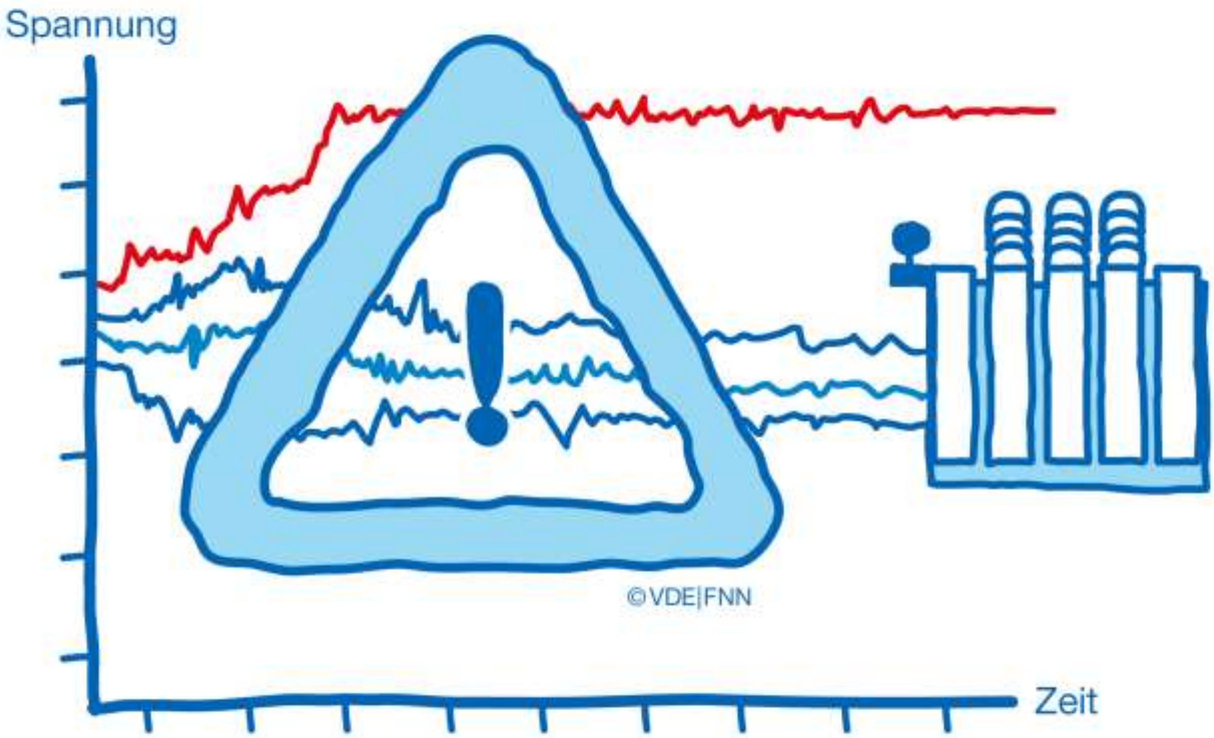

Analysis and assessment of the requirements on the performance of the equipment in case of temporary network conditions with voltages above U_m

Summary and recommendations for action

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Summary

The origin of the considerations are, on the one hand, the national and international network codes and, on the other hand, the changed transmission duties. In the European network codes, for the 380 kV, 220 kV and 110 kV network in Central Europe, a time-limited exceedance of the rated voltage of 420 kV, 245 kV and 123 kV with 440 kV, 253 kV and 127 kV for at least 20 min and at most 60 min is given. In Germany, the normal voltage range is generally maintained by means of grid-related technical measures. By changing the generation structure and the associated transmissionduties, depending on the specific situation and the allocation of the power factor correction systems, temporary voltages greater than U_m cannot be ruled out at some network nodes. In addition, further exceptional situations, such as system splitting, the connection of lines with partial cabling, or load shedding, are possible.

In the case of the equipment previously employed, which are generally specified for a permanent operating voltage U_m of 123 kV, 245 kV and 420 kV, it must be examined to what extent operation at voltages higher than the permanent operating voltage is possible. In this case, such a situation must first be considered from the perspective of the relevant standards. In addition, the possible limitations in functionality and physical phenomena that occur in the case of stresses caused by voltages greater than the admissable continuous operating voltage U_m must be clarified.

In Chapter 2, operations with voltages $>U_m$ are considered from the perspective of the standards and guidelines. From the definitions given in the standards, it can be assumed that permanent operation of equipment above the rated voltage is not permitted. Operation at power-frequency voltage higher than the rated voltage represents operation at temporary overvoltage. To what degree such a situation is permissible must be clarified within the framework of insulation coordination. The international and national network codes require a voltage of up to $1.05 * U_m$ for 30 and/or 60 minutes, before the network nodes in question are disconnected from the grid.

Chapter 3 explores the framework conditions for operation with voltages $>U_m$. To begin with, the empirical values of transmission and distribution system operators are analysed. In this analysis, clear differences both between the individual transmission system operators as well as the distribution system operators can be identified. Whilst in one of the transmission systems under consideration there were no exceedances of U_m apart from two exceptional situations, with one of the others there were exceedances of 1…2% in some substations that sometimes lasted several hours. In the case of a distribution system of a primarily urban character, the voltage in the representative substations remained more or less constant and at 110 kV was always clearly below U_m. In another distribution system with both an urban and rural character, the fluctuations in voltage were more pronounced, and sporadic exceedances of U_m occurred. In a few substations, exceedances of U_m of more than 5% were even observed for several hours.

The scenarios described by the FNN “Dielectric Strength” project group for the occurrence of operating voltages $>U_m$ could be confirmed for the scenario “Connection of long cable runs or hybrid transmission lines” based on simulation calculations and for the scenario “Failure of generation units” based on a current case example.

Chapter 4 deals with the fundamental design of the power equipment on the basis of the test specifications and the assumed framework requirements. Power equipment for the high and extra-high voltage network is designed for a service life of 40 to 50 years. The design is based on

the international standards (IEC standards), that cover numerous operational requirements, but not 100% of all situations that can occur during operation. On the other hand, for type tests, assumptions are made that only rarely or never occur under network conditions. It is the task of the system operator to analyse the operating conditions and the requirements and to specify the corresponding rated values.

In the present case, only the influence of the electric stress is considered. The technical verification that the equipment concerned is able to cope with the continuous stress over the assumed service life is carried out by means of a test with a long-duration power-frequency withstand voltage, mostly for a duration of 30…60 min. In the case of some equipment, this verification is also carried out with short-duration power-frequency withstand voltage , with a test duration of mostly 1 minute. Sufficient strength to withstand temporary overvoltages is verified by means of the short-duration or long-duration power-frequency withstand voltage test.

In the following, the performance in the case of temporary overvoltages is of particular interest. Based on the analyses of the data of the system operators and the national and European network codes, it is assumed that the equipment concerned will be stressed twice per week at 30 min each time with a temporary overvoltage of $1.05 * U_m$. It must be examined whether a limitation in the functionality of the equipment is to be expected due to these stresses and whether on an accumulated basis these will result in a noticeable reduction in service life. Both questions are considered for the different equipment – overhead lines, outdoor substations, switching devices, gas-insulated substations, instrument transformers, power transformers, surge arresters and cable systems – on the basis of the relevant standards and the specialist literature.

Chapter 5 deals with the possible limitations in functionality of the aforementioned equipment at $1.05 * U_m$.

The operation of an overhead transmission line with $1.05 * U_m$ has no impact on the fundamental rating of the spacing for an overhead transmission line, since the lightning impulse withstand voltage of the insulators is decisive for this. The corona behaviour of the conductor cable and accessories as well as the unified specific creepage distance of the insulators is generally measured in such a way that it also meets the requirements at 1.05 U_m.

The minimum clearance for outdoor substations in the 110 kV and 220 kV networks is determined by the rated lightning impulse withstand voltage and in the 380 kV network by the rated switching impulse withstand voltage. The rated lightning impulse withstand voltage is derived from the atmospheric overvoltages. For the rated switching impulse withstand voltage, as a rule a value of 1050 kV is applied, assuming switching overvoltages of 2.9 p.u., which, however, never occur in the German 380 kV networks. Therefore, the ratings of the minimum clearance of active parts in outdoor substations is sufficiently safe, even in the case of loads of $1.05 * U_m$.

For the design of gas-insulated substations (GIS) the rated lightning impulse withstand voltage that is derived from external overvoltages is decisive and is not influenced by the operating voltage. In addition, the rated lightning impulse withstand voltage should also demonstrate sufficient dielectric strength against internal overvoltages when switching disconnectors. Since these very fast front overvoltages are smaller than the coordination lightning withstand voltage, they are covered by the rated lightning withstand voltage.

If short-circuit currents in the range of the rated short-circuit current of the circuit-breaker are anticipated at network nodes with increased voltage of 1.05*U_m, the grid conditions in the case of the short circuit must be examined. If the ratio $X_0/X_1 < 2.5$, in solidly earthed networks with three-phase short circuits, the pole to clear factor is $k_{pp} < 1.3$ and thus the recovery voltage is smaller than that tested in the standard. In such cases, it is to be assumed that the circuit-breaker will cope even with a voltage of 1.05*U_m in this short circuit scenario.

The short line fault is tested in accordance with the standard with a short-circuit breaking current in relation to the rated short-circuit current. In practice, this short circuit scenario is caused by a single-phase fault together with a short-circuit current to earth of between 85…90% of the three-phase short-circuit current, so that the critical initial steepness is also lower. This means that this switching duty should also be managed.

Short circuits clear of earth are extremely rare. Therefore, even with the switching of transformer or reactor limited fault currents, a pole to clear factor of $k_{pp} \leq 1.3$ can be assumed, insofar as the transformer neutral point is earthed, so that the amplitude of the transient voltage equals only 87% of the normal value. This means that this switching duty should also be managed even at 1.05*U_m. If the transformer neutral point cannot be earthed for reasons of network engineering, an analysis of the transient recovery conditions, taking into account the natural frequency of the transformer, and a clarification are required whether this switching duty is governed by the circuit-breaker used.

In the case of the switching off of non-compensated lines at voltages of 1.05*U_m, restrike cannot be ruled out. If the line is energized at a voltage of 1.05*U_m, both the steady-state as well as the transient process is more pronounced. However, an impact on the circuit breaker at the sending and the receiving end of the transmission line by the transient overvoltages isnot to be expected, since this is covered by the ratings as per the standard.

Switching of small inductive currents at voltages of 1.05*U_m can increasingly result in re-ignitions. Re-ignitions can fundamentally be avoided through controlled switching. When setting the tripping time, however, it must be checked whether the functionality is guaranteed even in the case of increased operating voltage.

Switching of small capacitive currents with GIS disconnectors should also be possible at 1.05*U_m since this switching duty is tested with the 1.1-fold phase to earth voltage on the supply side and the 1.1-fold phase to earth voltage as pre-charge on the load side in accordance with the standard. In the case of conventional outdoor disconnectors, a slightly longer switching time has to be taken into account, which will be in the range of statistical variance, however.

Voltages of 1.05*U_m at transformers can result in an undue excitation in continuous operation. Because this acts for a short-time only, no undue overheating is to be expected. However, in every case greater noise in comparison with the rated voltage must be expected, also at underfrequencies permitted in the network codes. Transformers that are deemed to be short-circuit proof should be able to cope with the greater mechanical stress caused by the higher inrush current when energizing with 1.05*U_m. However, it must be checked how the protective devices react to the higher amplitudes of the inrush current.

In the case of operation of reactors with voltages of 1.05*U_m a higher power loss must be anticipated. This higher power loss will, however, only last for a maximum of 30 minutes and as a rule not occur at the maximum operating temperature of 40°C assumed for the rating, so that no undue temperature rise is to be anticipated. In every case there will be an increased noise level, since the noise is defined at the rated voltage and rated current.

Pursuant to the standard, the accuracy of the current and voltage transformers at voltages of 1,05*U_m is also guaranteed. By means of inductive voltage transformers in specific grid and system configurations, ferro-resonances can be avoided by the use of gapped-core voltage transformers. It is to be assumed that these transformers demonstrate a sufficient damping behaviour, even at 1.05*U_m.

In the case of the surge arresters usually installed in the German grid, no thermal overload is to be expected with a voltage of 1.05*U_m. It is solely in the 110 kV grid with resonant earthed neutral that arresters could become unstable, if pre-stressed with the full amount of the rated energy i, whereby this case has to be classified as rare. If it is true to occur, the thermal behaviour based on the manufacturer's specifications must be examined more closely.

The voltage tests carried out on cable systems within the framework of the type and on-site tests with a test duration of 30 to 60 min result in clearly higher loads than voltages of 1.05*U_m. Therefore, restrictions in functionality are not to be anticipated from this perspective.

In Chapter 6, the impact of voltages >U_m on the long-term and ageing behaviour are investigated depending on the duration and frequency of occurrence. Based on the analyses of the data of the system operators and the national and European network codes, two scenarios are considered. First of all, the stress of the relevant equipment presumed so far is accumulated twice per week for 30 min a time with a temporary overvoltage of 1.05*U_m over a service life of 40 years and thereof the lifetime consumption is derived from. Then it is examined at which stress duration at temporary overvoltage of only 1.025*U_m would result in a substantial ageing and/or reduction in service life respectively.

The considerations are based on the assumption that sufficient electrical long-term stability can be verified through a short and/or long-duration power-frequency withstand votage test as given in the standards. The ageing behaviour is derived from the voltage-timecharacteristic – service life dependent on the applied voltage, or V-t characteristic.

The thoughts are primarily related to the equipment in the 380 kV network. The findings can also be applied to the equipment in the 110 kV and 220 kV networks, since the ratio of the short-duration power-frequency withstand voltage to the rated voltage for this equipment is generally greater than that for the equipment in the 380 kV network.

The assumed short duration stress of the equipment of the 380 kV network with 105% of the continuous permissible operating voltage twice per week for 30 min each time does not result in a significant reduction in service life. A continuous load with 105% would, however, result in a clear reduction in service life by at least 50%. Thus such a load cannot be authorised, not only based on the valid standards, but also for physical reasons. This conclusion can also be applied to the equipment of the 110 kV and 220 kV networks.

The investigations of the service life performance in the case of temporary overvoltages of 1.025*U_m refer to the three types of equiment, GIS, transformers and cable, the ageing indices for the insulating systems of which are known from the literature. Continuous operation at 102.5% of the admissible continuous operating voltage results in a clear reduction in service life for the insulation systems of the equipment investigated here. The use of service life for the insulation systems of the equipment GIS and cable is 10 years and/or 12 years respectively. The service life of the transformer insulation system is reduced even more radically. Therefore, the duration of such operating conditions must be limited. If a service life reduction of 10% were to be permitted, the accumulated operating time with a voltage of 1.025*U_m would be at most 4 years.

Chapter 7 summarises the conclusions and proposes some recommendations for action. An operation of the high and extra-high voltage networks with voltages of 105% of the highest voltage for equipment U_m represents an operation at temporary overvoltages. This is permissible and is generally coped with by the equipment. In most cases, restrictions in functionality are not to be expected, since under real- network conditions, the service conditions thereby arising, are largely still covered by the assumptions in the relevant standards. The assumed stress with 1.05*U_m twice a week for 30 min each time, accumulated over an operating period of 40 years would not cause any significant reduction in service life. Also, even taking into consideration the ageing of the insulation media employed, no technically relevant reduction in service life is to be assumed.

At some equipment, certain restrictions in functionality could arise when operating at 1.05*U_m under specific operating conditions. In these cases, the following measures are recommended.

<u>Circuit breakers</u>

If in subsations with short-circuit currents close to the rated short-circuit current ncreased operating voltages are to be anticipated in a check must be made based on the specific network conditions, whether the circuit breaker applied could cope with switching duties at limit rating, in particular in case of terminal faults. Where necessary, circuit breakers with a higher rated short-circuit current must be used.

If non-compensated transmission lines under no load conditions are switched off at an increased operating voltage of 1.05*U_m, re-ignitions can no longer be excluded. In such cases, controlled switching of the circuit breakers is recommended.

<u>Transformers</u>

At transformers operated with 1.05*U_m considerably higher noise levels must be anticipated. Where necessary, it must be clarified whether undue overexcitation can occur in short-term operation.

<u>Reactors</u>

When operating ireactors at 1.05*U_m higher copper and iron losses must be taken into account as well as increased noise. It must be examined whether the additional losses could result in undue overheating in short-term operation.

<u>Voltage transformers</u>

In order to avoid stationary ferro-resonances, the use of gapped core inductive voltage transformers cores is recommended. Sufficient damping behaviour at 1.05*U_m should be checked by means of tests or simulations.

<u>Surge arresters</u>

If an earth fault should occur in the 110 kV resonant earthed system at increased operational voltage of 1.05*U_m and a fault duration of ≥30 minutes, thermal overloading of the arresters according to the standard cannot be ruled out. In such cases, the thermal performance of the arresters must be examined more closely based on the manufacturer’s specifications.

Cable systems

As well as the VPE cables considered here, external gas pressure cables and oil cables are used in the German high and extra-high voltage network. With these cable systems, it is not the dielectric but possibly the thermal ageing that limits the service life.

The assumed frequency and duration of the stress with 1.05*U_m does not result in any significant reduction in the service life of the equipment considered. However, a clearly greater frequency and/or stress duration wouldhave a negative impact on the service life of the equipment. Continuous operation at 1.05*U_m , would result in a clear reduction in service life based on the ratings that are assumed in the standards and is not permissible in view of the current standards. Even continuous operation with a minor voltage above U_m, e.g. with 1.025*U_m would result in an accelerated ageing. Operating conditions with voltages above U_m must therefore be restricted to an extent, necessary to guarantee system security. They must not be be used for load flow management or to avoid overload situations

Conclusions and recommendations for action

Continuous operation of the high and extra-high voltage networks with voltages greater than U_m cannot be permitted, not only due to the valid standards, but also for physical reasons. A temporary operation with voltages of 1.05*U_m represents an operation at temporary overvoltages. This mode is permissible, but its duration and frequency must be limited. In most cases, restrictions in functionality are not to be expected, since under the real-life network conditions, the operating conditions that would then arise, are largely still covered by the assumptions in the relevant standards. The assumed stress with 1.05*U_m twice a week for 30 min each time accumulated over an operating period of 40 years would not cause any significant reduction in service life. Also, even taking into consideration the ageing of the insulation media employed, a technically relevant reduction of service life is not to be assumed.

The functionality of the equipment at an operating voltage of 1.05*U_m benefits from the safety margins that are derived from the assumptions made in the standards. These safety margins are used operationally during the operation at 1.05*U_m and are therefore "consumed" as margins. However, it cannot be assumed (even if it is not to be excluded categorically) that this is accompanied by a greater outage risk , yet under these conditions there is no more margin for further increased operating voltages of > 1,05*U_m

In the case of the equipment listed in the following, certain restrictions in functionality could arise when operating at 1.05*U_m under the specific operating conditions already named. In these cases, the measures that have been given are recommended.

<u>Circuit breakers</u>

If increased operating voltages cannot be excluded in the systems with short-circuit currents in the range of the rated short-circuit current of the installed circuit breakers, a check must be made based on the specific network conditions, whether switching duties at limit ratings, in particular terminal faults, would be coped with. Where necessary, circuit breakers with a higher rated short-circuit current must be used.

In the case of switching off transformer limited faults, transient recovery voltages not covered by the standard must be anticipated, if the transformer neutral point is not earthed. In such cases, an analysis of the transient recovery conditions, taking into account the natural frequency of the transformer concerned, must be carried out and it must be clarified, whether the circuit breaker used will cope with the switching duty.

If non-compensated transmission lines are de-energized at the increased voltage of 1.05*U_m , restrikes can no longer be excluded, in particular if the circuit breakers used are able to interrupt the capacitive current with very short arcing times. In such cases, restrikes can be avoided by controlled switching of the circuit breakers.

When switching small inductive currents at a voltage of 1.05*U_m, re-ignitions can occur more frequently. These can be avoided by controlled switching. However, it should also be checked whether, with the tripping instant that has been set, switching off without re-ignitions is also guaranteed even in the case of increased operating voltage.

<u>Transformers</u>

In the case of transformers at operation with 1.05*U_m , considerably higher noise levels must be anticipated. Overheating is improbable due to the duration of the increased voltage of just 30 minutes. Where necessary, it must be clarified whether undue overexcitation can occur in short–duration operation.

Reactors

When operating Reactorsors at 1.05*U_m, higher copper and iron losses must be taken into account as well as increased noise. It must be examined whether the additional losses could result in undue overheating in short-duration operation.

Voltage transformers

In order to avoid stationary ferro-resonances, the use of inductive voltage transformers with gapped cores is recommended. By application of these transformers, even in the case of operation with 1.05*U_m, no stationary ferroresonances should be generated. However, a sufficient damping behaviour at 1.05*Um should be checked by means of tests orsimulations.

Surge arresters

If an earth fault occurs in the 110 kV resonant earthed system at the increased voltage of 1.05*U_m, , a thermal overload of the arresters rated according to the standard cannot be ruled out completely in the case of a fault duration ≥ 30 minutes. In such cases, the thermal behaviour of the arresters must be examined more closely based on the manufacturer's specifications. It would be made easier, if the loading of the arrester with full rated energy could be excluded. The overloading of the arresters through load shedding at 1.05*U_m must be excluded, insofar as the voltage regulator cuts back the infeeding generator within 10 seconds to U_m . Where necessary, the regulator concept must be checked.

The assumed frequency and duration of stresses with 1.05*U_m does not result in any significant reduction in the service life of the equipment considered. A clearly greater frequency and/or load duration would, however, have a negative impact on the service life of the equipment. Continuous operation with 1.05*U_m cannot be permitted from a physical perspective on the one hand, since this, based on the rating specified in the standards, would lead to a clear reduction in the service life. On the other hand, continuous operation at voltages above the rated voltage is not admissible according to the valid standards, but merely operation with temporary overvoltages. This operating case must be taken into account within the framework of the insulation coordination.

Even permanent operation with a minor voltage above the operational voltage, e.g. with 1.025*U_m, would result in accelerated ageing and thus to a reduction in service life to sometimes under 50%. Operating conditions with voltages above U_m must therefore be restricted to an extent necessary to guarantee network safety. They must not be be used for load flow management or to avoid overload situations.