. type A in the D1 grid, type B in the D2 grid).

When comparing power generation mode and low-power and shutdown operation, the contributions of other influencing factors of the PSA (e.g. operation of the diesel generators at low load, unavailability due to inspection or maintenance) are considered to be lower for a shutdown plant as the plants concerned have longer grace periods for measures to be taken in the event of emergency diesel generator malfunctions when required or suitable remedial measures can be taken or have already been planned in individual plants (e.g. increasing the diesel load through suitable coupling circuits and/or manually taking individual emergency diesel generators out of service).

### **6.5.2 Impact of a higher frequency and a longer duration of a loss of offsite power on the results of current PSA and on the safety level of the plants**

The results of various PSA studies show that both the frequency of losses of offsite power and their duration have a direct and significant influence on the core damage frequency. It can therefore be deduced that, in practice, reducing the duration of emergency diesel power challenges by replacing their in-feed as early as possible – i.e. restoring the auxiliary power supply from the external grid – is highly important for reducing the core damage frequency.

It is therefore recommended that further developments in recent findings regarding the “frequency of failure

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of all offsite supply options” and the “duration of grid failure” be monitored closely in order to assess the impact on PSA results and, if necessary, derive corresponding measures. /E-5/.

### **6.5.3 Previous basis for the requirements for the operating times of emergency diesel generators (short-term or long-term loss of offsite power)**

The new Safety Requirements for German Nuclear Power Plants [4] now contain a clear definition of short-term and long-term loss of offsite power. According to [4], a short-term loss of offsite power (< 10 hours) is assigned to Level of Defence 2, while a long-term loss of offsite power (> 10 hours) is assigned to Level of Defence 3 (see also Chapter 6.1).

According to the new Safety Requirements [4], a long-term loss of off-site power must continue to be considered a design basis accident resulting from the failure of the plant's design auxiliary power supply, as specified in the Incident Guidelines [6].

The final report on the safety review of nuclear power plants in the Federal Republic of Germany by the RSK from 1988 [24] refers to relevant statements by the operators (at that time, plant and grid operators were still united in one company) regarding the electrical power supply. According to this, the operators stated - based on their precautions and investigations - that after a large-scale grid failure caused by an electrical fault, the nuclear power plants could be supplied again with auxiliary power from the grid within one to two hours. For this reason, the RSK considered a planning value of two hours for plant-internal accident management measures – from the start of the interruption of supply to the restoration of supply to the nuclear power plants from the grid – to be realistic and sufficient at the time for design-basis events (Level of Defence 4). During this time, the power supply to safety-critical consumers would be provided by the emergency diesel generators of the emergency power system, as specified by the design. This planning value of two hours was also used to derive the required battery capacity for a beyond-design-basis failure of all emergency diesel generators (station blackout).

This RSK recommendation from 1988, together with the corresponding requirements of the RSK Guideline for PWRs [5], has formed the basis for the design of the 220 V and 24 V batteries of the emergency power system in German nuclear power plants.

Following the adoption of the new Safety Requirements [4] in 2012 and the current recommendations of the RSK on the robustness of German nuclear power plants in light of the events at the Fukushima nuclear power plant in Japan [25, 26], some more extensive requirements have now emerged. In [26], the RSK recommends in particular that it should be demonstrated that the three-phase power supply required for vital safety functions is available even if there is no grid connection for up to one week. Furthermore, the direct current supply required for vital functions should be available even when there is no three-phase power supply for up to 10 hours. A specific requirement for the operation of the emergency diesel generators is set out in [4], as previously in Chapter 22 of the RSK Guidelines for PWRs [5] "Systems for heat removal after accidents". According to this, if the control room is inoperable, it must be ensured that the plant can be brought to a safe state with the aid of the remote shutdown station without manual intervention and can remain in this state for

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at least 10 hours (so-called 10-hour self-sufficiency). To this end, at least the emergency diesel generators must be in operation for this period if power supply from the offsite grid or the unit generator is no longer possible. The fuel and lubricating oil supplies for these generators must therefore be dimensioned accordingly. As early as in 1980, KTA 3702.1 [13] contained the requirement that fuel storage tanks and fuel operating tanks be dimensioned in such a way that fuel for 72 hours of operation of the emergency power supply facilities can be kept in stock. The supply in the oil pan of the diesel engine or in an associated lubricating oil tank had to be sufficient for at least 10 hours of operation without falling below the minimum level. These requirements are reflected unchanged in the currently valid KTA 3702 [8].

According to the new Safety Requirements [4], backup measures must be provided, in particular to ensure electrical power supply in the event of a prolonged unavailability of grid connections or all external grids, so that these measures can take over the electrical power supply after three days at the latest. The equipment required for this purpose must be kept either on the power plant site or in the immediate vicinity of the plant and must be protected against external hazards.

## **6.6 Power supply for nuclear power plants in the post-operational phase**

This point concerns the question of which different initial conditions regarding the power supply for nuclear power plants in the post-operational phase need to be considered in terms of the availability of grid connections, emergency diesel generators and their mode of operation.

For plants in the post-operational phase, the requirements of the nuclear regulations regarding the availability of grid connections and emergency power supply (in particular emergency diesel generators) continue to apply as long as there is nuclear fuel in the plant.

Of the events to be considered in accordance with the previous Incident Guidelines [6] and the new Safety Requirements [4], those directly related to reactor operation can be disregarded for plants in post-operation. For the remaining events, some of the boundary conditions of the safety analysis have changed and need to be evaluated. Failures and disruptions in the electrical power supply must be taken into account.

For the prolonged operation of emergency diesel generators in plants that are no longer intended for power operation, it must be taken into account that for these plants, there are less stringent requirements for the operation of emergency core cooling and residual-heat removal systems in the event of a loss of offsite power. This leads to a reduction in the diesel load in the event of a loss of offsite power. Prolonged operation of the emergency diesel generators below a minimum load of approx. 30% (manufacturer-dependent specification) has a negative effect on the operating behaviour and reliability of the diesel generators as the combustion processes in the engine are not optimal when operating in this load range and coking may occur in the combustion chamber. Furthermore, when operating in the minimum load range, the bearing load is higher than in the upper load range, which leads to correspondingly greater wear. As a result, individual affected plants have already planned measures to increase the diesel load (using options for manually switching consumers to individual emergency diesel generators) in conjunction with the manual decommissioning of emergency diesel generators that are then no longer needed. Accordingly, it should be checked for all plants in post-operation to

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which extent low-load operation of the emergency diesel generators for at least 72 hours may have an adverse effect on the reliability of the generators and to what extent suitable precautions against such a longer-term mode of operation are necessary. /E-6/.

## **7 Definitions**

- **n-1 operation**

Principle of grid operation that a secure power supply can still be maintained even if the most powerful feed-in facility or corresponding components in the grid (transformers, lines, etc.) fail.

- **Redispatch**

Reducing the load or increasing generation behind the bottleneck while simultaneously increasing the load or reducing generation in front of the bottleneck.

- **Nominal voltage in the extra-high voltage grid**

For the 380/400 kV voltage level in the extra-high voltage grid, the designations 380 kV/400 kV are used interchangeably in the following chapters of this report. The increase in nominal voltage is due to harmonisation across Europe.

- **Low-power and shutdown operation**

Low-power and shut-down operation begins when permanent subcriticality is reached and ends when criticality is reached with the aim of power input [35]

- **Standstill mode**

A plant is in standstill mode when it can resume power operation from low-power and shutdown operation [36]

- **Post-operation**

A plant is in post-operation when power operation has been permanently terminated but there is still nuclear fuel in the plant [36]

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## 8 Summary of the recommendations

- /E-1/** To the RSK's knowledge, not all plants are equipped with an automatic warning system that alerts the control room personnel to an overvoltage or undervoltage in the auxiliary power supply and prompts them to take manual actions. It is recommended that such a warning system for overvoltage and undervoltage be installed in all plants. In addition, the resulting measures should be specified in the plants' operating manuals.
- /E-2/** At European level, a binding European grid code in the form of an EU directive is currently being developed under the leadership of ENTSO-E. The provisions of such a grid code may also have an impact on the operation and safety of nuclear power plants, e.g. in the form of specifying permissible operating ranges for voltage, frequency, power and operating time in the event of deviations of these parameters from the nominal values. Due to the fundamental importance of this interface definition, the RSK recommends that the BMU urge grid operators to take into account the safety-related designs and operating conditions of German nuclear power plants when drafting the ENTSO-E grid code.
- /E-3/** It is not possible to give a generic answer to the question of the extent to which prolonged operation of continuous drives or control drives at frequencies above the nominal value (50 Hz) in all plants - regardless of the mode of operation - may lead to the unintentional activation of overload protection devices. This requires knowledge of the types used and the setting values of the component-related protective devices, the system-level protection limits, and the duration and level of the overfrequency. In the opinion of the RSK, especially the prolonged operation at frequencies above the nominal frequency but within the requirements of TC-2007 requires separate, plant-specific consideration, taking into account the respective tripping characteristics of the protection devices.
- /E-4/** In the opinion of the RSK, it should be ensured on a plant-specific basis that contractual agreements exist between nuclear power plant operators and transmission system operators regarding the priority supply of nuclear power plants and that these agreements will continue to apply in future to the low-power and shutdown operation as well as post-operational phases of the plants.
- /E-5/** From today's perspective, neither national nor international operating experience suggests that any changes are necessary in the design of German nuclear power plants with regard to their auxiliary power supply options or their energy supply to safety-critical consumers in the event of a grid failure. It is therefore recommended that further developments in recent findings regarding the "frequency of failure of all offsite supply options" and the "duration of grid failure" be monitored closely in order to assess the impact on PSA results and, if necessary, derive corresponding measures.

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**/E-6/** As prolonged operation of the emergency diesel generators below a minimum load of approx. 30% (manufacturer-dependent specification) has a negative effect on the operating behaviour and reliability of the diesel generators, it should be checked for all plants in post-operation to which extent low-load operation of the emergency diesel generators for at least 72 hours may have an adverse effect on the reliability of the generators and to what extent suitable precautions against such a longer-term mode of operation are necessary.

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