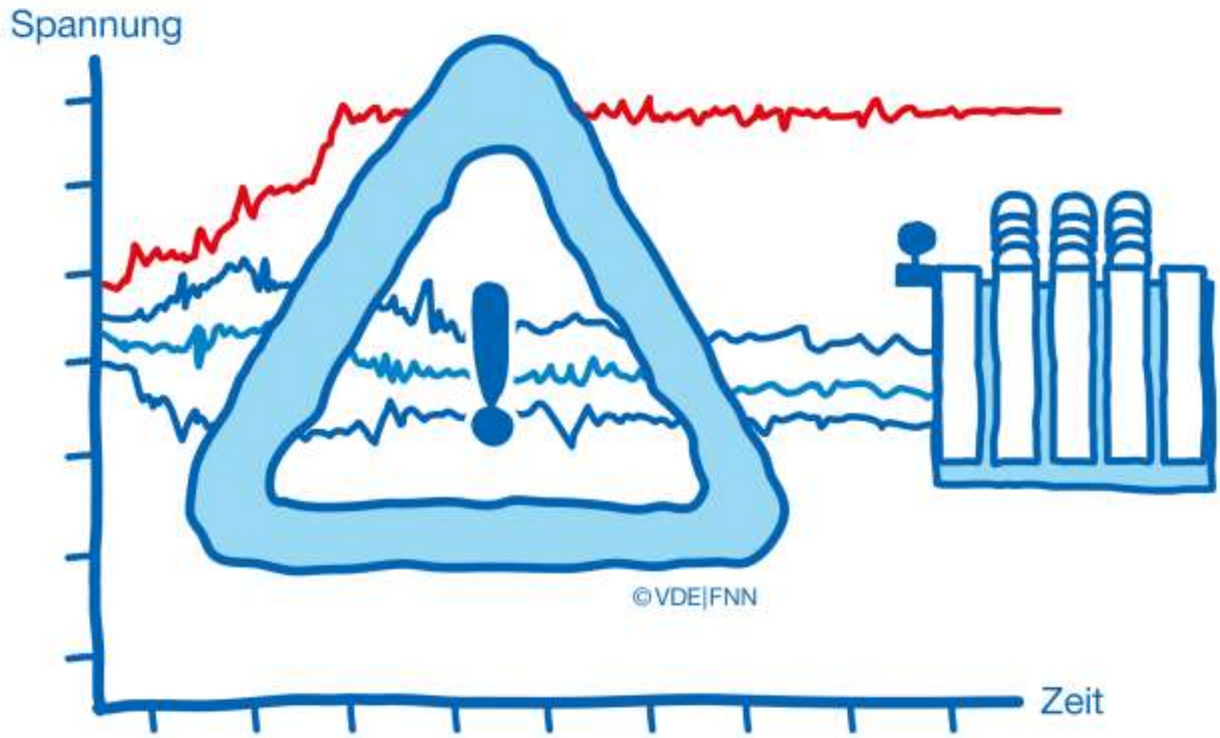


Analysis and assessment of the requirements on the performance of the equipment in case of temporary network conditions with voltages above U_m

October 2019

VDE FNN

Analysis and Assessment of Requirements on the Capability of Power Equipment in the Case of Temporary System Conditions above U_m

(English translation of the study:
„Analyse und Bewertung der Anforderungen an das Leistungsvermögen der Betriebsmittel im Falle von temporären Netzzuständen mit Spannungen oberhalb U_m“)

Oktober 2019

Prof. Dr.-Ing. C. Neumann

Prof. Dr.-Ing. V. Hinrichsen

Analysis and assessment of requirements on the capability of power equipment in the case of temporary system conditions above U_m

Table of contents

Table of contents ... 4
Abbreviations and symbols ... 6
Summary ... 11
1. Introduction ... 11
2. Operation with voltages >Um from the perspective of the standards and guidelines ... 12
2.1. Terms and definitions given in the VDE standards ... 12
2.2. International and national network codes ... 13
3. Boundary conditions for operation at voltages >U_m: Operation at temporary overvoltages, duration, critical situations ... 15
3.1. Inspection and analysis of the empirical values in the case of transmission and distribution system operators ... 15
3.1.1. Transmission system operators ... 15
3.1.2. Distribution system operators ... 17
3.2. Scenarios for the occurrence of power frequency voltages >U_m ... 18
4. Fundamental design of equipment, testing requirements and boundary conditions assumed ... 22
5. Possible restrictions to the functionality of equipment in the case of operation with voltages >U_m ... 24
5.1. Overhead transmission lines ... 24
5.2. Outdoor substations ... 25
5.3. GIS substations ... 25
5.4. Switching devices ... 26
5.4.1. Circuit breakers, interrupting short-circuit currents ... 26
5.4.2. Circuit breakers, switching of capacitive currents ... 32
5.4.2.1. De-energising of transmission lines ... 32
5.4.2.2. Energising of transmission lines ... 35
5.4.3. Interruption of small inductive currents ... 36
5.4.3.1. Current chopping ... 36
5.4.3.2. Overvoltages ... 37
5.4.3.3. Transient recovery voltage ... 39
5.4.3.4. Re-ignitions ... 41
5.4.4. Disconnectors ... 41
5.4.4.1. GIS disconnectors ... 41
5.4.4.2. Outdoor disconnectors ... 42
5.5. Transformers ... 42

5.6. Reactors ... 44
5.7. Instrument transformers (Current and voltage transformers) ... 45
5.7.1. Accuracy ... 45
5.7.2. Ferro-resonances ... 45
5.8. Surge arresters ... 47
5.9. Cable systems ... 49
5.10. Summary of assessment ... 50
6. Impact of voltages > U_m on the long-term and ageing performance depending on the duration and frequency of occurrence ... 53
6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*U_m over a service life of 40 years ... 53
6.1.1. Overhead transmission lines ... 53
6.1.2. Outdoor substations ... 53
6.1.3. Switching device ... 53
6.1.4. GIS switchgear ... 54
6.1.5. Current and voltage transformers ... 56
6.1.6. Power transformers ... 56
6.1.7. Surge arresters ... 59
6.1.8. Cable systems ... 59
6.2. Summarized assessment of the service life of equipment in the 380 kV systems, as well as in 220 kV and 110 kV systems in the case of short-duration stress with 1.05*U_m ... 68
6.3. Scenario 2: Possible ageing and/or reduction in service life due to temporary overvoltages of 1.025*U_m with longer stress durations ... 68
6.3.1. GIS switchgear ... 68
6.3.2. Power transformers ... 69
6.3.3. Cable systems ... 69
6.4. Summarized assessment of the service life of 420 kV equipment in the case of longer duration stress at 102.5% of the continuous permissible operating voltage ... 70
7. Conclusions and recommendations for action ... 71
8. References ... 69
Appendix: About the authors ... 72

Abbreviations and symbols

Abbreviations

AKS	Short line fault
AWE	Auto-reclosure
FNN	Forum Netztechnik/Netzbetrieb in VDE
KKS	Terminal fault
STATCOM	Static synchronous compensator
T10	10 % terminal fault current
T30	30 % terminal fault current
TAR	Technical connection rules
USCD	Unified specific creepage distance

Symbols

C_L	Capacitance of the inductive load
C_N	Capacitance of the feeding system
C_P	Capacitance of the switching gap
C_t	Resulting capacitance in parallel to the switching gap
$E_{d0,01\%}$	0,01 %-breakdown field strength (breakdown field strength with 0,01% breakdown probability)
$E_{d50\%}$	50 %-breakdown field strength
$E_{d99,99\%}$	99,99 %-breakdown field strength
f	Actual system frequency
f_r	Rated frequency
I_k	Rated short-circuit current
I_{k1e}	Single-phase-to-earth fault current
I_{k3}	Three phase short-circuit current
I_L	Short-line fault current
i_{ch}	Chopping current
k_a	Overvoltage factor at interruption of transformer magnetizing current
k_c	Capacitive voltage factor
k_{pp}	First-pole-to-clear factor
k_{tov}	TOV factor of an arrester (ratio of the admissible power-frequency voltage to rated voltage according to the voltage-time curve of the arrester)
L_b	Leakage inductance between system and breaker
L_L	Inductance of the inductive load
L_N	Short-circuit inductance of the feeding system
L_P	Inductance of the switching gap
N	Ageing index
P_r	Rated power of a transformer

s_L	Steepness of the line side transient recovery voltage
T_t	Duration of the power-frequency voltage or overvoltage respectively
$U_{90\%\_ff\_is}$	90 %-lightning withstand voltage of the insulator string installed in the line
U_{hf}	Max. VFT overvoltage in p.u.
u_L	Line side transient recovery voltage
U_m	Highest voltage for equipment
U_{max}	Highest voltage at rated frequency, at which a continuous operation must be possible
U_n	Nominal system voltage
U_N	System voltage
U_r	Rated voltage
u_{max}	Chopping overvoltage
u_N	Line-to-ground voltage of the feeding system
u_{NC}	Voltage at the capacitance C_L at the instant of current chopping
u_{tr}	Transient recovery voltage
W_{ch}	Energy stored on the load side
X_0	Zero-sequence reactance
X_1	Positive-sequence reactance
Z_0	Zero-sequence surge impedance
Z_1	Positive-sequence surge impedance
Z_L	Surge impedance of a line
$\frac{C_t \cdot U_r^2}{\alpha\ P_r}$	”Chop Parameter” in s
α	Ratio of magnetising current to rated current
δ	Earth-fault factor
δ_L	Load shedding factor
λ	Chopping number
σ	Standard deviation

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 transmission duties, 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 normally specified for a continuous 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 continuous operating voltage is possible. In this case, such a situation must first be considered from the perspective of the relevant standards. In addition, possible limitations in functionality and physical phenomena that occur in the case of stresses caused by voltages greater than the admissible 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 continuous operation of equipment above the rated voltage is not permitted. Operation at power-frequency voltage higher than the rated voltage represents an 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 $>U_m$. First, 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 project group “Dielectric Strength” 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 simulations and for the scenario “Failure of generation units” based on a current case study.

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

The design is based on the international standards (IEC standards), which cover numerous operational requirements, but not 100% of all conditions that can occur during operation. On the other hand, for type tests, assumptions are made that only rarely or never occur under system 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, gas-insulated substations, switching devices, instrument transformers, power transformers, surge arresters and cable systems – based on the relevant standards and the technical 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 clearances of an overhead transmission line, since the lightning impulse withstand voltage of the insulators is decisive for this. The corona behaviour of the conductors and accessories as well as the unified specific creepage distance of the insulators is generally designed 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 system is determined by the rated lightning impulse withstand voltage and in the 380 kV system 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 system. Therefore, the ratings of the minimum clearance of active parts in outdoor substations is sufficiently safe, even in the case of stresses of 1.05*U_m.

For the design of gas-insulated substations (GIS) the rated lightning impulse withstand voltage derived from external overvoltages is decisive and is not affected 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 first-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 with this short circuit scenario even at a voltage of 1.05*U_m.

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 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 switching of transformer limited fault currents, a pole to clear factor of $k_{pp} \leq 1.3$ can be assumed, insofar as the transformer neutral 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 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 is required, whether this switching duty is governed by the circuit-breaker applied.

In the case of de-energising non-compensated lines at voltages of 1.05*U_m, restrikes 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 is not 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 generally be avoided by 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 scatter, 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 any case greater audible 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 any case, there will be an increased audible 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. Ferro-resonances, excited by inductive voltage transformers in certain system and substation configurations, can be avoided by the use of gapped-core voltage transformers. It is to be assumed that these transformers exhibit a sufficient damping behaviour, even at 1.05*U_m.

In the case of the surge arresters usually installed in the German system, no thermal overload is to be expected with a voltage of 1.05*U_m. Solely in the 110 kV system with resonant earthed neutral arresters could become unstable, if pre-stressed with the full amount of the rated energy, 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 stresses 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 performance is 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 of twice per week for 30 min each time with a temporary overvoltage of 1.05*U_m is accumulated 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 voltage test as given in the standards. The ageing behaviour is derived from the voltage-time characteristic – service life dependent on the applied voltage, or V-t characteristic.

The thoughts are primarily related to the equipment in the 380 kV system. The findings can also be applied to the equipment in the 110 kV and 220 kV system, 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 system.

The assumed short duration stress of the equipment of the 380 kV system 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 stress with 105% would, however, result in a clear reduction in service life by at least 50%. Thus, such a stress cannot be admitted, 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 system.

The investigations of the service life performance in the case of temporary overvoltages of 1.025*U_m refer to the three types of equipment, 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 system 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 the equipment. In most cases, restrictions in functionality are not to be expected, since under real system 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, 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.

Circuit breakers

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

If non-compensated transmission lines under no load conditions are de-energised 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.

Transformers

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

Reactors

When operating reactors 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.

Voltage transformers

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

Surge arresters

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

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

The frequency and duration of the stress with 1.05*U_m assumed does not result in any significant reduction in the service life of the equipment considered. However, a clearly greater frequency and/or stress duration would have 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.

1. Introduction

In recent years, network codes have been published at the European level, the requirements of which are not clearly reflected in the international, European and national industrial standards (IEC, CENELEC, VDE). Although as a rule, the maximum continuously permitted voltages in the network codes of 420 kV, 245 kV and 123 kV correspond with the rated voltage U_r for the equipment applied, in the network codes a time-limited exceedance of this voltage to 440 kV, 253 kV and 127 kV is permitted. The time-limited restriction for Central Europe is given as minimum 20 min and maximum 60 min. In the German TARs for the connection of generation units, a maximum duration of 30 min is given.

In Germany, the normal voltage range $\leq U_m$ is generally complied with by means of network technology measures, such as the use of transformers with voltage regulation equipment and compensation devices (e.g. rotating phase shifters, shunt reactors or STATCOM). However, the change in the generating structure from consumer-close to consumer-distant generation creates new challenges in maintaining the voltage stability in the high and the extra-high voltage network. Depending on the relevant operating conditions – high load or light load – and on the arrangement of the power factor correction units in the system, at some network nodes temporary voltages greater than U_m cannot be excluded. In addition, further exceptional situations, such as system split, energizing of lines with partial cabling, or load shedding, are possible.

Since the equipment previously employed in the 110 kV, 220 kV and 380 kV system, are generally specified for a continuous operating voltage of 123 kV, 245 kV and 420 kV, it must be examined, to what extent operation at voltages higher than the continuous operating voltage is possible. In this case, such operating conditions must first be considered from the perspective of the relevant standards. In addition, possible limitations in functionality and physical phenomena occurring in the case of stresses caused by voltages greater than the continuous operating voltage must be clarified. For such an assessment, stresses that are derived from the test conditions specified in the different standards shall be used.

2. Operation with voltages >U_m from the perspective of the standards and guidelines

2.1. Terms and definitions given in the VDE standards

The following voltage definitions are used in the VDE standards:

- DIN EN 60038, April 2012 [7]:

Section 3.1 Nominal voltage of a network

Suitable, rounded voltage value for the designation or identification of a network

Section 3.2 Highest voltage of a network (excluding transient or abnormal conditions)

Highest value of the operating voltage that occurs under normal operating conditions at any one time at any point in the network

NOTE: Transient voltages, e.g. of switching operations and temporary voltage fluctuations are excluded

- VDE 0111 Part 1 [8],

Section 3.8: Nominal voltage of a network, U_n:

A suitable approximate value of voltage used to designate or identify a system

Section 3.9: Highest voltage of a system, U_s:

highest voltage of a system: The highest value of operating voltage which occurs under normal operating conditions at any time and at any point in the system.

Section 3.10: Highest voltage for equipment, U_m:

The highest r.m.s. value of phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment Standards. Under normal service conditions specified by the relevant apparatus committee this voltage can be applied continuously to the equipment

From the definitions given above, it can be assumed that continuous operation of equipment above the rated voltage is not permitted. Operation at power-frequency voltages higher than the rated voltage represents operation at temporary overvoltage. To what extent such a situation is permissible, must be clarified within the framework of insulation coordination. A coordination procedure must be used for this that describes the representative overvoltage by the amplitude/duration frequency distribution of the temporary overvoltages to be expected in operation (Section 2.3.2 in [8]).

Pursuant to VDE 0111, Part 1, temporary overvoltages are described as follows:

Section 3.17.2: Temporary overvoltage

Power frequency overvoltage of relatively long duration

NOTE: The overvoltage may be undamped or weakly damped. In some cases its frequency may be several times smaller or higher than power frequency

More precise information of the wave shape of overvoltages as well as the standardised voltage waveform and the standardised withstand voltage test can be found in Table 1 in [8]. For the category, "Temporary overvoltages" see Figure 1.

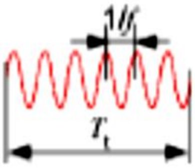
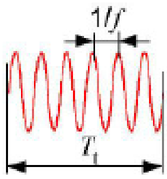
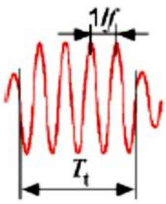
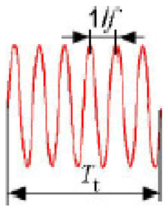
	Voltage and/or overvoltage shapes	Range of voltage and/or overvoltage shapes	Standard voltage shapes	Short-duration alternating voltage test
Con-tinuous		**f = 50 Hz od. 60 Hz** **$T_t \geq 3600$ s**	 **f = 50 Hz od. 60 Hz**	To be determined by the relevant apparatus committees
Temporary		**10 Hz < f < 500Hz** **$0{,}02 \text{ s} \leq T_t \leq 3600$ s**	 **48 Hz ≤ f ≤ 62 Hz**	Short-duration power frequency test

Figure 1: Classes and shapes of overvoltages, Standard voltage shapes and Standard withstand voltage tests for the category "continuous operating voltage" and "temporary overvolages" (according to [8])

2.2. International and national network codes

In the transmission code 2007 of the German transmission system operators [1], it is required that the 380 kV, 220 kV and/or 110 kV network feeding generation units must be able to supply active power at a voltage of 440 kV, 253 kV and/or 127 kV. As a max. duration, 30 min are given (Figure 2). Only after this, these may be disconnected from the corresponding network node.

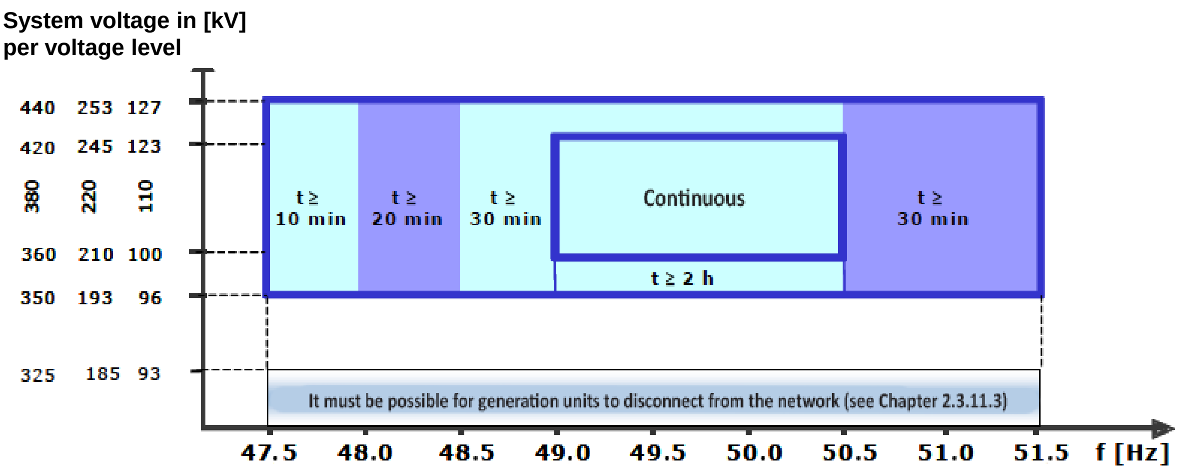


Figure 2: Requirements for the output power of the generation units to the system for specific time durations depending on the system frequency and system voltage [1]

The operation of generation units at voltages >U_m was, however, already required in the Grid Code 2000 “Network and system rules of the German transmission system operators”, issued by the German Verbundgesellschaft [2].

At a European level, network codes for the grid connection of generators [3] as well as for demand connection [4] were published in 2016. In both papers, the following voltages are prescribed at the grid connection point for central Europe (Table 1).

Table 1: Voltages for the grid connection point for continental Europe pursuant to the network codes for the grid connection of generators and for the load connection (in accordance with [3], [4])

Reference voltage	Voltage range	Duration
110 kV	99 kV … 123 kV	unlimited
	123 kV … **127 kV**	min: 20 min, **max: 60 min**
220 kV	198 kV … 246 kV	unlimited
	246 kV … **253 kV**	min: 20 min, **max: 60 min**
400 kV	360 kV … 420 kV	unlimited
	420 kV … **440 kV**	min: 20 min, **max: 60 min**

The network codes are legislative acts and must be incorporated in national law. In Germany, the implementation is carried out via VDE FNN within the framework of the technical connection rules [5], [6].

3. Boundary conditions for operation at voltages >U_m: Operation at temporary overvoltages, duration, critical situations

The network codes introduced in Chapter 2.2 assume that, under certain system conditions, operating voltages can occur that exceed the rated voltages of the equipment. The duration is, however, limited to a maximum of 60 min. In the following it will be discussed, under what conditions such situations could occur. In addition, the empirical values of different German transmission and distribution system operators are analysed. The considerations are based on data that were made available to the FNN project group “Dielectric strength”, based on a survey by the authors of this study. For reasons of anonymization, this is not referenced in the following.

3.1. Inspection and analysis of the empirical values in the case of transmission and distribution system operators

The considerations are based on the empirical values of several transmission system operators as well as various distribution system operators with primarily urban systems and with mixed systems of urban and rural characteristics.

3.1.1. Transmission system operators

In the transmission system of system operator 1, there were two disturbance events, during which voltages >U_m occurred. These are dealt with as examples in chapter 3.2. Otherwise the voltage was always below the maximum (continuous) admissible voltage U_m = 420 kV. Figure ***3*** shows the voltage distribution over a year in seven 380 kV substations. The mean voltage lies between 408 kV and 413 kV.

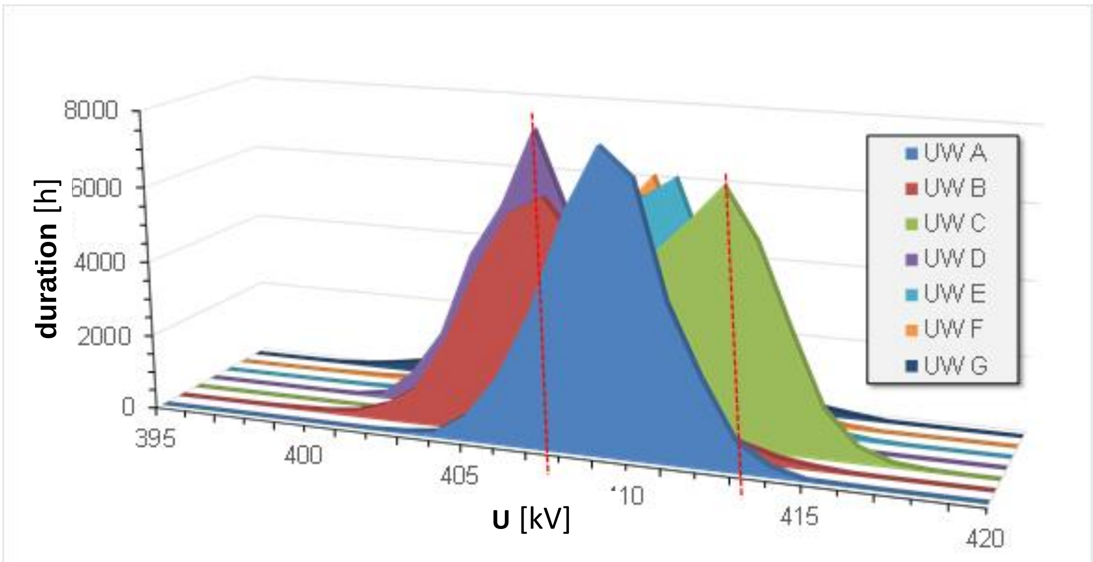


Figure 3: Voltage distribution over a period of one year in seven 380 kV substations of transmission system operator 1

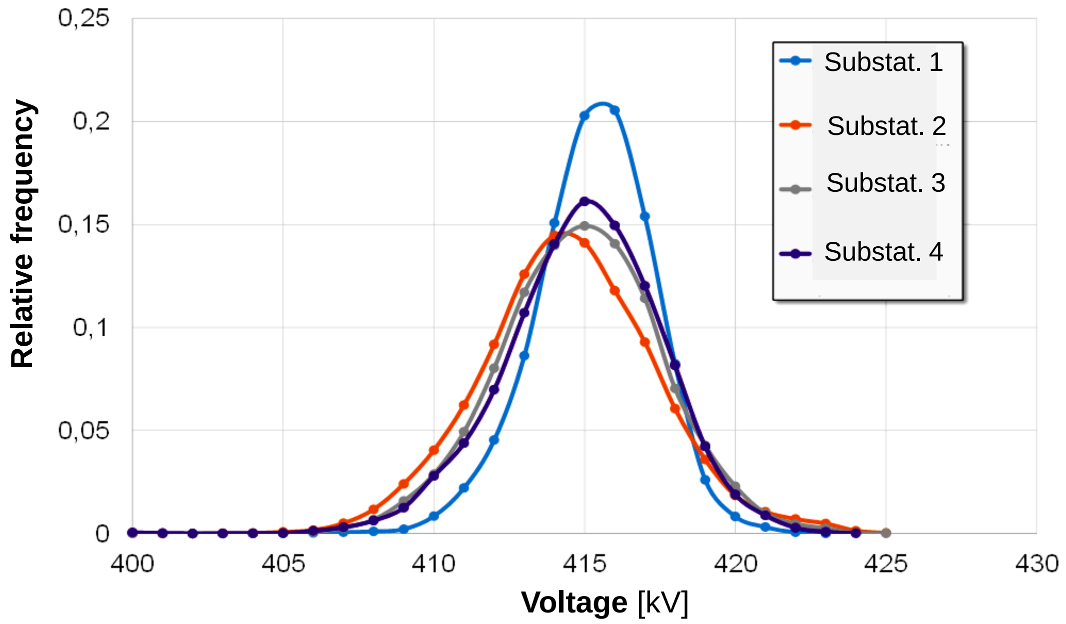


Figure 4: Voltage distribution over a period of one year in four 380 kV substations of transmission system operator 2

From the data of the transmission system operator 2, it can be seen that occasionally voltages of >420 kV occur in this system. In Figure 4 the voltage distribution over a year for four 380 kV substations is shown as an example. Voltages of up to 425 kV occur. Figure 5 shows the voltage distribution in substation 2 for the years 2013 to 2017. The frequency of voltages >420 kV has increased in the past years, whereas the mean voltage at 412 kV has not altered, but its frequency simply decreased.

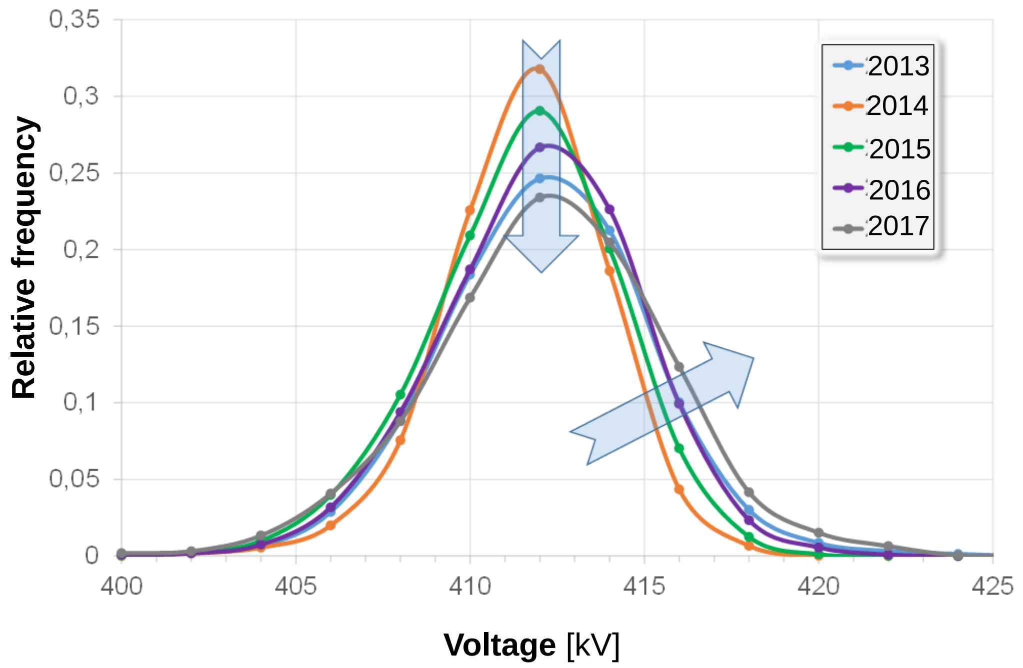


Figure 5: Exemplary voltage distribution in a 380 kV substation of transmission system operator 2

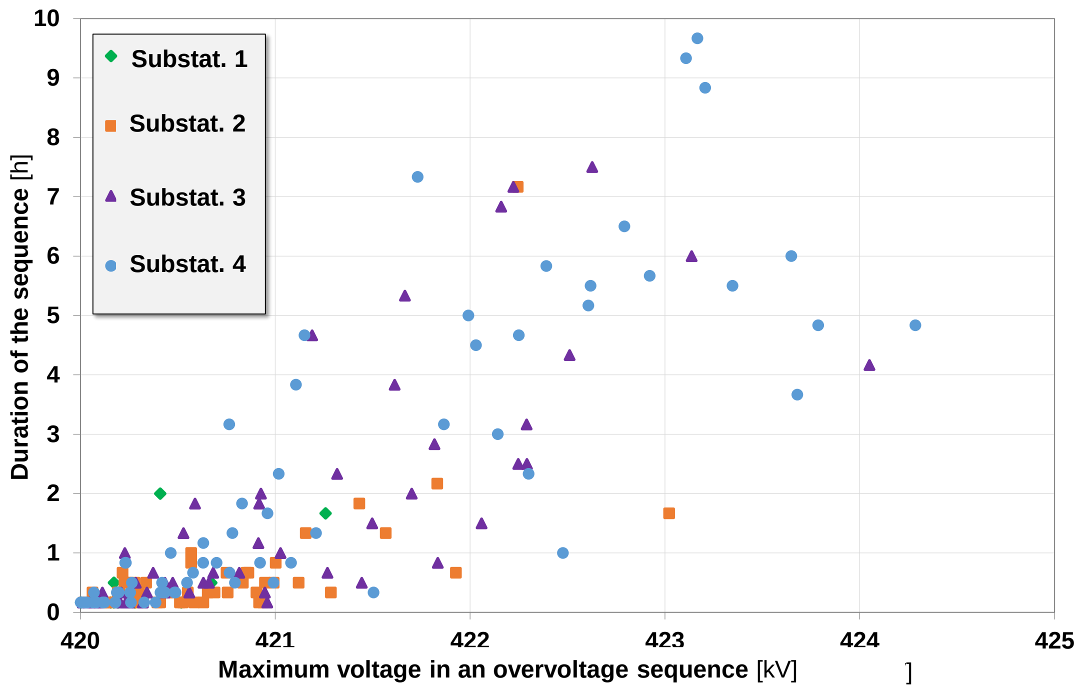


Figure 6. Duration and maximum temporary overvoltage in four 380 kV substations of transmission system operator 2

The duration of the overvoltages in the four 380 kV substations under consideration can be seen in Figure 6. According to this, the highest overvoltages and overvoltage durations respectively occur in substation 3 and 4 with 423 kV for 6 h and 9 h respectively and 424 kV for 4 h and 5 h respectively.

3.1.2. Distribution system operators

From the primarily urban distribution system, typical 15 min maximum values for two representative network nodes were selected (Figure 7). The curves show that the voltages only deviate marginally from the nominal system voltage of 110 kV. The voltage only once briefly reached a value of 116 kV. Voltages > U_m = 123 kV are unknown in this network.

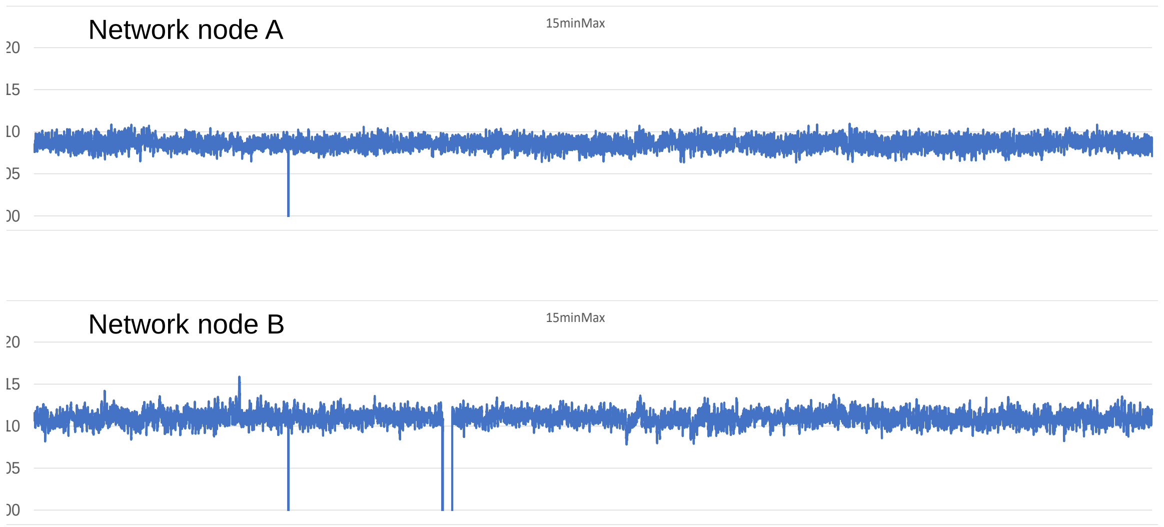


Figure 7: 15 minutes maxima at two typical network nodes in a primarily urban distribution system

The second example refers to the operational experience of the system operator with a system with both urban and rural characteristics. In these systems, sporadically voltages above 123 kV with a maximum value of 133 kV have been reported. Since these overvoltages occur sporadically but not systematically, no information can be given about their frequency of occurrence. The duration can be several 15 min. A typical example is presented in Figure 8.

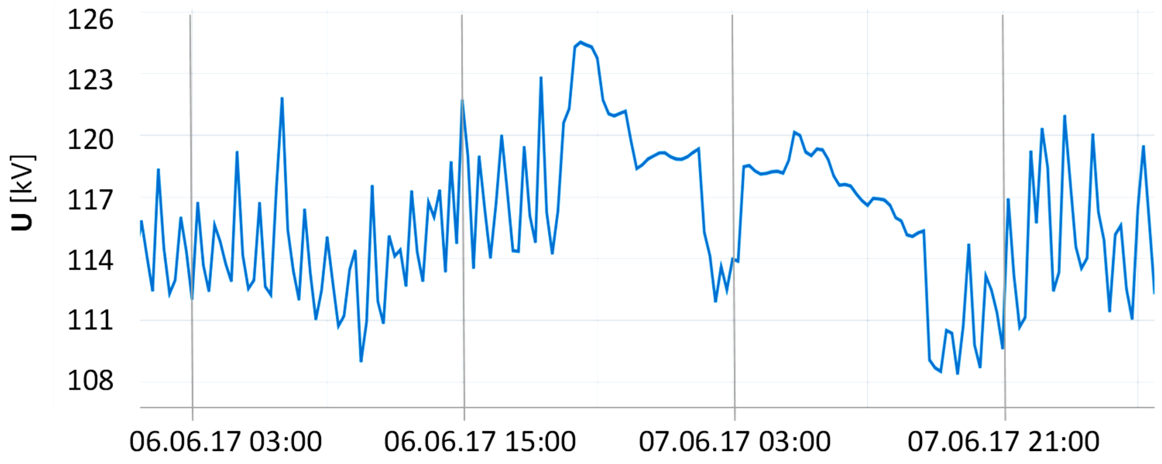


Figure 8: Voltage characteristic at a network node in a urban and rural 110 kV system with

3.2. Scenarios for the occurrence of power frequency voltages >U_m

Scenarios for the occurrence of power frequency voltages > U_m given by the FNN "Dielectric Strength" project group are shown in Table 2.

Scenario 1 can be examined in more detail based on simulations, and scenario 4 based on recorded network events.

Table 2: Scenarios for occurrence of power-frequency voltages >U_m

No.	Abbreviation	Description	Probable voltage	Estimated frequency of occurrence	Duration
1	Energization of long cable sections or transmission lines	When energizing long cable sections or OHL transmission lines Due a higher voltageoccurs at its receiving end than at the sending end due to the Ferranti effect. This voltage then stresses the switching chamber of circuit breaker at the receiving end. In the case of cable connections operated by one system operator, only, the time for connection to the system will be short, i.e. <10s because of the automatic switching conrol equipment mostly applie. In the case of cable connections between neighbouring system operators, the connection to the system is generally carried out manually, so that longer times must be expected here.	up to 440kV	20 - 100 / Jahr	10s - 15min
2	Light load case	Overhead transmission lines that are only marginally loaded act like capacities. Normally, larger network regions are affected by such light load situations. As a remedial measure, individual overhead transmission lines are switched off and reactors are switched on, if available.	some kV above Um	100-300 / year	1-5 h
3	Islanding	If the network should be splitted, it is likely that generation and loads will no longer remain in balance, so that the voltage in the island network with a surplus of supply will experience a higher voltage.	up to 440kV	1 / 10 years	1h
4	Outage of generation	In case of an outage of generation attempts are made to keep the network stable by reconfiguring the grid accordingly. During this period, the system management can increase the voltages in order to reduce the load currents. In such cases, it is possible that these voltages will remain for a certain period of time.	up to 440kV	1 / 10 years	1 h
5	Load shedding	If the frequency in the system should drop to a critical level, load shedding is introduced to stabilise the system. In consequence, that can result in temporarily increased voltages.	up to 440kV	1 / 10 years	1h
6	Heavily loaded networks with a high percentage of capacitive compensation	Heavily loaded power lines must be capacitively compensated correspondingly. If under this sevice conditions a power line has to be switched off due to a fault, the remaining network will have an surplus of capacitive reactive power. This will increase the voltage, since the MSCDN compensation facilities are normally not adjustable in steps.	up to 440kV	1 - 5 / year	1h
7	Heavily loaded networks with a high percentage of cables	Cables provide a certain capacitive reactive power for the transmission system, which is to a certain degree generally compensated by reactors. If the setting of power factor correction is affected by cut-off (e.g. switching off a part of the system fitted with reactors), this can result in a voltage increase due to the surplus of capacitive reactive power.	up to 440kV	1/100 years	1h
8	Reconfiguration of the system with MSCDN facilities or facilities supplying capacitive reactive power	If a reconfiguration of a system with a large MSCDN facility is required, a voltage increase can occur when opening the coupling bay due to a reduction in the short-circuit power of the busbars with MSCDN connected.	up to 440kV	20 - 100 / year	30min
9	Load tripping in the start-up network	The reactive power balance must be monitored in the start-up networks. Load tripping can affect the reactive power balance and lead to a voltage increase.	up to 440kV	1/100 years	30min

3.2.1. Energizing of long cable sections or hybrid transmission lines (scenario 1)

The simulation refers to a 180 km long hybrid transmission line consisting of 15.2 km of double cable in total and 163 km of overhead line (Figure 9) [9]. In the middle, there is a compensation facility with a capacity of 50…250 Mvar.

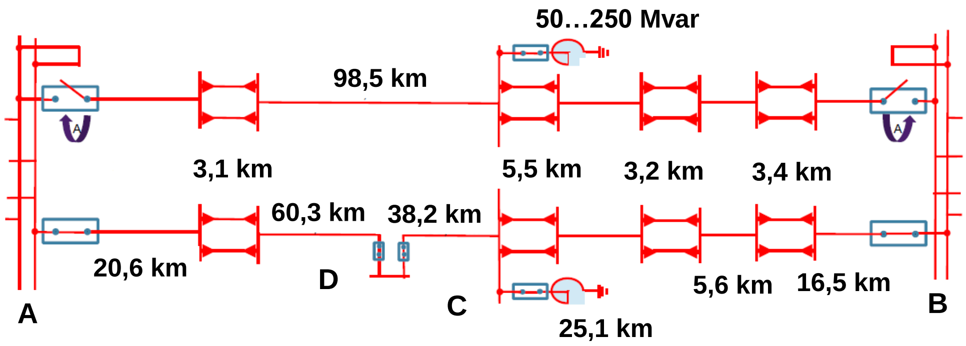


Figure 9: Energizing of a hybrid line, 180 km in length; 15, km double cable, 163 km overhead line [9]

When connecting with a pre-defined compensation power of 250 Mvar, voltages as shown in Table 3 a occur at the receiving end. With a lower or no compensation power, voltages as shown in Table 3 b can be expected.

Table 3: Voltage at the receiving end of the line when energizing the hybrid line according to Figure 9

a) Energization without compensation Voltage before energization: 410 kV		
Switching-on in	Voltage in B [kV]	Voltage in A [kV]
Station A	441 kV	418 kV
Station B	424 kV	463 kV

b) Energization with 250 Mvar compensation capacity Voltage before energization: 410 kV		
Switching-on in	Voltage in B [kV]	Voltage in A [kV]
Station A	427 kV	414 kV
Station B	417 kV	432 kV

Even at a full pre-defined compensation capacity, voltages at the receiving end that are clearly above the rated voltage are to be expected. Without any or with too little compensation power, considerable overvoltage of more than 460 kV can occur.

The values given in Table 3 are therefore realistic for compensation levels that are found in practical operations.

3.2.2. Outage of generation units (Scenario 4)

Figure 10 shows voltage characteristics, which were recorded in the event of an outage of generation units. Figure 10 a refers to failure in the transmission system with subsequent separation of wind turbines (approx. 1500 MW) in the secondary system. The reason for the voltage characteristics according to Figure 10 b was the outage of a power station in the adjacent transmission system.

In the case of failure 1, the voltage rises to 435 kV for a short time and returns again to U_m after 3 min. In the case of failure 2, the voltage rises to more than 430 kV within 4 min and does not return to U_m until more than 20 min. Thus, the values assumed in Table 2 for this scenario are realistic.

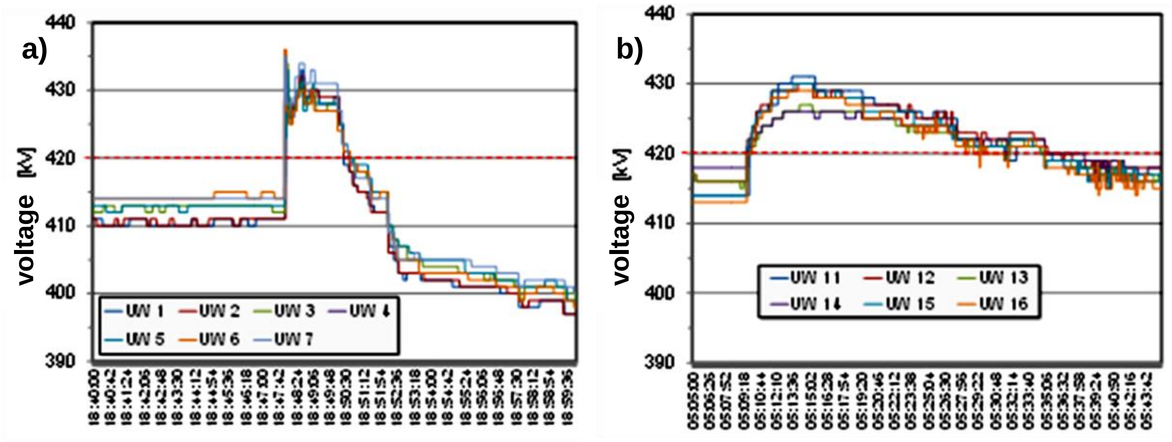


Figure 10: Voltage characteristic in case of an outage of a generation units

a**) Fault in the transmission system with subsequent separation of wind turbines (approx. 1500 MW in the secondary system**

b) Fault at a power station in the neighbouring transmission system

4. Fundamental design of equipment, testing requirements and boundary conditions assumed

Equipment for the high and extra-high voltage systems is designed for a lifetime of several decades. However, it has to be borne in mind that the systems of the future will be more heavily loaded and will be run much closer to their limits. The design is based on the international standards (IEC standards), that cover numerous operational requirements, but do not cover 100% of all the conditions that occur during operation. On the other hand, in the case of the type tests, assumptions are made that never or only rarely occur under system conditions. Thus the test standard for high voltage circuit breakers, for example, assumes first-pole-to-clear factors of $k_{pp.}$ = 1.3 in the case of short-circuit currents. Such high factors will not occur in the system in the area of substations with high short-circuit currents, where currents in the range of the rated short-circuit current are to be expected. Experience shows that smaller first-pole-to-clear factors are to be anticipated here. Therefore, it is the task of the system operator to analyse the operating conditions and the requirements and to specify the corresponding ratings.

In the case of the rating and design of equipment, various stresses must be taken into account. In the present case, only the influence of the electrical stresses is considered. The fundamental dielectric stress of the equipment and the technical verification by adequate HV testing can be seen in Figure 11. In this, power-frequency and transient processes must be differentiated. Beside the permanent service voltage, the equipment is subject to temporary overvoltages, which as a rule are also of power-frequency nature. Stresses caused by transient phenomena occur on the one hand due to faults and/or switching operations in the grid that result in slow front overvoltages with a slow front time in the range of some 100 µs. On the other hand, stresses are caused by fast front and very fast front overvoltages. Fast front overvoltages with rise times of less than a microsecond to several microseconds are caused by lightning strikes, but can also be the result of re-strikes and re-ignitions. Very fast front overvoltages with rise times of several nanoseconds up to some 100 nanoseconds occur when switching GIS disconnectors.

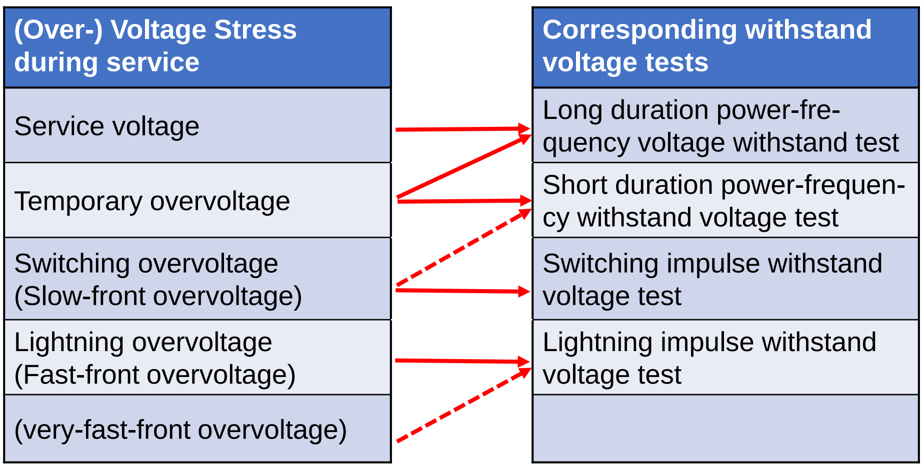


Figure 11: Relationship between voltage or overvoltage stress during service and the technical verification by adequate HV testing

The technical verification that the equipment concerned is able to cope with the continuous service voltage over the assumed service life is carried out by means of a test with a long-duration power-frequency withstand voltage test, mostly for a duration of 30…60 min. In the case of some equipment, this verification is also carried out with a short-duration power-frequency withstand voltage test, with a test duration of mostly one minute. Sufficient strength with regard to temporary overvoltages is verified by means of the test with short-duration or long-duration power-frequency withstand voltage test. Sufficient strength with regard to slow front overvoltages is verified by means of a test with switching impulse withstand voltage, and the fast and very fast front overvoltages by means of a test with lightning impulse withstand voltage.

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 for 30 min each time with a temporary overvoltage of 1.05*U_m. It must be investigated, whether a restriction in the functionality of the equipment is to be anticipated due to these stresses. In this, both stationary and quasi-stationary as well as transient processes must be considered. On the other hand, it must be clarified, whether these stresses accumulated over the operating time result in a noticeable reduction in the service life. Both questions are considered for the different equipment – overhead lines, outdoor substations, gas-insulated substations, switching devices, instrument and power transformers, surge arresters and cable systems – based on the relevant standards and the technical literature.

5. Possible restrictions to the functionality of equipment in the case of operation with voltages >U_m

5.1. Overhead transmission lines

The internal and external clearances of overhead transmission lines are derived from the 90% lightning impulse withstand voltage $U_{90\%\_ff\_is}$ of the insulator chain used in the transmission line [10]. Lightning overvoltages are external overvoltages that are not affected by the current operating voltage. The temporary overvoltage assumed above therefore has no impact on the fundamental rating of the clearances of an overhead line.

A higher operating voltage, however, can have an impact on the corona performance of the overhead line – conductor and fittings. In particular, 380 kV lines are to be considered here. As a rule, these are fitted with a four-conductor bundle with at least 22 mm conductor diameter, which in the case of an operating voltage of 420 kV, exhibits a conductor field gradient of 16.5 kV_{rms}/cm. This conductor field gradient is sufficiently distant from the corona onset field strength of approx. 22 kV_{rms}/cm calculated according to [11], so that even with a temporary overvoltage of 1.05*U_m , no undue high corona is to be expected. The corona behaviour of the fittings is not critical, since in the tests a corona inception voltage above the 1.1-fold maximum operating voltage is required.

For the ratings of the overhead line insulators, beside the lightning impulse withstand voltage, the pollution performance under operating voltage is of importance. The porcelain and composite insulators used in the high and extra-high voltage systems are generally designed for medium pollution. The unified specific creepage distance (USCD; related to the phase to earth voltage) is between 32…36 mm/kV depending on the insulator type.

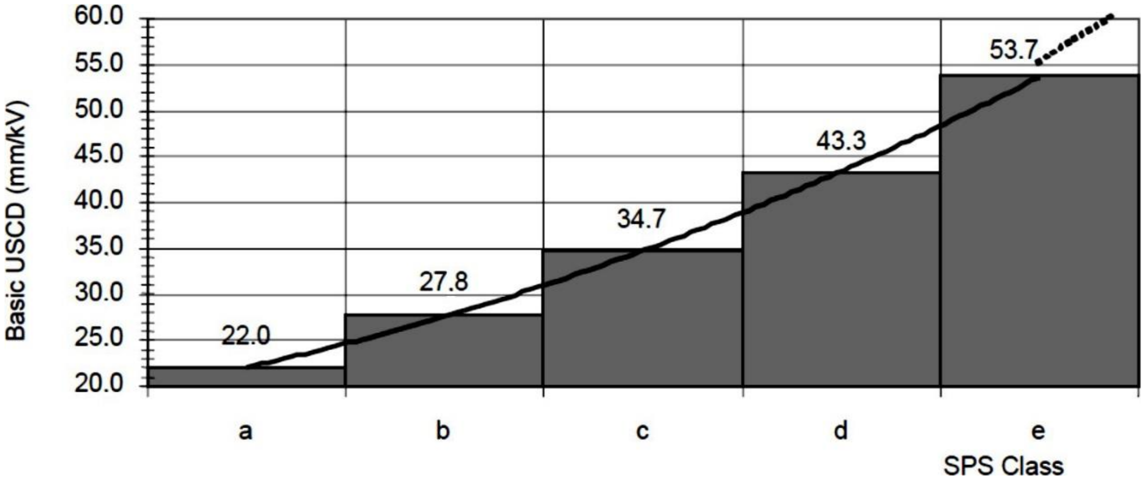


Figure 12: Unified specific creepage lengths as a function of the contamination class [12]

a very light b light c medium d heavy e very heavy pollution

Pursuant to IEC 60815-2 [12], a unified specific creepage distance of 31…38 mm/kV is permissible for medium pollution (Figure 12). In the case of composite insulators, a reduction in the creepage distance to 75% is additionally possible due to their hydrophobic surface. In addition, it must be considered that in the majority of the areas of the system there is only light pollution. Thus a temporary stress with 1.05*U_m is without noticeable impact on the pollution performance of the overhead line insulators.

5.2. Outdoor substations

The minimum clearances of active parts in outdoor substations are determined according to [6] in area I (1 kV < $U_m \leq$ 245 kV) by the rated lightning impulse withstand voltage and in area II (U_m > 245 kV) by the rated switching impulse withstand voltage [13]. Since the rated lightning impulse withstand voltage is derived from the atmospheric overvoltages, a 5% higher operating voltage in 110 kV and 220 kV outdoor substations would not have an impact on the minimum clearances. In 380 kV outdoor substations, a rated switching impulse withstand voltage of 1050 kV is generally applied, which assumes switching overvoltages of 2.9 p.u. However, such switching overvoltages can only occur with three-phase auto-reclosing, if a preloaded transmission line re-energized. The German transmission system, however, is only operated with single-phase auto-reclosing, whereby switching overvoltages of only 2.3 p.u. come into consideration. Therefore, the rating of the minimum clearance of active parts is sufficiently save, even in the case of stresses with 440 kV.

The equipment used in outdoor substations must be considered according to the relevant standards (see below). A possible restriction in functionality in the case of an operating voltage of 1.05*Um has to be investigated, taking into account the ratings carried out in the standards.

5.3. GIS substations

For the design of gas-insulated switchgears and substations (GIS), the rated lightning impulse withstand voltage is decisive [14], t. This voltage is derived from external (atmospheric) overvoltages and is not influenced by the relevant operating voltage. The lightning impulse withstand voltage should also prove a sufficient dielectric strength against internal overvoltages when switching disconnectors. These very fast front overvoltages can be 2.0 p.u. in the vicinity of the relevant disconnector. These surges create travelling waves in the whole of the GIS substation. Due to the reflections and refractions, very complex wave formations are created and the overvoltages display a spatial distribution. In general, the highest overvoltages are reached at the open end of the substation.

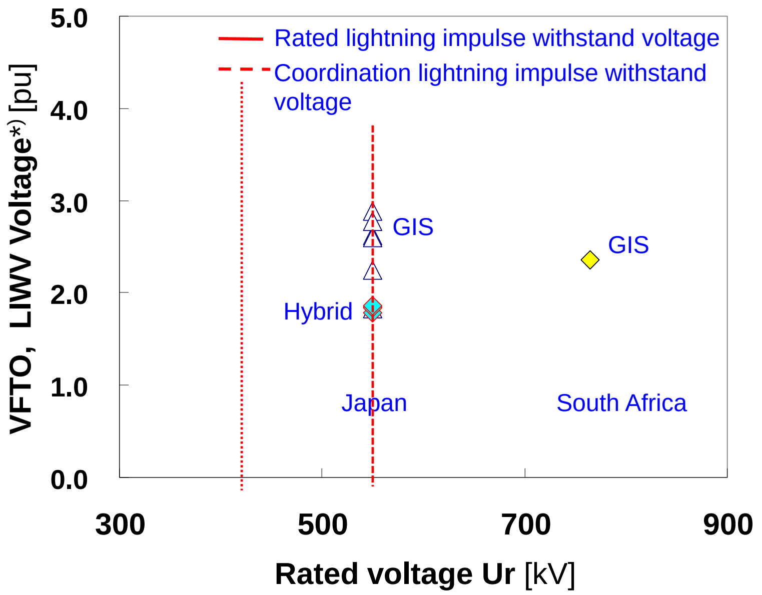


Figure 13: Comparison of the very fast transient overvoltages ascertained for different GIS configurations with the rated and coordination lightning impulse withstand voltages (accord. to [16])

***) VFTO Very fast transient overvoltages**
LIWV Rated lightning impulse withstand voltage

In [16], very fast transient overvoltages caused by switching of disconnectors have been ascertained for different GIS configurations (Figure 13). Although the results given in p.u. values refer to 550 kV and 750 kV substations, they should also apply for 420 kV GIS substations, since the system dimensions are similar.

From Figure 13, it can be seen that the very fast transient overvoltages are smaller than the coordination lightning impulse withstand voltage, i.e. the very fast transient overvoltages are covered by the rated lightning impulse withstand voltage. The figure also shows that the margin reduces with increased rated voltage, i.e. this fact is of particular interest in the case of GIS substations in the extra-high voltage network. If very fast transient overvoltages now occur at operating voltages of 1.05*U_m, the margin to the lightning impulse withstand voltage becomes smaller. In the case of sound insulation performance, this effect can, however, be ignored. A comparison of the insulation behaviour of SF_6 gas-insulated systems in the case of very fast transient overvoltages (switching of GIS disconnectors) and fast front overvoltages (lightning overvoltages) (Figure 14) shows that the breakdown voltage slightly increases with rising steepness [16]. Thus the strength in the case of stresses caused by very fast transient overvoltages is covered by the rated lightning impulse withstand voltage, even if the amplitude of the very fast transient overvoltage is 5% higher [17].

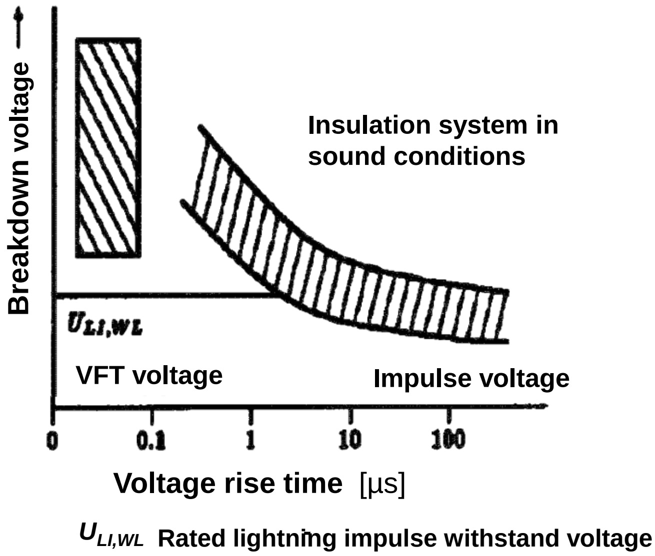


Figure 14: Voltage-time characteristic of quasi homogeneous arrangements in SF_6, general presentation (accord. to[16])

5.4. Switching devices

5.4.1. Circuit breakers, interrupting short-circuit currents

In accordance with [18], initial symmetrical short-circuit currents of mains-operated short-circuits are calculated with a voltage of 1.1*$U_n/\sqrt{3}$. The factor 1.1 takes into account the ratio between the highest continuous operating voltage, which corresponds with the rated voltage and the nominal system voltage. In the case of operating voltages >U_m, greater short-circuit currents occur than calculated in the short-circuit current calculation. In the case of operating voltages of 1.05*U_m, 5% higher short-circuit currents have be taken into account. Since the transient voltage upon interrupting short-circuit currents is related to the rated voltage according to VDE 0671-100 [20], a higher operating voltage of 105% of the rated voltage would cause a 5% higher amplitude in the transient voltage.

Thus interrupting short-circuit currents in the case of voltages of 1.05*U_m could lead to an overstress of the circuit breaker. In the assessment, how far such an overstress of the circuit breaker is probable, further considerations, such as the boundary conditions assumed in the standards, the boundary conditions in the network, the frequency of single-phase and multi-phase faults phase-to-earth and clear of earth, the switching performance in the case of lower current steepness etc. must be taken into account.

5.4.1.1. Terminal faults

The short-circuit current switching capability of a circuit breaker results from the current to be interrupted and the recovery voltage. The recovery voltage is determined by the amplitude factor γ and the first-pole-to clear-factor k_{pp}, which is itself dependent on the method of neutral-point connection of the system. The transmission system in Germany is solidly earthed. In the case of solidly earthed neutral, a first-pole-to-clear factor of k_{pp} = 1.3 is assumed. In the 110 kV system, solidly earthed neutral as well as resonant earthed neutral via Petersen coils is found. In the case of resonant earthed neutral, a first-pole-to clear factor of k_{pp} = 1.5 is assumed. In general, the first-pole-to-clear factor is determined from the ratio of zero-sequence reactance X_0 to positive-sequence reactance X_1 to

$$k_{\text{pp}} = \frac{3X_0}{X_1 + 2X_0}$$

As Figure 15 [21] shows, the first-pole-to-clear factor k_{pp} = 1.3 is produced for a ratio X_0/X_1 = 3.25. In a system with an isolated neutral or resonant earthed neutral, the zero-sequence reactance is very large. With $X_0/X_1 \rightarrow \infty$ the first-pole-to-clear factor is k_{pp} = 1.5 [21].

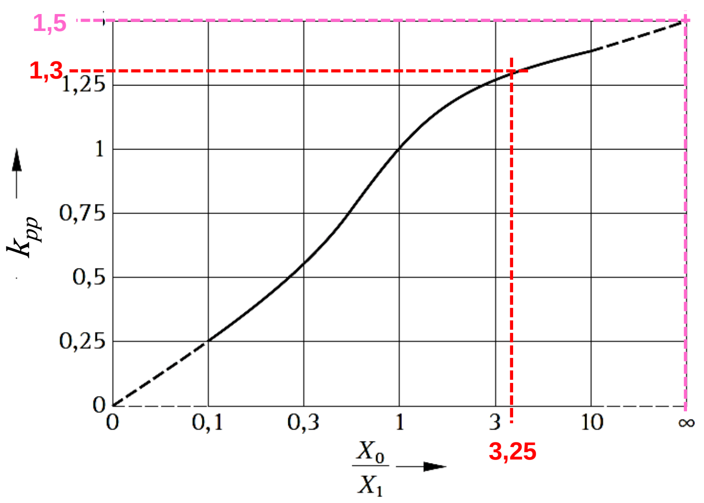


Figure 15: First-pole-to-clear factor depending on the ratio X_0/X_1 (accord. to [21])

The highest short-circuit current occurs in the case of a terminal fault, in other words in the case of a three-phase short circuit directly at the terminals of the circuit breaker.

2017	High voltage		Extra high voltage	
	1/(100 km *a)	%	1/(100 km *a)	%
Earth fault	4,24	66,8%		
Single-phase short circuit to earth	1,48	23,3%	1,02	93,1%
Two-phase short circuit	0,09	1,4%	0,06	5,3%
Three-phase short circuit	0,04	0,6%	0,01	1,1%
Others	0,51	8,0%	0,006	0,5%

Figure 16: Frequency of different types of short-circuits or faults respectively in the German HV and EHV system [22]

As can be seen from Figure 16 [22], a three-phase short circuit in the extra-high voltage system only occurs with a frequency of 0.01 per 100 km circuit length and year, i.e. with a frequency of approximately 1% of all the short circuits occurring in the system. In the high voltage system, the fault rate is even lower. Most frequently in the extra-high voltage system, we see a single-phase-to-earth fault, in which the short-circuit current is generally lower than in the three-phase fault, just as with the first-pole-to-clear factor of the recovery voltage. As a rule, a first-pole-to-clear factor of $k_{pp1} \approx 1.0$ is assumed here. However, circuit breakers in the transmission system are designed for three-phase to earth faults.

In the case of all other short circuits – single-phase-to-earth faults, double-phase faults to earth and free of earth,– the amplitude and the steepness of the transient recovery voltage is smaller [23] (Figure 17). The amplitude and the steepness of the transient recovery voltage depends on the ratio of zero-sequence reactance X_0 to positive-sequence reactance X_1 and zero-sequence surge impedance Z_0 to positive-sequence surge impedance Z_1 respectively.

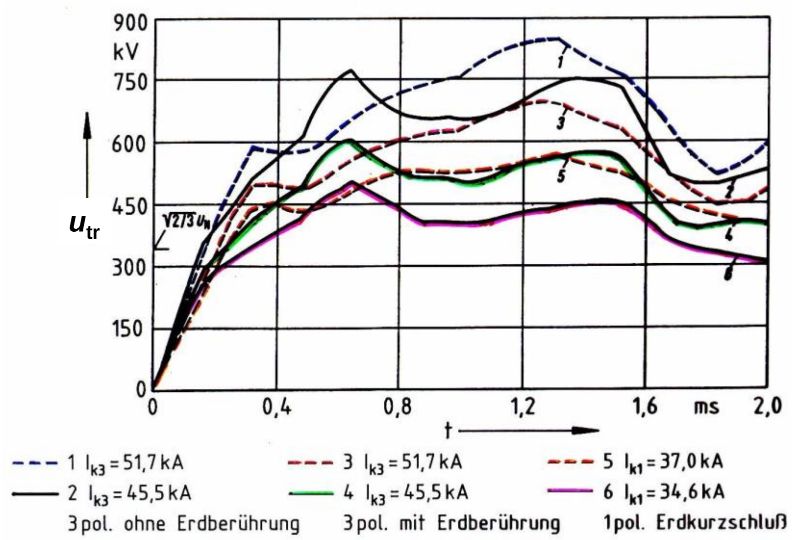


Figure 17: Transient recovery voltage in the 380 kV system in case of different types of faults [23]

The highest three-phase short-circuit current must be interrupted by a circuit breaker in the case of a fault at a feeder in the immediate vicinity of the substation, because the current is fed by the system impedance without any damping by line impedances. Since the ratio X_0/X_1 in these cases is generally < 3, a first-pole-to-clear factor that is lower than the first-pole-to-clear factor of k_{pp} = 1.3 assumed for this switching duty. The evaluation of the data of a transmission system operator shows that, in the 380 kV system with three-phase short-circuit currents between 60 and 80 kA, the ratio X_0 / X_1 lies somewhere in the region of 2…2.5 (Figure 18 a), which corresponds to a first-pole-to-clear factor of k_{pp} = 1.1…1.25. Only in one case (marked with a red circle) the ratio X_0 / X_1 = 3 is identified for a short-circuit current of 61 kA. Similar ratios are given for the 220 kV system (Figure 18 b). Here, in the case of three-phase short-circuit currents between 40 and 63 kA, the ratio is X_0 / X_1 < 2.5.

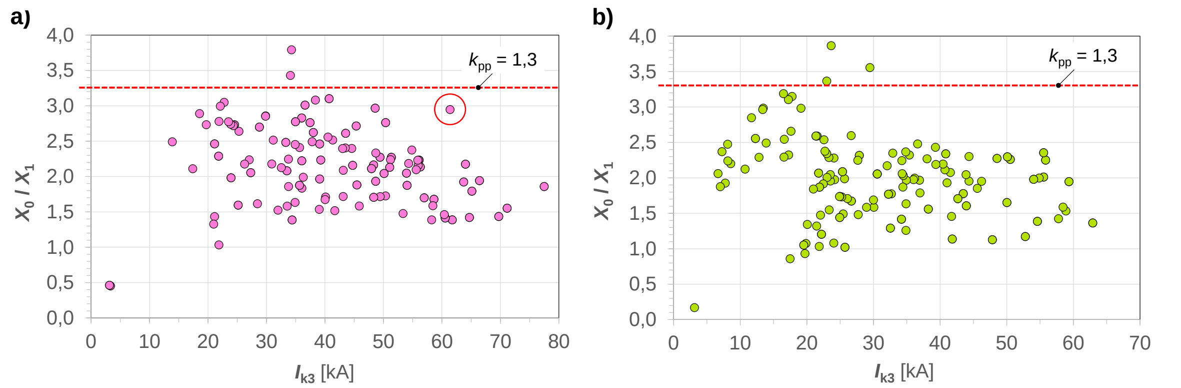


Figure 18: Ratio X_0/X_1 depending on the three-phase short-circuit current I_{k3} for the 380 kV and 220 kV system of a TSO not specified here

a) 380 kV system **b) 220 kV system**

Therefore as a rule, the amplitude of the transient voltage is lower in these systems than the tested transient recovery voltage, i.e. the circuit breaker would be less heavily stressed even at interruption of the rated short-circuit current.

In addition, it must be borne in mind that the short-circuit current in general is clearly below the rated short-circuit current and a circuit breaker in principle can interrupt a larger d*u*/d*t* with a smaller d*i*/d*t*. This issue can be seen in Figure 19 [24]. If a 63 kA circuit breaker would have to switch off 80% of the rated short-circuit current only at its deployment site, the steepness of the transient recovery voltage may be almost twice as large. That would mean, the breaker would still cope with the 5% greater steepness at a voltage of 105% of the rated voltage without any problem.

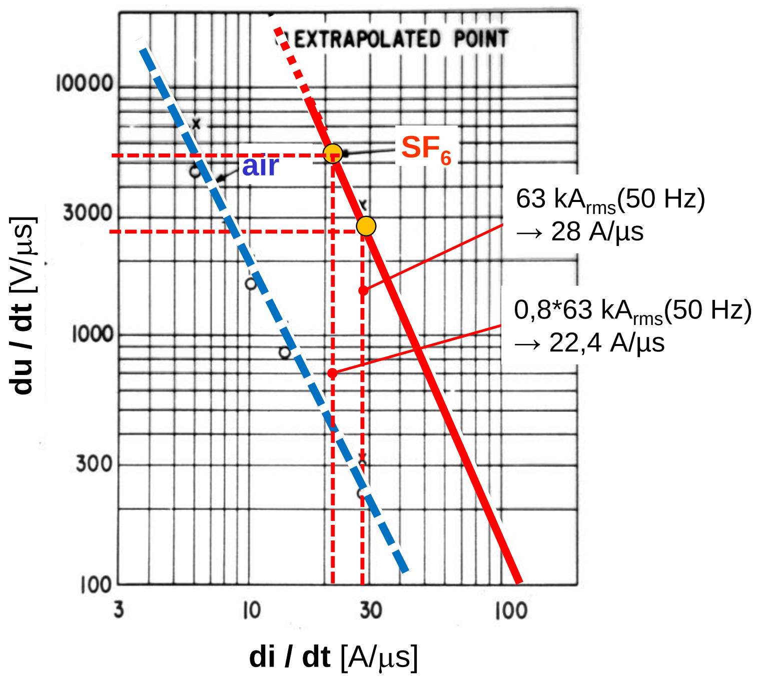


Figure 19: Dielectric recovery of switching gaps in ait and SF6 depending on the current steepness di/dt, accord. to [24]

It can therefore be assumed that the switching of short-circuit currents at 1.05*U_m is governed by the circuit breakers applied in the 380 kV and 220 kV system. If the breaker is already loaded with rated short-circuit breaking current at operating voltage according to U_m , then the switching performance at voltages greater than the rated voltage must be clarified with the manufacturer. Such a case can be seen in the system marked with a red circle in Figure 18 a. It is often the case that the same interrupting unit (breaking chamber possibly equipped with a grading capacitor and closing resistor) is also used for higher rated voltages, e.g. for 550 kV or 300 kV instead of 420 kV or 245 kV rated voltage.

Circuit breakers for the 110 kV system are also designed for three-phase short circuits. As a rule, even in the solidly earthed systems, breakers are used that are designed for a first-pole-to-clear factor k_{pp} = 1.5. These breakers should also be able to govern short-circuit currents of 105% of the rated current, because the recovery voltage only equals 87% of the rated voltage, taking into account the facts presented in Figure 19. When switching in systems with an isolated or resonant earthed neutral and loaded with the rated short-circuit breaking current, the switching performance in the case of voltages greater than the rated voltage must be clarified with the manufacturer. Generally, in this voltage range, too, the same switching chamber is also used for the rated voltage of 145 kV.

5.4.1.2. Short-line faults

The short-line fault represents a particular stress for a circuit breaker. Although the breaking current is lower than the rated short-circuit current, the breaker is particularly stressed by the high steepness of the transient recovery voltage due to the travelling wave phenomena on the line side directly after the interruption of the current. The steepness of the line side is determined by

$$s_L = {}^{du_L}/_{dt} = Z_L * {}^{di_L}/_{dt} = \sqrt{2}\,\omega\, Z_L * I_L \qquad (5.4.1)$$

with

Z_L surge impedance of the line
I_L short-line fault current

In the case of SF_6 circuit breakers, mainly employed nowadays, the 90% short-line fault current is seen as particularly critical. At short-line fault testing according to the standard, the short-circuit current related to the three-phase short-circuit current is applied [20]. However, the short line fault generally occurs as the result of a single-phase-to-earth fault, which, in the solidly earthed networks, mostly equals 80…90% of the three-phase short-circuit current, as shown by the evaluation of the data of a TSO not described in more detail here (Figure 20).

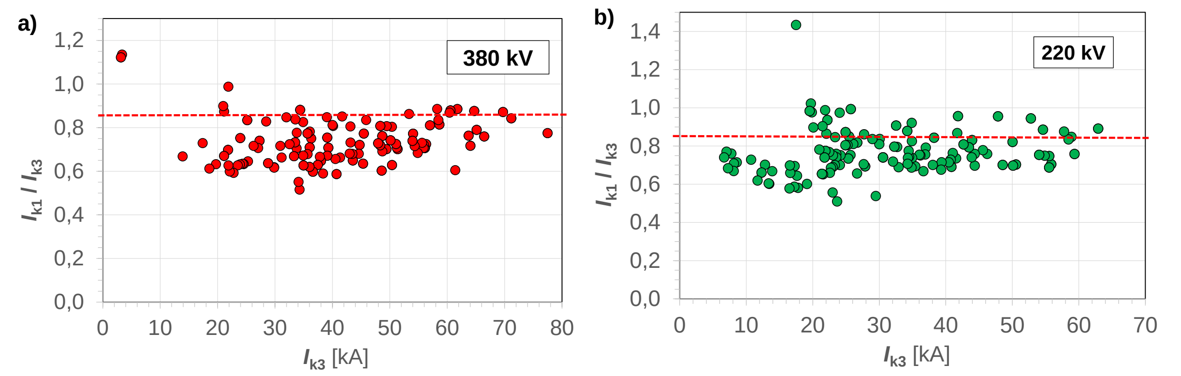


Figure 20: Ratio of the single-phase-to-earth short-circuit current to three-phase short-circuit current I_{k1}/I_{k3} depending on the three-phase short-circuit current I_{k3} for the 380 kV and 220 kV system of TSO

Therefore, under the short-line fault conditions, the current steepness d*i*/d*t* and the line side voltage steepness s_L that occur in the system are generally lower than the steepness tested according to the standard. A short-line fault that occurs with an operating voltage of $1.05*U_m$ should therefore be managed by the breakers used in the transmission system and the solidly earthed 110 kV system, as the following example illustrates (Figure 21).

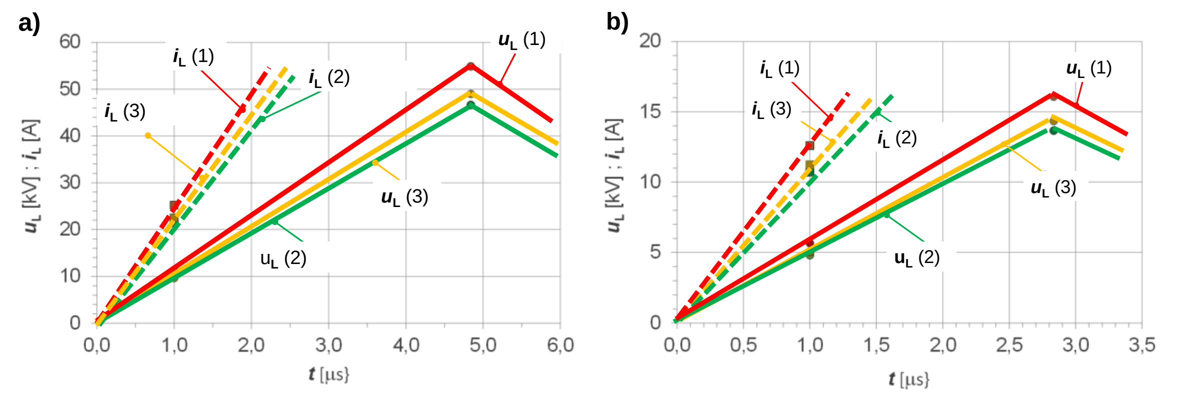


Figure 21: Line side transient recovery voltage u_L and current i_L at 90% SLF, related to 3-phase short-circuit current (1), single-phase to earth short-circuit current (2) and single-phase-to-earth short-circuit current at $U = 1{,}05*U_m$ (3)r

Figure 21 a shows the line side transient recovery voltage u_L calculated according to (5.4.1) and the current i_L at 90% short-line fault for a 420 kV/63 kA circuit breaker. In Figure 21 b, the same switching duty is shown for a 123 kV/31.5 kA breaker. In both cases of application, both the steepness of the line side transient recovery voltage as well as the current steepness at

1.05*U_m is lower than the steepness tested according to the standard [20], if a short-line fault caused by a single-phase-to-earth fault is assumed.

The three-phase short-line fault in a resonant earthed 110 kV system does not need to be further considered here, since a three-phase short circuit is extremely rare. Moreover, it is highly unlikely that such a short circuit would occur in a line length that leads to a 90% short-line fault current.

5.4.1.3. Transferred short-circuit currents

The switching of transferred short-circuit currents, e.g. 10% and/or 30% of the terminal fault current (T10 and/or T30), must be considered in particular in the case of faults close to transformers. In this case, the short-circuit current is limited by the transformer impedance and amounts to about 10% to 30% of the rated short-circuit current. The transient recovery voltage is determined by the natural frequency of the transformer, which is somewhere between 5…10 kHz depending on the voltage level [25].

Beside the method of neutral-point connection of the transformer, it must be distinguished, whether the fault arises on the primary or secondary side of the transformer. In this case, the standard assumes a three-phase short circuit free of earth and/or transformers without an earthed neutral and prescribes a first-pole-to-clear factor k_{pp} = 1.5 for this switching duty [26]. The current draft of the standard [20] prescribes a first-pole-to-clear factor of 1.3 for 245 kV and 420 kV breakers, however, with the stated amplitude factor of 1.76 the same transient recovery voltage (steepness and peak value) results as in the currently valid standard [19]. In a note in [20], it is stated that transformer-limited faults with X_0/X_1 greater than 3.0 (e.g. transformers with non-effective earthed neutral in effective earthed systems) are covered.

At a voltage of 1.05*U_m, a 5% higher amplitude of the transient recovery voltage compared to the standard would occur with 123 kV as well as with 245 kV and 420 kV circuit breakers. Since a three-phase short circuit free of earth is extremely rare, a first-pole-to-clear factor of k_{pp} = 1.3 can be assumed, insofar as the transformer neutral point is earthed. In this case, an amplitude of the transient voltage of 1.05*87% = 91% of the standard value can therefore be assumed. This means that this switching duty should also be managed even at 1.05*U_m.

If the transformer neutral-point is not earthed, a first-pole-to-clear factor of k_{pp} = 1.5 must be assumed for this switching duty. Transformer neutral points at network nodes, for which voltages of 1.05* U_m are to be expected, should therefore be earthed.

If this measure is not possible for reasons of network engineering, as it can be the case, e.g. with generator transformers, it must be clarified, whether the breaker applied can cope with the 5% increase in the transient recovery voltage. In this, it has to be considered that, due to the high natural frequency of some transformers, a greater steepness than that given in the standards can occur in unfavourable cases of application [25].

5.4.2. Circuit breakers, switching of capacitive currents

5.4.2.1. De-energising of transmission lines

Circuit breakers must switch capacitive currents in the magnitude of some 10 A to a few 100 A. The SF_6 circuit breakers used today can interrupt these currents with very short arcing times. In order to ensure restrike-free switching, a corresponding dynamic dielectric strength d*u*/d*t* of the switching gap is required. This fact should be mentioned with the aid of the cold characteristic curve of a 420 kV SF_6 circuit breaker. Such a cold characteristic curve – which is the function of the dielectric strength subject to the striking distance of the switching gap – is suitable for a first estimation of the dynamic dielectric strength, for as long as it is possible to ignore the impact of the current. This is permissible with SF_6 breakers in the aforementioned current range

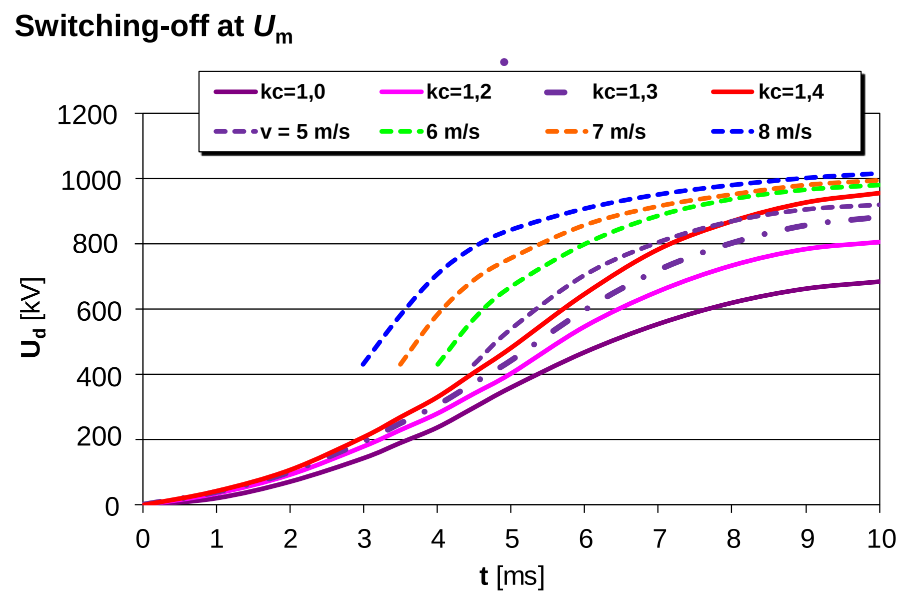


Figure 22: Dynamic dielectric strength of the switching gap for different contact speeds *v* and transient recovery voltages for different capacitive voltage factors k_c in the capacitive switching case related to a 420 kV circuit breaker with two interrupting units [27]

Figure 22 [27] shows in a dotted line the dynamic dielectric strength of the switching gap of a 420 kV breaker with two interrupter units for different contact speeds, whereby the x-axis is scaled on a time-dependent basis. Next to this, the transient voltage for the different capacitive voltage factors k_c is shown as a solid line. Beside the voltage factors in accordance with the standard, the factor k_c = 1.3 is shown as a chain dotted line. This factor is chosen by some system operators, in order to take into account the capacitive coupling with the adjacent circuits in service.

It is recognised that, in the case of a capacitive voltage factor k_c = 1.4, restrikes are no longer to be anticipated only if the contact speed is at least 6 m/s. The illustration assumes an arcing time of $t_L \approx 0$. If greater arcing times were assumed, the performance would improve, since the transient recovery voltage becomes effective at larger contact distances, only. However, it has been shown that SF_6 circuit breakers are able to interrupt capacitive currents with arcing times of < 0.5...1 ms. Figure 22 shows the worst case conditions that correspond with the test conditions in the standard for circuit breakers of class C2 (breakers with a very low restrike probability). In addition, it has to be taken into account that the standard since 2004 requires test-specific proof on a pre-stressed breaker for breakers of this class.

If the switching is carried out at the higher operational voltage of 1.05*U_m, in the case of a contact speed of 6 m/s, which would suffice for a successful switch with k_c=1.4 at U_m , restrikes can no longer be excluded (Figure 23).

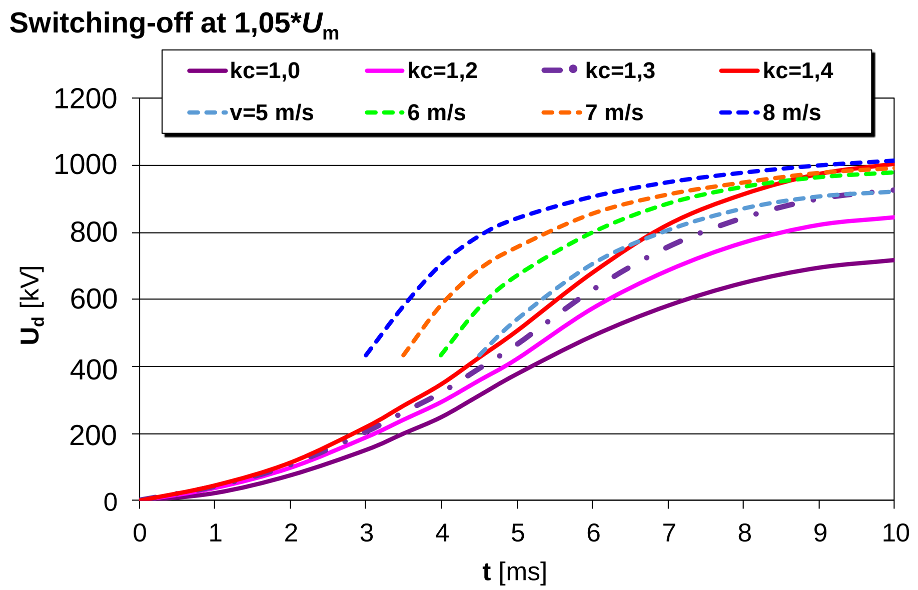


Figure 23: **Dynamic dielectric strength of the switching gap for different contact speeds *v* and transient recovery voltages for different capacitive voltage factors k_c as presented in Figure 22, but at switching-off at a operating voltage of 1,05*U_m (accord. to [27])**

In the case of greater arcing times, the performance would improve, since the transient recovery voltage becomes effective in the case of larger contact distances. Greater arcing times can be achieved by controlled switching, insofar as the switch is tripped in such a way that the contact separation takes place several milliseconds before the current zero.

If the line to be de-energised is a shunt reactor compensated line, the risk of restrikes is smaller. Thanks to the shunt reactor, the load-side voltage does not remain on the peak value of the voltage, but oscillates with the resonance frequency of the reactor and the line capacitance. As a rule, a degree of compensation <1 is selected, so that a resonance frequency of < 50 Hz is set. The recovery voltage resulting in this case is exemplarily shown in Figure 24 (according to [26]). In any case, it is lower than in the case of the non-compensated transmission line.

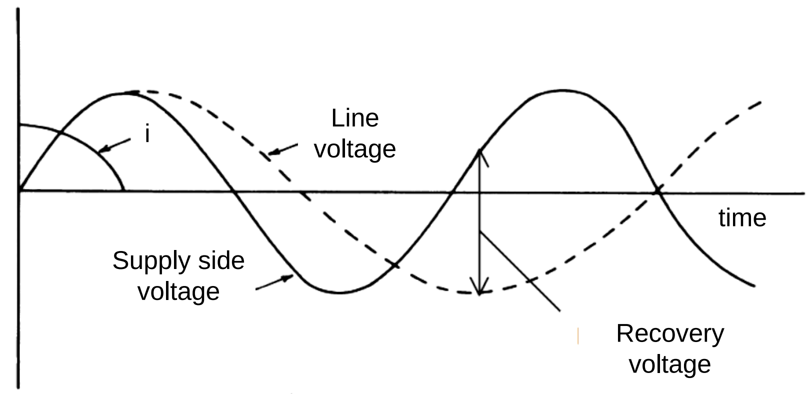


Figure 24: Supply side and load side voltage at de-energising of shunt compensates lines (according to [26])

5.4.2.2. Energising of transmission lines

Beside de-energizing energizing of overhead lines must also be considered as a switching duty. This switching duty is of particular interest because of the overvoltages that occur. At this, a power-frequency and a transient content has to be distinguished (Figure 25) [28].

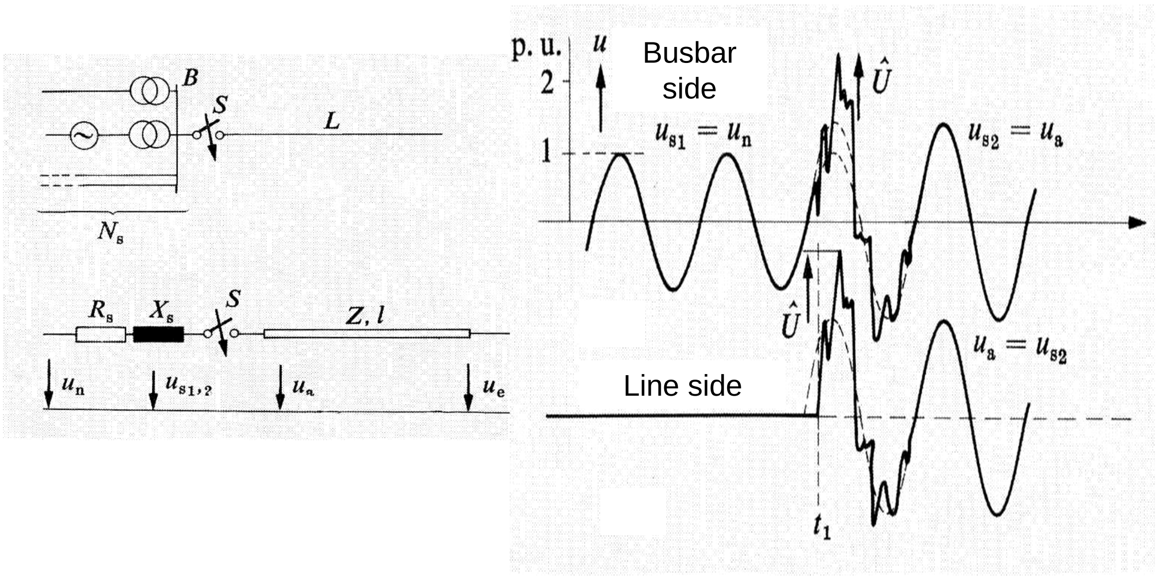


Figure 25: Voltage characteristic at energising an overhead line [28].

After switching on at instant t_1 the voltage u_a at the sending end of the line must be set to the new value u_{s1} created by the new circuit state due to the line energised. This occurs by means of a transient process in the form of a travelling wave on the line with a peak value $\hat{U}$ and an interaction with the supply network. Since a transmission line operating at no-load represents a capacitive load, the steady-state power-frequency voltage u_{s2} is greater than the voltage u_{s1}. Thus, the transient process is superimposed to the increased power-frequency voltage after closing. Due to the Ferranti effect, the voltage at the receiving end of the transmission line operating at no-load is higher than at the sending end. In consequence, the closing overvoltage at the end of the line is also greater. The amplitude of the transient voltage is dependent on the phase angle of the instant of closing t_1. The smallest overvoltage is generated, if the closing is possible at voltage zero, the highest when closing at maximum voltage.

In this switching process, the overvoltage factors are at 2 p.u., maximum 2.8 p.u. Even higher overvoltage factors of up to 3.5 p.u. can occur when closing a precharged line, which is possible in the case of three-phase auto-reclosing. Since, in the German system, as a rule, single-phase auto-reclosing is carried out, only, or a precharge can be discharged, by example by inductive voltage transformers at both ends of the lines during the auto-reclosing time, such high overvoltages do not need to be considered.

If the line is energised at a voltage of 1.05*U_m, both the power-frequency as well as the transient process is more pronounced. Impact on the circuit breaker at the sending and receiving ends of the lines by the transient overvoltages is, however, not to be anticipated, since 420 kV circuit breakers are generally designed for a rated switching impulse withstand voltage of 1050 kV that assumes a switching overvoltage of 2.9 p.u. In the case of 123 kV and 245 kV circuit breakers, these overvoltages are covered by the short-duration power-frequency test voltage. The power-frequency voltage at the receiving end of the line can, however, be greater than the voltage at the sending end (1.05*U_m), as the example in chapter 3.2.1 also shows.

A reduction of the closing overvoltage can be achieved, if the line is energised by means of closing resistors. A further option is controlled switching, also known as synchronous switching. In this case, the breaker is tripped in such a way that it closes at voltage zero.

5.4.3. Interruption of small inductive currents

The term "small inductive currents" refers to rated currents of reactors for reactive power compensation, that can equal up to 200 A in the transmission system. In addition to this, de-energising of unloaded transformers must be considered. Figure 26 shows the single-phase equivalent circuit for interrupting small inductive currents.

With the corresponding switching processes, the phenomenon of current chopping and the resulting overvoltages, as well as the transient recovery voltage and possible re-ignitions, are important [21], [29].

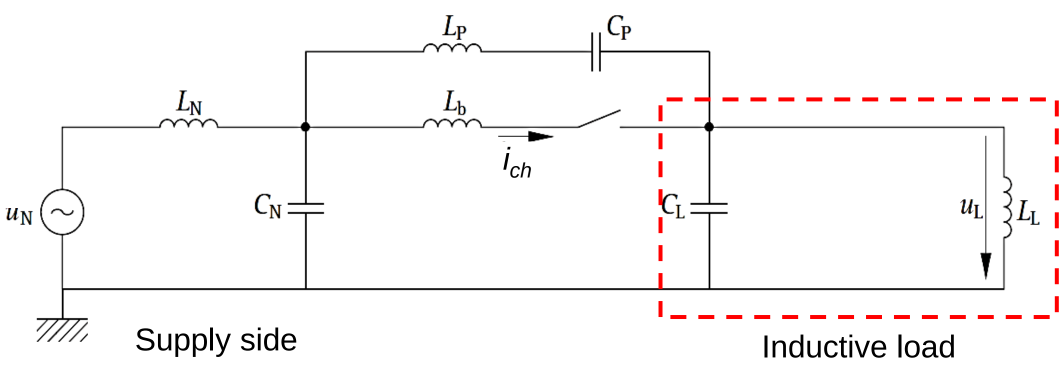


Figure 26: Single-phase equivalent circuit for switching of small inductive currents (according to [21])

u_N	**Line-to earth voltage of the supply network**
L_N, C_N	**Short-circuit inductance and capacitance of the supply network**
L_L, C_L	**Inductance and capacitance of the inductive load**
L_P, C_P	**Switching path inductance and capacitance**
L_b	**Leakage inductance between supply side and breaker**

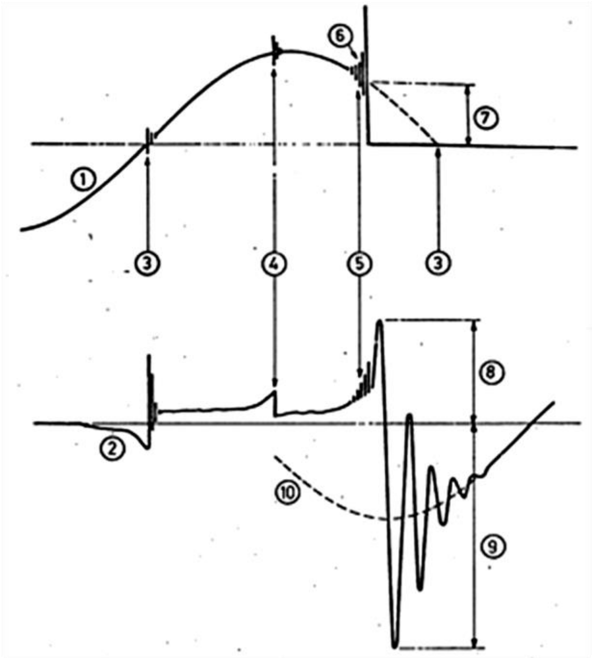
5.4.3.1. Current chopping

In the case of small currents, the electric arc between the contacts becomes unstable. The arc current starts to oscillate and tends to current chopping before the natural current zero. Figure 27 gives an example of the current and voltage characteristic in the case of current chopping.

For the chopping current i_{ch} the following correlation is given in the literature, e. g. [21], [29]:

$$i_{ch} = \lambda \cdot \sqrt{C_t} \qquad (5.4.2)$$

with i_{ch} in A, C_t in F and the dimensionless chopping number λ.



1 **Current passing the cb**
2 **Voltage across the cb**
3 **Natural current zero**
4 **Arc instability**
5 **Arc instability and**
6 **current chopping**
7 **Current characteristic at current chopping**
8 **Arc voltage with extinguishing peak**
9 **Maximum of recovery voltage**
10 **Supply voltage**

Figure 27: Current and voltage characteristic in case of current chopping (according to [29])

C_t is the resulting capacitance parallel to the switching gap consisting of the system capacitance C_N, load capacitance C_L and switching gap capacitance C_P. Since the system capacitance C_N normally is much greater than the load capacitance C_L and the switching gap capacitance C_P is considerably smaller than the load capacitance C_L, is $C_t \approx C_L$.

If the breaker has *n* switching units per pole, the chopping current is

$$i_{ch} = \lambda \cdot \sqrt{n \cdot C_t} \qquad (5.4.3)$$

Indeed, the chopping number λ is dependent on the relevant breaker design, but can also be used for the relative comparison. Typical values for SF_6 circuit breakers are $\lambda = (4…17)*10^4$. Assuming a breaker with two interrupter units and one parallel capacity of $C_t = 4$ nF, as can be found for extra-high voltage transformers, for example, the chopping current is between 4…17 A. This value would not change with a voltage of 1.05*U_m, as can be seen from the comparison (5.4.3).

5.4.3.2. Overvoltages

If current chopping happens, the inductive load is separated from the network and the energy $^1/_2\, L_L i_{ch}^2$ remains stored in the load inductance L_L With regard to the capacitance C_L the voltage would be u_{NC} at the instant of current chopping. The energy stored in the capacity is $^1/_2\, C_L u_{NC}^2$. Thus, at the instant of current chopping the energy stored on the load side results to

$$W_{ch} = {}^1/_2\, L_L i_{ch}^2 + {}^1/_2\, C_L u_{NC}^2 \qquad (5.4.4)$$

If, following an interruption, the total energy is re-loaded as purely electrical, the following applies

$$W_{ch} = {}^1/_2\, C_L u_{max}^2 \qquad (5.4.5)$$

The peak value of the voltage at the terminals for the inductive loads results

$$u_{\max} = \sqrt{u_{\mathrm{NC}}^2 + i_{\mathrm{ch}}^2 \, {}^{L_\mathrm{L}}/_{C_\mathrm{L}}} \qquad (5.4.6)$$

Shortly before the natural zero of the load current, as it would be the case with the interruption of inductive load currents > 100…150 A, u_{NC} is approximately the same as the peak value of the supply voltage $\hat{u}_N$. For the chopping overvoltage u_{max} then it follows

$$u_{\max} \approx \sqrt{\hat{u}_{\mathrm{N}}^2 + i_{\mathrm{ch}}^2 \cdot {}^{L_\mathrm{L}}/_{C_\mathrm{L}}} \qquad (5.4.7)$$

In the case of a 5% higher supply side voltage of 1.05*U_m, the load-side overvoltage would be 5% higher at maximum, since only the first term on the root is dependent of the supply-side voltage.

In the case of current chopping at the peak value results in $u_{NC} = 0$, and u_{max} results in

$$u_{\max} \approx i_{\mathrm{ch}} \cdot \sqrt{{}^{L_\mathrm{L}}/_{C_\mathrm{L}}} \qquad (5.4.8)$$

As in this case no electrical energy is stored in the load capacitance C_L, the chopping overvoltage u_{max} is not dependent on the supply side voltage u_N, but only on the chopping current i_{ch}.

With interrupting of the magnetising current of transformers, current chopping has also to be taken into account [21]. In the literature for this case, an overvoltage factor k_a is given for cold-rolled metal as a function of the "chop parameter" $\left(\frac{C_\mathrm{t} \cdot U_\mathrm{r}^2}{\alpha\, P_\mathrm{r}}\right)$. C_t is the parallel capacitance (consisting of the input capacitance of the transformer and the supply line capacities) in F, U_r the rated voltage in V, P_r the rated power in W and α the ratio of the magnetising current to the rated current [29]. The function

$$k_\mathrm{a} = f\left(\frac{C_\mathrm{t} \cdot U_\mathrm{r}^2}{\alpha\, P_\mathrm{r}}\right) \qquad (5.4.9)$$

is shown in Figure 28.

In Figure 28, the overvoltage factor k_a is plotted as an example with the technical data of a 400/120 kV/250 MVA transformer and a 115/10.5kV/30 MVA transformer for the primary rated voltage and for 1.05* U_m (U_m = 420 kV and/or 123 kV).

Figure 28 shows that the overvoltage factor is low and only marginally affected by the higher voltage.

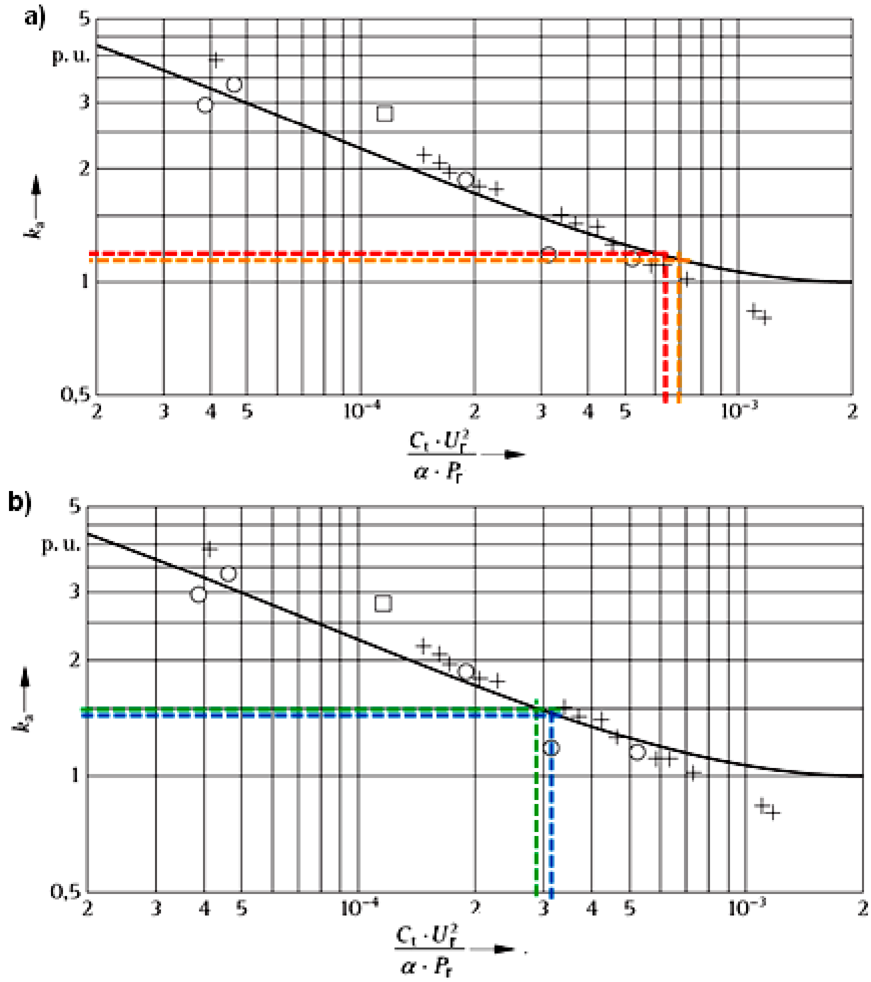


Figure 28: Overvoltage factor at interruption of magnetizing currents of Transformers (according to [21])

a) **Example 400/120 kV transformer, 250 MVA; C_t = 4.28 nF; α = 0.043%**

b) **Example 115/10.5 kV transformer, 30 MVA; C_t = 2.88 nF; α = 0.044%**

5.4.3.3. Transient recovery voltage

After interrupting the current, the switching gap is stressed by the transient recovery voltage, i.e. the difference between the power-frequency voltage of the supply side and the high frequent voltage of the load side (Figure 29).

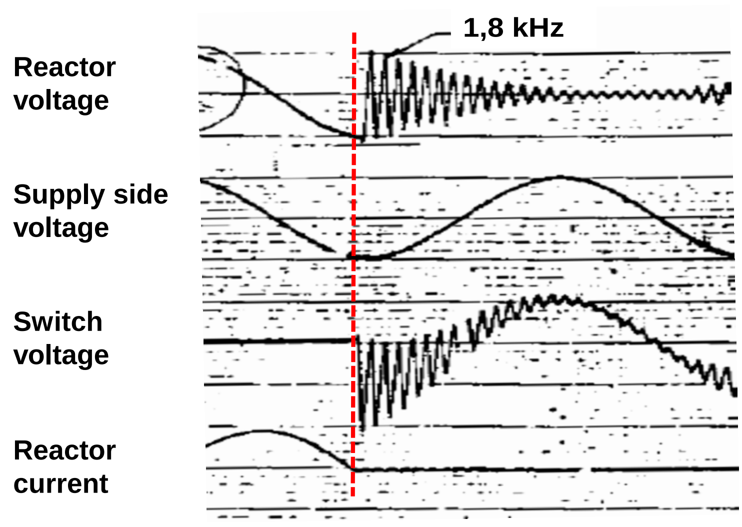


Figure 29: Transient recovery voltage when switching reactors (according to [29])

If the reactor is being operated at a voltage of 1.05*U_m before being switched off, a transient recovery voltage that is increased by 5% occurs. Since the breaker is able to interrupt the reactor current with a short arcing time, but the dielectric strength of the switching gap is insufficient, in the case of small inductive current switching, re-ignitions have generally to be taken into account. Due to the greater steepness and amplitude of the transient recovery voltage, increased re-ignitions can occur with operation at 1.05*U_m. However, in the case of increased transient recovery voltage, a breaker failure is not to be anticipated. The transient recovery voltage in the inductive switching duty according to [30] is less critical than switching the 10% short-circuit current according to [20]. In the current range in question, the dielectric performance of the switching gap has priority. Figure 30 shows the envelope of the transient voltage for the corresponding switching duties.

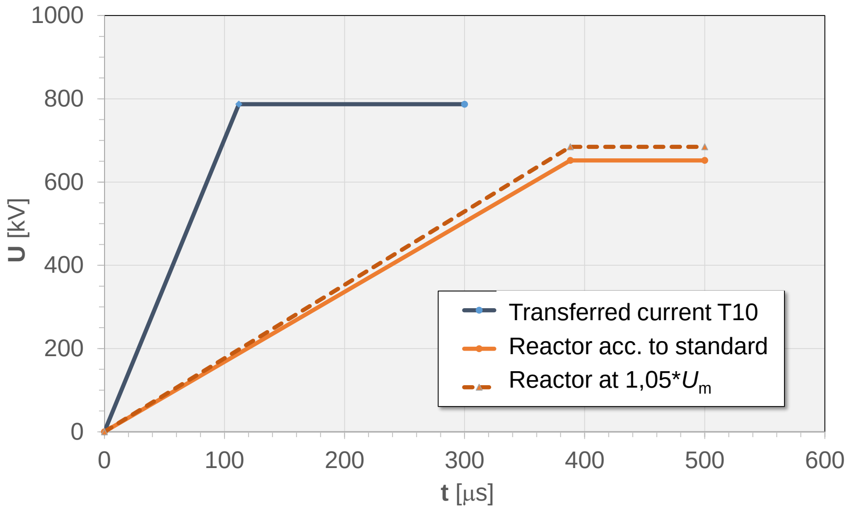


Figure 30: Transient recovery voltage when switching transferred current T10 and reactor switching at U_m and 1,05*U_m; comparison of the envelopes

5.4.3.4. Re-ignitions

As already described above, greater occurrence of re-ignitions has to be taken into account with operation at 1.05*U_m. Re-ignitions are associated with high frequency transients that can heavily stress the insulation of the equipment connected. Therefore, particularly in the case of operation of reactors with 1.05*U_m, it is to be recommended that re-ignitions should be avoided, whereby an arcing time of at least 5 ms should be aimed at by controlled switching. When setting the instant of tripping command, it should be checked, if the targeted arcing time, including scattering, guarantees an interruption without re-ignition even in the case of a 5% higher transient recovery voltage.

5.4.4. Disconnectors

As safety elements, disconnectors must guarantee a higher level of dielectric strength in the switching gap than to earth. In the case of 123 kV and 245 kV equipment, this is proven by a test with power frequency voltage and the lightning impulse voltage [28], [31]. Thus, there is no direct correlation to the operating voltage. In the case of 420 kV equipment, beside these tests, an additional test with the switching impulse voltage is carried out, whereby one pole is on the operating voltage 420 kV*√2/√3 = 343 kV. The other pole is subjected to switching impulse voltage of 900 kV corresponding to 2.6 p.u. Since this value, as already described in chapter 5.2, is clearly higher than the switching overvoltages of max. 2.3 p.u. to be anticipated in the German 380 kV network, the strength of the switching gap should not inadmissibly be affected by an increased operating voltage of 1.05*U_m even with 420 kV disconnectors.

5.4.4.1. GIS disconnectors

When switching small capacitive currents with GIS disconnectors, transients with overvoltages in the frequency range of several MHz up to some 10 MHz with superimposed travelling waves (very fast transient overvoltages / VFTO) occur [32]. These transients (VFTO) are generated by the steep voltage collapse in SF_6 in the case of a re-ignition. Particularly critical are such processes, which present both, a high overvoltage amplitude as well as a high frequency in the transient.

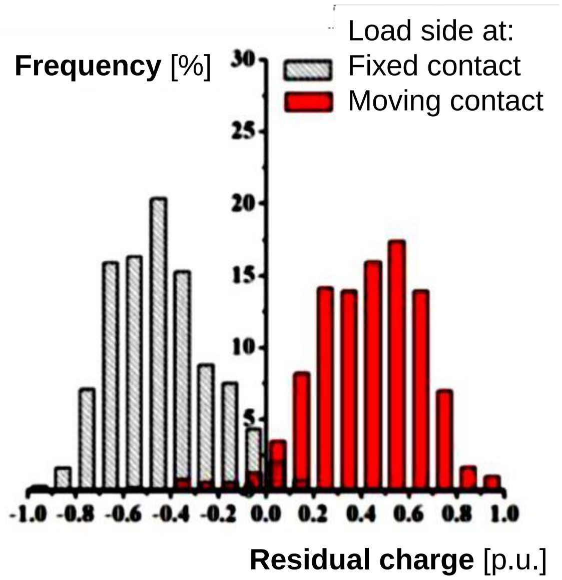


Figure 31Distribution of residual charge, if load side connected either to fixed or to moving contact [35]

Those phenomena occur when switching short bus ducts of 3…7 m in lengths [33], [34]. Here, overvoltages of a maximum of 1.5 p.u. are to be expected, if there is no precharge on the load side, that means, if the re-ignition is connected with a voltage step of ΔU = 1.0 p.u. Since, due to a preceding opening operation, a precharge of -1.0 p.u. cannot be excluded (Figure 31) and thus a voltage step of ΔU = 2.0 p.u. at a re-ignition can occur, leading to maximum overvoltages of about 2 p.u.. This value U_{hf} can be calculated from the maximum value without residual charge according to the following equation [34]:

$$U_{hf}\,(\Delta U = 2.0\text{ p.u.}) = 2\cdot[U_{hf}\,(\Delta U = 1.0\text{ p.u.}) - 1] + 1 \qquad \text{in p.u.} \qquad (5.4.10)$$

In the case of an inappropriate design of the disconnector, an earth fault could be caused by these events, if the electric arc between the switching contacts are able to stray to the earthed enclosure (Figure 32).

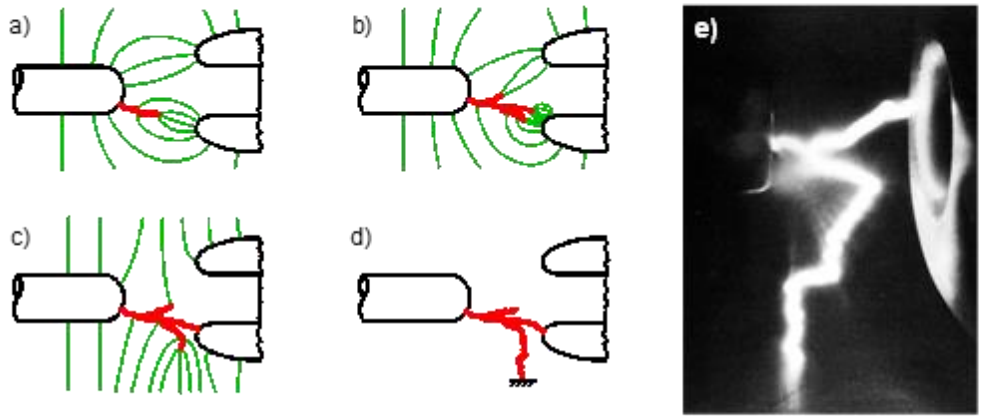


Figure 32: Leader discharge development between the switching contacts and flashover to the earthed enclosure (according to [32]

However, such a fault is not to be anticipated even with an operating voltage of 1.05*U_m, if the GIS disconnector has been tested according to VDE 0671-102 Appendix F [28]. This test is carried out with (1.1/√3)-fold rated voltage on the supply side and a corresponding DC voltage as precharge on the load side.

5.4.4.2. Outdoor disconnectors

In the case of switching outdoor disconnectors, numerous continuous re-ignitions and re-strikes occur, similar to the switching of GIS disconnectors. Depending on the switching speed and the current to be switched, the switching process can last 1…2 seconds. If such a switching operation is carried out at an operating voltage of 1.05*U_m, a slightly longer switching duration is to be anticipated, but this will still be in the range of the statistical scatter.

5.5. Transformers

Operation with 1.05*U_m has an impact on the magnetic and dielectric stress of the transformer. With regard to the magnetic stress, depending on the tapping position of the on-load tap changer (OLTC), overexcitation can occur. In the following, additional warming and increased audible noise can occur. In VDE 0523-76-1 [36] it is specified that it must be possible for a transformer to be run without damage even in continuous operation with full load at an overexcitation of 105% and at no load at an overexcitation of 110% of the rated voltage. The prerequisite given in [36] “within the prescribed values of U_m for the transformer winding” should initially be ignored in the following, since the overexcitation is being considered in short-duration operation. In the case of a K-fold current value, the overexcitation must be limited with a rated frequency according to (5.5.1)

$$U/U_{\mathrm{r}} \cdot 100 \leq 110 - 5 \cdot K\ (\%) \qquad (5.5.1)$$

However, the rated voltage U_r for transformers generally does not correspond with the highest continuous permissible voltage for equipment U_m. Therefore, the magnetic stress of a transformer at 1.05*U_m must be evaluated with relation to the primary rated voltage U_{r1}.

The primary rated voltage U_{r1} is often selected in such a way that the mid-tap position is U = U_m, taking into account a permissible overexcitation of 105% at full load. Examples for the rating of network transformers can be found in Table 4.

Table 4: Examples of transformer ratings

U_m	U_{r1}	U_{r2}	U_{r3}
420 kV	400 kV ±16 % in ±13 positions	120 kV	30 / 33 kV
123 kV	115 kV ±16 % in ±9 positions	10,5 / 11 kV	

Insofar as the transformers are designed as given in the table, no undue overexcitation occurs in continuous operation with operating voltages of 1.05*U_m in the mid-tap position of the OLTC. If loaded, undue overexcitation in continuous operation can occur depending on the load current. However, because this is of a temporary nature according to the assumption in chapter 4, no undue overheating is to be expected. However, in any case higher audible noise levels have to be anticipated in comparison with the rated voltage.

In the case of deviations from the rated frequency, the factor f / f_r (f = current network frequency, f_r = rated frequency) must be taken into account. In the case of permissible underfrequencies according to [37] down to 48.5 Hz (48.5 Hz ≤ f < 50 Hz) for 30 min, a short duration of overexcitation cannot be excluded. This means that higher noise levels can occur, although any undue heating is not to be expected due to the short duration.

With regard to the dielectric stress, it can be stated that this is covered by the voltage tests according to the standard [37]. However, it must be clarified whether a reduction in the service life due to the ageing effects caused by the frequency and duration of the stress is to be expected. These considerations follow in chapter 6.

When energizing a transformer, depending on the instant of closing, an inrush current is created that can be many times higher than the operating current, if the saturation characteristic of the transformer is taken into account [38].

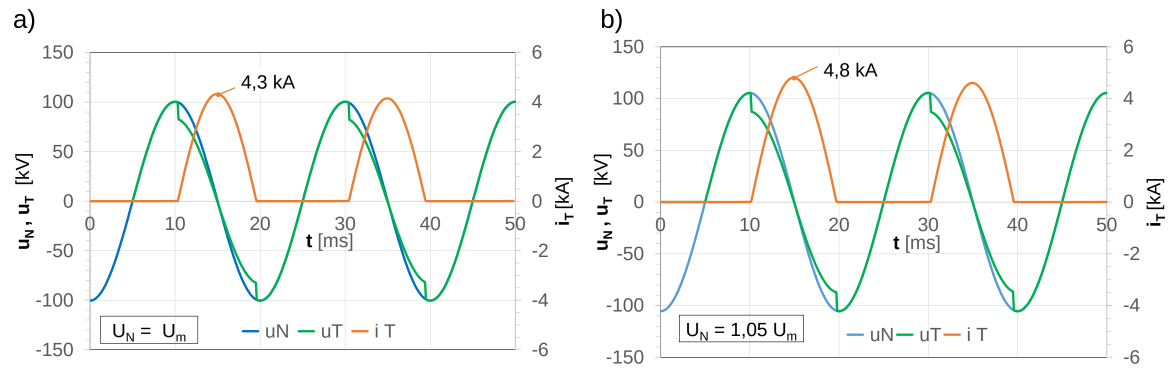


Figure 33: Inrush current of an unloaded transformer without system capacitance; closing instant: voltage zero (according to [38])

a) closing at U_m **b) closing at 1.05*U_m**

In the case of a rating close to the knee-point of the magnetising characteristic, when closing at voltage zero, the making current will very quickly reach saturation so that a large making current will flow. As an example, a transformer is considered with a magnetising characteristic in which the knee-point is at the 1.1-fold of the rated value [38]. The making current amounts to 4.3 kA (Figure 33 a).

In the case of closing at an operating voltage of 1.05*U_m , the transformer is driven even further into saturation, so that the making current rises even further. As Figure 33 b shows, the peak value of the making current has risen to 4.8 kA, i.e. by more than 10%. As a result, the transformer windings will be stressed with magnetically induced forces that are greater than the forces derived from the rated values. However, these should not result in an overstress, since the short-circuit stress is decisive for the magnetic-mechanical design of the winding. Therefore, it is to be assumed that transformers deemed to be short-circuit-proof will also cope with closing at operating voltages of 1.05*U_m.

However, it must be checked, how the protective devices react to the higher amplitudes of the inrush current. As a rule, inrush currents are suppressed by the protective devices.

Generally, high making currents when energizing transformers can be avoided by controlled switching. If these measures are intended to be employed, the circuit breaker in question has to be equipped with a corresponding device.

5.6. Reactors

Similar to transformers at reactors also the rated voltage U_r can deviate from the highest continuous permissible voltage for equipment U_m or the maximum operating voltage U_{max} respectively. Therefore, also with reactors, the magnetic and dielectric stress must be considered when operating with 1.05*U_m in relation to the rated voltage U_r . A typical example for the rating of a shunt reactor can be seen in Table 5. At 1.05*U_m a greater input current compared with the rated voltage U_r flows and results in a higher power loss.

Table 5: Example of shunt reactor ratings

U_m	U_r	U_{max}
420 kV	400 kV	420 kV

The power loss is the result of the copper and magnetising losses. Since, as a rule, air-gap reactors are applied, there will still be a linear behaviour also at 1.05*U_m. Thus, the power loss would rise more or less quadratically. In the present case, the power loss at 1.05*U_m will be 10% higher than at the maximum operating voltage U_{max}. However, this higher power loss will only last for a maximum of 30 minutes and, as a rule, not occur at the maximum ambient temperature of 40°C assumed for the rating, so that no undue overheating is to be anticipated. In the case of reduced cooling power, undue temperature rise cannot be excluded. However, in any case there will be increased audible noise, since the noise is defined for the rated voltage and rated current. An increase due to the higher magnetising current as well as the higher load current must be anticipated.

5.7. **Instrument transformers** (Current and voltage transformers)

5.7.1. Accuracy

Instrument transformers have the task of transmitting the actual measured value correctly in amplitude and phase angle. The permitted deviation with the accuracy given is specified in VDE 0414-9-2 and VDE 0414-9-3 [39] respectively. According to this, for current transformer the ratio error and the phase displacement is defined at 5%, 20%, 100% and 120% of the rated current, and for voltage transformers, for each voltage between 80% and 120% of the rated voltage.

Thus, even with operating voltages of 1.05*U_m no restrictions in the accuracy of the voltage transformers are given, likewise of the current transformers even with the assumption of a 5% higher operating current.

5.7.2. Ferro-resonances

In specific substation and network configurations with inductive voltage transformers, ferro-resonances occur which are excited by a transient event and are the result of an interaction of the non-linear main inductance of the voltage transformer L_H and the substation capacitances to earth C_2. Depending on the losses in this series resonant circuit, stationary or damped ferro-resonances occur. Stationary ferro-resonances can cause thermal and dielectric overstressing of the equipment.

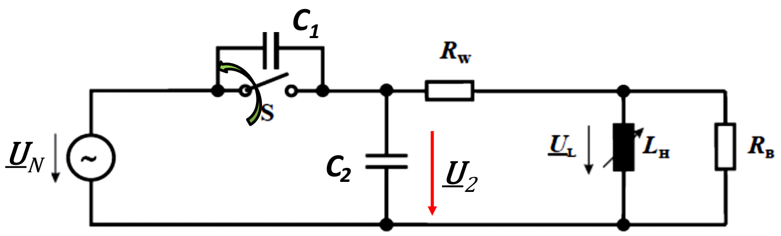


Figure 34: Typical substation configuration for occurrence of ferro-resonances

A typical substation configuration, in which even stationary ferro-resonances are often created, is shown in Figure 34 [40]. By switching off the switch S, the capacitance C_2 discharges via the voltage transformer and, as a result, depending on the circuit parameters (magnetizing characteristic, capacitances), voltage U_N and switching instant, stationary or damped ferro-resonances are excited. Stationary ferro-resonances can occur, if the series resonant circuit is constantly supplied with energy via the grading capacitance C_1 of the circuit breaker S, that compensates the ohmic, the eddy current and hysteresis losses. For mitigation, the use of inductive voltage transformers with a gapped core has proved to be effective.

Since, as well as the losses, the further circuit parameters have a considerable impact on the ferro-resonance performance, when changing these parameters, also when operating the arrangement with a voltage of 1.05*U_m, it must be checked, whether the decaying oscillation behaviour is still given. Such a test can be carried out by means of tests or simulations, insofar as an appropriate simulation model is available [41].

Figure 35 shows the result of the experimental verification of a 420 kV gapped core voltage transformer at U_m, 1.05*U_m and 1.1*U_m by a transmission system operator, not named more closely here. It can be seen that, in the present case, the design measure adopted is suitable in the case of voltages of 1.05*U_m and even at 1.1*U_m, to avoid stationary ferro-resonances.

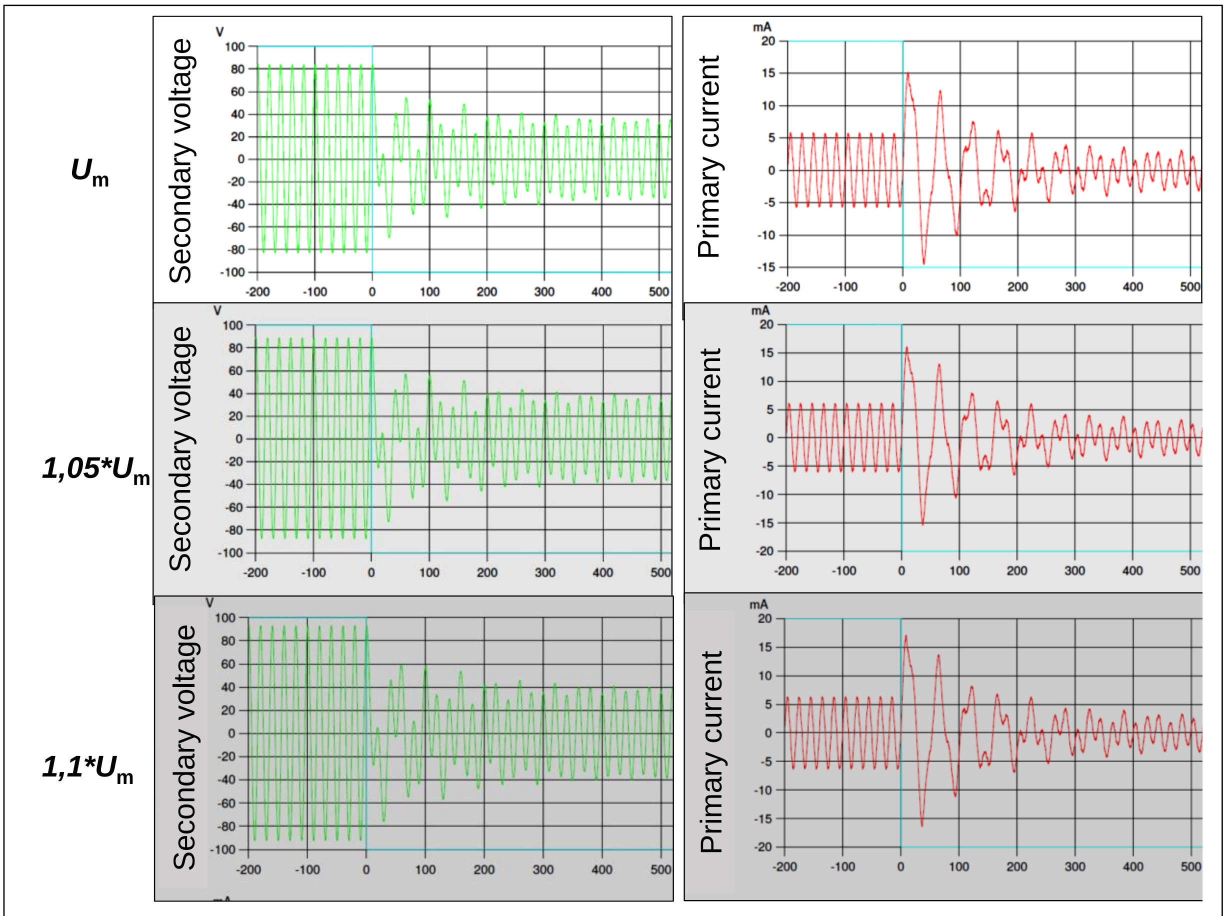


Figure 35: Ferro-resonance behaviour of a 420 kV gapped core voltage transformer at U_m, 1.05*U_m and 1.1*U_m; verification test by a transmission system operator, not named more closely here

The circuit parameters correspond with those of a typical outdoor feeder with a circuit breaker grading capacitance C_1 = 250 pF and input capacitance C_2 of a SF_6 insulated combined instrument transformer of ~250 pF. In the case of other circuit parameters C_1 and C_2, a separate test of the oscillation characteristic is required even with the same magnetic design of the voltage transformer. Thus, for example, in gas-insulated, metal-enclosed switchgear, the grading capacitance C_1 is considerably larger due to the metal enclosure and the capacitance C_2 considerably smaller, since beside the input capacitance of the voltage transformer, there is an earth capacitance of a few 10 pF, only (Figure 36).

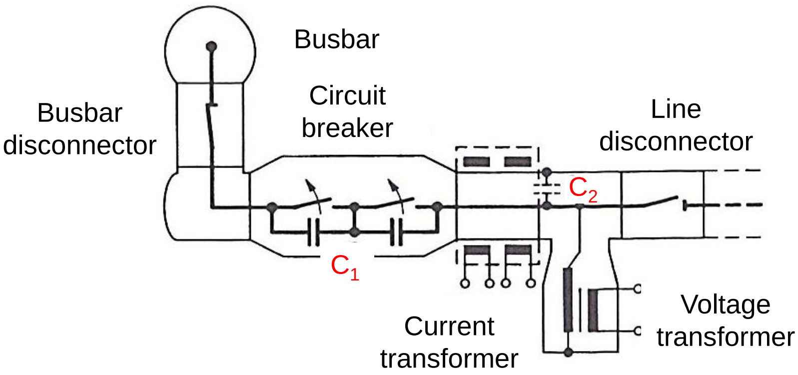


Figure 36: GIS arrangement according to Figure 34 tending to ferro-resonances

5.8. Surge arresters

For the rating of surge arresters temporary overvoltages are taken into account by the corresponding choice of the maximum permissible continuous voltage, as well as the rated voltage, i.e. the overvoltage permissible for a duration of 10 s [42][43]. In this way, a (thermal) overloading can be avoided.

In Table 6, the standard values for continuous voltage and rated voltage in the German systems are illustrated [44], whereby in the 110 kV systems, a distinction is drawn between systems with solidly earthed neutral and resonant earthed neutral. Basically, the characteristic values of surge arresters are presented with relation to the system voltage U_s (U_m is not defined for arresters).

Table 6: Characteristic values of arresters commonly used in German systems

Nominal system voltage (kV)	**System earthing**	**Continuous volotage** (kV)	**Rated voltage** [1)] (kV)		**Operating voltage** $1{,}05 \cdot U_s / \sqrt{3}$ (kV)
110	resonant	123	144		75
110	solidly	75	126		75
220	solidly	160	216		149
380	solidly	260	360		255

[1)] according to. VDE 0675-1, 08-2000: Temporary overvoltages permissible for 10 s

In Table 6, it can be seen that, even with an operating voltage of 1.05*U_m , no thermal overload of the arrester is to be expected. In addition, the fact must also be taken into consideration that in parts of the network, which are operated with a voltage of 1.05*U_m , temporary overvoltages due to earth faults or load shedding occur. In such cases, it is possible that voltages greater than the permitted continuous voltage of the arrester may occur. Based on the voltage time characteristic of a surge arrester, it must then be checked, whether this could lead to an overload of the arrester.

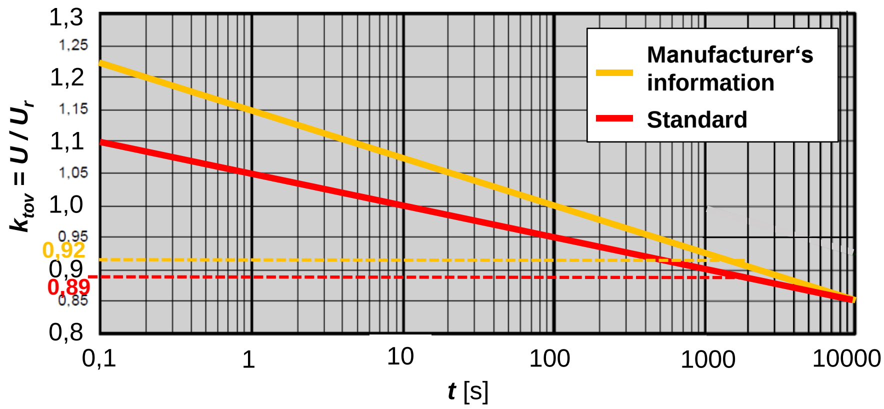


Figure 37: Voltage time characteristic of an arrester (according to [42])

First, the earth fault in a 110 kV resonant earthed systems shall be considered. For the assumed duration of 30 min with the increased operating voltage of 1.05*U_m , an earth fault with a voltage at the surge arrester of 1.05*123 kV = 129 kV is generated. The relevant voltage time characteristic of the surge arrester for this case can be seen in Figure 37. First, the characteristic according to the standard is illustrated, in which the rated voltage is based on a duration of 10 s. The factor k_{tov} in this case is U/U_r = 129 kV/144 kV = 0.89. Then, a characteristic is shown as given by many manufacturers, in which the rated voltage is based on a duration of 100 s. In this case k_{tov} results to k_{tov} = 0.92. The characteristic curves apply for the case that the surge arrester is pre-loaded with the full nominal energy and correspondingly heated up.

From Figure 37 it can be seen that the permissible voltage is slightly exceeded, if the standard characteristic curve is assumed (1.05*U_m = 129 kV > 0.89*144 kV = 128.2 kV). This means that, in the case of pre-loading up to the amount of the nominal energy, the surge arrester could become thermally unstable. However, if the manufacturer's specifications are assumed, even this operating condition would be managed without any problems (1.05*U_m = 129 kV < 0.92*144 kV = 132.5 kV).

In the following, the single-phase-to-earth fault in the solidly earthed system will be considered. The earth fault factor is assumed to be $\delta \leq 1.4$ and the fault duration ≤ 1s [45]. The factor k_{tov} for the single-phase-to-earth fault can be seen in Table 7.

Since for all voltage levels the factor k_{tov}<1.05 applies (permissible factor according to voltage

Table 7: Factor k_{tov} for phase-to-earth fault in solidly earthed systems at operating voltage of 1.05*U_m

U_m (kV)	δ*1,05*U_m/√3 (kV)	U_r (kV)	k_{tov}
123	104	126	0,83
245	208	216	0,96
420	356	360	0,99

time characteristic, Figure 37, for the duration of 1 s), in the case of the single-phase-to-earth fault with a fault duration ≤1 s and even with an operating voltage of 1.05*U_m, no thermal overload of the surge arrester is to be anticipated.

Finally, the temporary overvoltages in the case of load shedding are considered. With a load shedding factor δ_L ≤1.5 [45], for an operating voltage of 1.05*U_m , a factor k_{tov} is calculated according to Table 8. Since the voltage is generally driven back down to the generator voltage by the voltage regulator after approx. 1 second, even in the case of load shedding at an increased voltage of 1.05* U_m , no thermal overload of the surge arrester is to be anticipated.

Table 8: Factor k_{tov} for load-shedding i at operating voltage of 1.05*U_m

U_m (kV)	δ_L*1,05*U_m/√3 (kV)	U_r (kV)	k_{tov}
123	112	126	0,89
245	223	216	1,03
420	382	360	1,06

5.9. Cable systems

The following considerations are based on the standard cable systems nowadays with cables with extruded insulation and their accessories. They can analogously also be applied for cable systems with other kinds of insulation.

The test voltages of cables with extruded insulation and their accessories are given in VDE 0276-632 and VDE 0276-2067 respectively, Table 4 [46] [47]. According to this, within the framework of the type tests for cable systems in 110 kV, 220 kV and 380 kV systems, voltage tests with power-frequency voltage according to Table 9 must be carried out.

Table 9: Type tests for XLPE cables with power-frequency voltage (according to [46], [47])

Nominal voltage U_n (kV)	Highest duration permissible voltage U_m (kV)	Alternating current test (kV)	Test duration (min)		Operating voltage	
					1.05*U_m / √3 (kV)	1.05*U_m (kV)
110 [1)]	123	160	30		75	129
110	123	160	30		75	
220	245	318	30		149	
380	420	440	60		255	

[1)] Systems with resonant earthed neutral

As can be seen from Table 9, the voltage tests carried out within the framework of the type test lead to clearly higher stresses than the temporary overvoltages assumed here. Restrictions in functionality for cable systems are therefore not to be anticipated from this perspective.

5.10. Summary of assessment

If equipment in the high and extra-high voltage system is operated at voltages higher than the rated voltage, certain restrictions in functionality must be taken into consideration.

Overhead transmission lines

The operation of an overhead transmission line with 1.05*U_m has no impact on the fundamental rating of overhead line clearances. Impact on the corona performance of the conductor and the fittings is not to be anticipated since the conductor field gradient is clearly below the onset field strength and the fittings are tested with 1.1*U_m respectively. The unified specific creepage distance of the insulators is generally be rated in such a way that it satisfies the requirements for medium pollution even at a voltage of 1.05*U_m.

Outdoor substations

The minimum clearances for outdoor substations in the 110 kV and 220 kV system are determined by the rated lightning impulse withstand voltage and in the 380 kV system 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 corresponding to an assumed switching overvoltage of 2.9 p.u. is set. However, such high switching overvoltages cannot occur in the German 380 kV system. Therefore, the ratings of the minimum clearances of active parts in outdoor substations is sufficiently safe, even in the case of loads of 1.05*U_m.

GIS substations

For the design of gas-insulated switchgear (GIS), the rated lightning withstand voltage is decisive. This is derived from external overvoltages and is not affected by the operating voltage. In addition, the rated lightning impulse withstand voltage should also demonstrate sufficient dielectric strength against overvoltages caused by switching of disconnectors. Since the very fast front overvoltages are smaller than the coordination lightning impulse withstand voltage, they are covered by the rated lightning impulse withstand voltage. If the very fast front overvoltages now occur during operation with 1.05*U_m, the margin to the lightning impulse withstand voltage indeed becomes smaller, but in the case of sound insulating conditions, this effect can be disregarded.

Circuit breakers

If short-circuit currents at a network node in the range of the rated short-circuit current are to be anticipated during operation with 1.05*U_m, the grid conditions in the event of a short circuit must be tested, in particular the ratio of the zero sequence reactance X_0 to the positive sequence reactance X_1. If the ratio X_0/X_1 is < 2.5, the first-pole-to-clear factor at three-phase short circuits in solidly earthed systems is k_{pp} < 1.3 and thus the recovery voltage is smaller than that tested according to the standard. In such cases, it is to be assumed that the breaker will cope even with a voltage of 1.05*U_m in this short circuit scenario. Equally, the short line fault should be coped with, since this switching duty is tested in accordance with the standard with a short-circuit current based on the rated short-circuit current, but in practice it is generally caused by a single-phase-to-earth short-circuit current amounting to 85…90% of the three-phase short-circuit current. Thus the initial steepness, critical for this switching duty, is smaller as well.

Switching of transferred short-circuit currents due to faults close to the transformer, e.g. (T10) should also be coped with by 1.05*U_m, insofar as a transformer neutral is earthed. In this case, it is possible to assume a first-pole-to-clear factor k_{pp} = 1.3, if three-phase faults free of earth are excluded. In this case, an amplitude of the transient recovery voltage of 1.05*87% of the standard value can be assumed. If, for reasons of network engineering, the earthing of the transformer neutral is not possible, it must be clarified, whether the breaker applied, taking into account the natural frequency of the transformer, will cope with the higher transient voltage (amplitude and steepness).

In the case of switching off non-compensated lines at operating voltages of 1.05*U_m, re-ignitions cannot be excluded. In particular if the test duty was carried with k_c =1.2 and 1.3, only. The de-energising of shunt reactor compensated power lines is less critical, because the recovery voltage is lower due to the low frequency oscillation of the line side. If the line is energised at a voltage of 1.05*U_m, both the power-frequency as well as the transient process is more pronounced. However, undue impact on the circuit breaker at the sending and the receiving end of the transmission line by the transient overvoltages is not to be expected, since this is covered by the ratings according to the standard. The power-frequency voltage at the receiving end of the power line can, however, be greater than 1.05*U_m.

When switching small inductive currents, the phenomenon of current chopping and the resulting overvoltages as well as the transient recovery voltage and possible re-ignitions must be considered. Since the current chopping is not dependent on the voltage, the value would not change at an operating voltage of 1.05*U_m. However, the load-side overvoltage can be up to 5% higher. Due to the greater steepness and amplitude of the transient recovery voltage, increased re-ignitions can occur with operation at 1.05*U_m. However, a switching failure is not to be anticipated, since the transient recovery voltage in an inductive switching duty is less critical than with the switching of the 10% rated short-circuit current T10, where the dielectric performance of the switching gap is of priority, too. Re-ignitions can be avoided by controlled switching. When setting the tripping time, it should be checked, whether interruption without re-ignition even in the case of a 5% higher transient voltage is guaranteed.

Disconnectors

The 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 voltage as pre-charge on the load side in accordance with the standard. In the case of outdoor disconnectors, a slightly longer switching time has to be taken into account, but that will be in the range of the statistical scatter.

Transformers

In the case of operating voltages of 1.05*U_m, it is possible that depending on the OLTC setting an undue overexcitation in the continuous operation could be caused. However, because this overexcitation is of short duration, only, no undue overheating is to be expected. However, in any case higher audible noise levels must be anticipated in comparison with the rated voltage. In the case of permissible underfrequencies and durations according to [4], short duration overexcitation that could result in a higher level of audible noise development cannot be ruled out. In the case of energizing at 1.05*U_m, the transformer will be mechanically stressed more strongly due to the higher inrush current. Transformers that are deemed to be short-circuit-proof should also be able to cope with this stress. However, it must be checked how the protection equipment react to the higher amplitudes of the inrush current.

Reactors

The power loss of reactors due to the copper and magnetic losses is higher at operation with 1.05*U_m than with the maximum operating voltage U_{max}. However, since this higher power loss lasts for only 30 minutes at maximum and, as a rule, does not occur at the maximum operating temperature of 40°C assumed for the rating, no undue overheating is to be anticipated. In any case, however, higher audible noise levels occur.

Current and voltage transformers

The accuracy of the current and voltage transformers according to the standard is also given in the case of operating voltages of 1.05*U_m. Ferro-resonances excited by the inductive voltage transformers can be avoided, if gapped core voltage transformers are used. Such voltage transformers are generally without ferro-resonances even at 1.05*U_m. However, the performance with regard to ferro-resonances at voltages $>U_r$ should be checked by experimental investigations or by simulations.

Surge arresters

In the case of the surge arresters commonly applied in the German grid, no thermal overload is to be expected at a voltage of 1.05*U_m. Solely in the resonant earthed 110 kV system arresters could become unstable, if prestressed with the full nominal energy, whereby this case has to be classified as rare. If it were to occur, the thermal performance must be examined more closely, based on the manufacturer's information.

Cable systems

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 stresses than the voltages of 1.05*U_m assumed here. Restrictions in functionality for cable systems are therefore not to be anticipated from this perspective.

6. Impact of voltages > U_m on the long-term and ageing performance depending on the duration and frequency of occurrence

Equipment is fundamentally designed in such a way that it meets the operational requirements according to the type of the equipment over a service life of 30…50 years. In order to guarantee sufficient long-term dielectric strength, the equipment is subjected to a short and/or long-duration power-frequency withstand test. The voltage test level and voltage test duration can be derived from the voltage-time characteristic for the 0.01% breakdown probability of the equipment – service life depending on the voltage applied or V-t characteristic.

The following considerations primarily refer to equipment in the 380 kV system. The findings can also be applied to the equipment in the 110 kV and 220 kV system, since the relation of short-duration power-frequency test voltage to rated voltage for this equipment is generally greater than that for the equipment in the 380 kV system. The results therefore represent a worst-case assessment for the 110 kV and 220 kV equipment.

Based on the analyses of the data of the network operators and the national and European network codes, two scenarios and their impact on the long-term and ageing performance are considered. To begin with, it is assumed that the equipment under consideration is stressed twice a week for a period of 30 min each time with temporary overvoltage of 1.05*U_m. The stress is accumulated over an assumed service life of 40 years (corresponding to 350,400 h and/or 2.1*10^7 min respectively), resulting in a stress duration of 2,080 h and/or 7.3*10^4 min and/or 0.6% of the operating time with increased voltage respectively, and the use of service life is derived from this. Afterwards it is examined, at which stress duration a temporary overvoltage of only 1.025*U_m would result in substantial ageing or reduction in service life respectively.

6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*U_m over a service life of 40 years

6.1.1. Overhead transmission lines

Since, with overhead transmission lines, air is primarily used as the insulating medium and air insulation does not age, service life considerations in the case of overhead lines from dielectric perspectives are not required.

6.1.2. Outdoor substations

In the case of outdoor substations, air is used as insulating medium in the same way as with overhead lines. Therefore, here too, apart from the equipment used, service life considerations do not need to be employed.

The equipment used in outdoor substations have to be considered according to the relevant standards. A possible reduction in service life due to temporary overvoltages have to be examined, taking into account the ratings made there.

6.1.3. Switching device

According to VDE 0671-1 [14] , within the framework of the type and test, switching devices are subjected to a one-minute power-frequency voltage test with 520 kV phase-to-the earth and 610 kV across the open switching device. If a service life of ≥ 40 a is assumed, a lifetime characteristic according to Figure 38 is created. It must be noted that this curve and the curves derived for the other equipment do not represent any threshold values, but are derived from the tests voltages given in the standards.

6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*Um over a service life of 40 years

Figure 38 shows that, with continuous operation at 1.05*U_m, a clear reduction in service life to almost less than half is to be anticipated (from 2*10^7min to (7.1…8.9)*10^6 min). With the assumed accumulated stress shown in scenario 1 of 1.25*10^5 min with 105% voltage, the service life reduction, however, would only be approx. 0.6*10^5 min and would therefore be hardly noticeable.

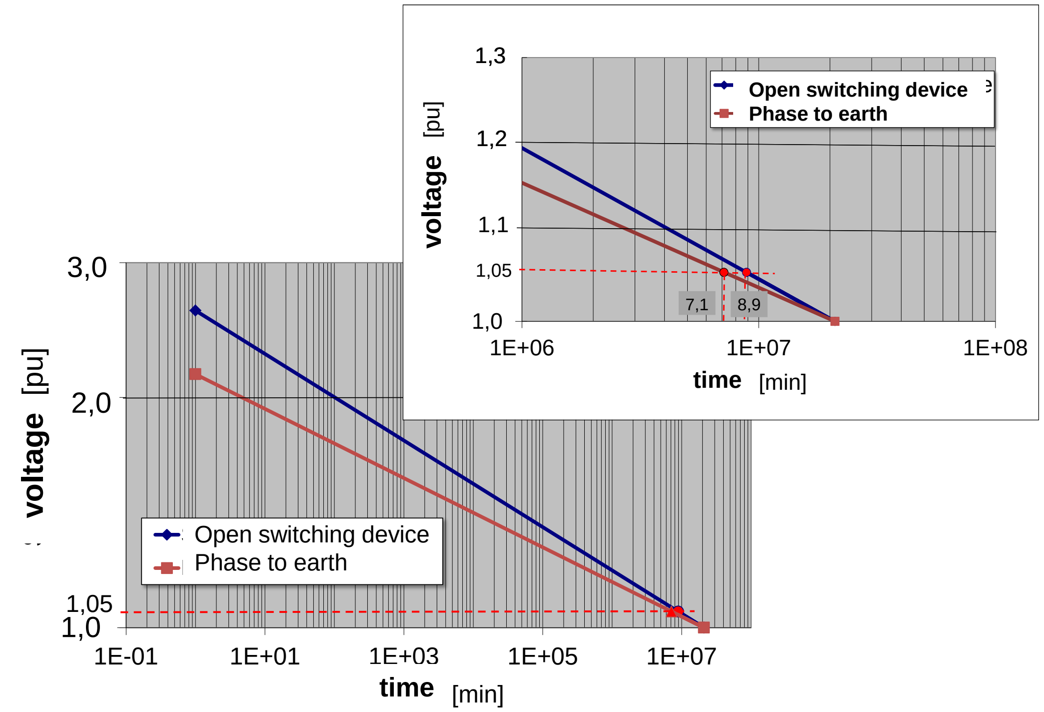


Figure 38: Lifetime characteristic of switching devices derived from the test in VDE 0671-1

6.1.4. GIS switchgear

At gas-insulated switchgear on all assemblies and transport units a one-minute power-frequency test with 650 kV phase to earth is carried out as a routine test. After erection on site, the complete system is tested with 515 kV for one minute. At the same time, a partial discharge measurement at 295 kV corresponding to the 1.2-fold phase-to-earth voltage is carried out. In this case, the partial discharge test voltage is generally applied for at least 15 min. In addition, the partial discharge magnitude is frequently measured at 420 kV, whereby the test voltage is applied for 3 min.

6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*Um over a service life of 40 years

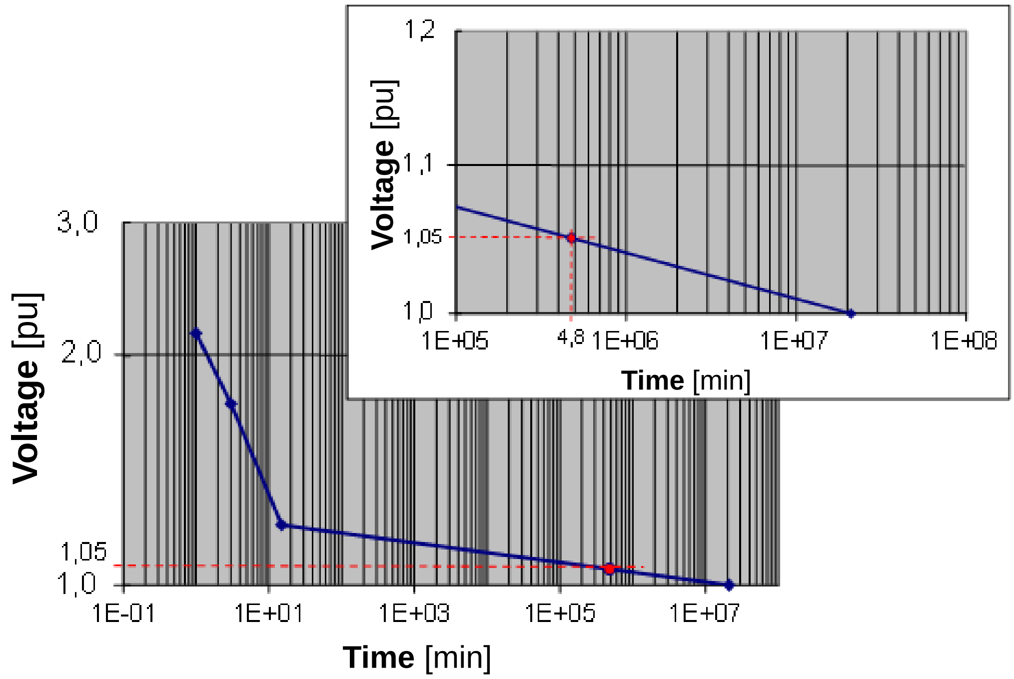


Figure 39: Lifetime characteristic of GIS derived from the tests in VDE 0671-203

The characteristic shown in Figure 39 is derived from the measuring points presented in VDE 0671-203. According to this, a continuous operation with 105% of the rated voltage, would lead to a considerable reduction in service life. However, since the increased voltage only lasts for a duration of 0.6% of the assumed operating time of 40 a, a hardly noticeable service life reduction of approximately a quarter of a year is to be anticipated.

If the ageing performance of the insulation system used in gas-insulated switchgear – SF_6 gas insulation and solid insulation made of epoxy resin – is considered, it must be noted that the SF_6 gas insulation is not subject to ageing.

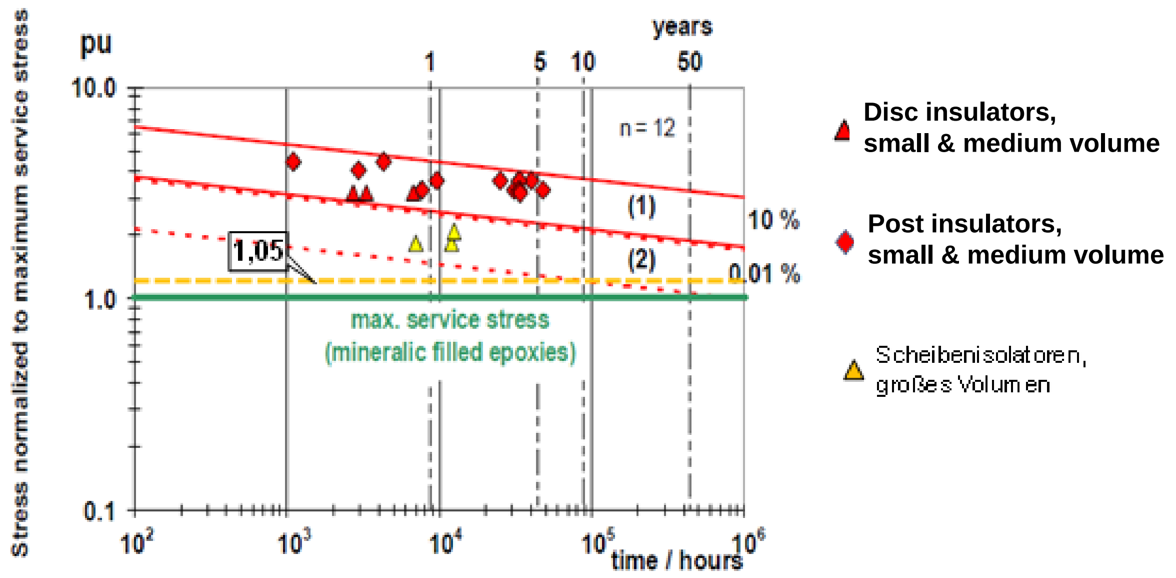


Figure 40: Lifetime characteristic of disc and post insulators made of mineral filled epoxy resin related to the maximum operational stress [17]

The insulation elements made of epoxy resin are designed for a service life of at least 50 years.

Their operating field strength is far below the dielectric breakdown field strength of the insulation material. Figure 40 shows a typical example of lifetime characteristic of support and disc insulators made of mineral filled epoxy resin [17]. Raising the operational stress by 5% would reduce the service life of the insulator to a negligible extent. Short-duration higher operating voltages for a total of <1% of the total operating time have no significant influence on the service life of the insulators overall.

Thus, at gas-insulated switchgear, no premature ageing or reduction of service life is to be anticipated by a short-duration increase in the voltage to 105% of the rated voltage.

6.1.5. Current and voltage transformers

Current and voltage transformers are subjected according to VDE 0414-9-1 to 9-4 [39] within the framework of the routine test to a one-minute power-frequency test with 630 kV. For voltage transformers, a rated voltage factor of 1.9 for a duration of 4 h is often required. If a service life of ≥ 40 a is further on assumed, the characteristic shown in Figure 41 results from the aforementioned test values.

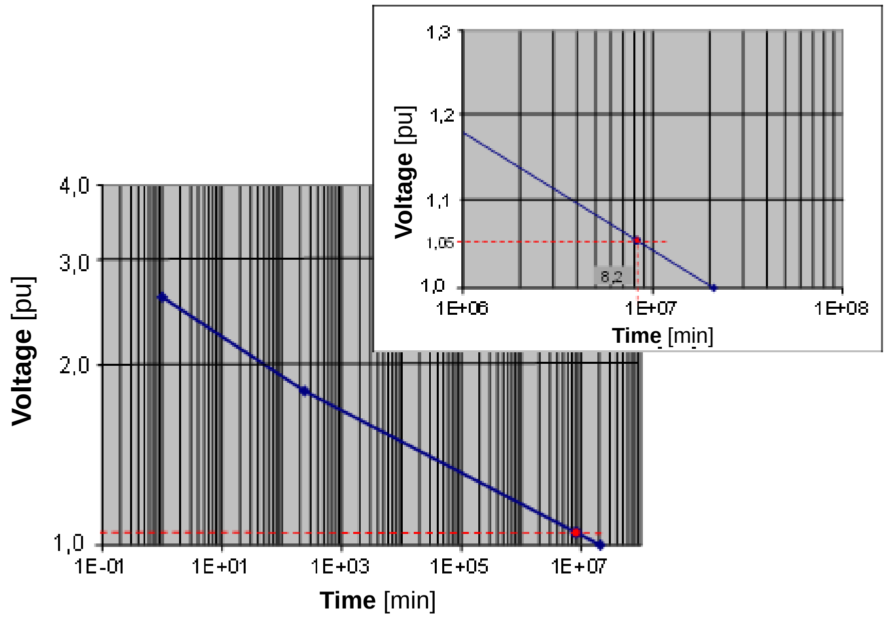


Figure 41: Lifetime characteristic for voltage transformers derived from the tests according to VDE 0414-9-1 to 9-4 [39]

Continuous operation with 105% of the rated voltage would result in a distinct reduction of service life of approximately 50%. However, since the increased voltage only lasts for a duration of 0.6% of the assumed operating time of 40 a, a hardly noticeable service life reduction of approximately 0.1 year is to be anticipated.

6.1.6. Power transformers

According to VDE 0532-76-3 [37], power transformers are subjected as part of the routine test to a one-minute alternating voltage test with a voltage of 630 kV to earth and a one-minute induced voltage test of 1.8*U_r/√3 and/or √3*U_m/√3. Since this test is generally carried out with a test frequency of 150 Hz, the test duration is (120*50 Hz/150 Hz) s = 40 s. The test is combined with a partial discharge measurement at (1.58*U_r)/√3 and/or (1.5*U_m)/√3 respectively, test duration 1 h. For U_r = 400 kV and U_m = 420 kV this results in a short-duration test voltage of 416 kV and/or 420 kV respectively and a long-duration test voltage of 365 kV and/or 364 kV respectively. As a rule, the higher test voltage is used. The characteristic resulting from these data can be seen in Figure 42.

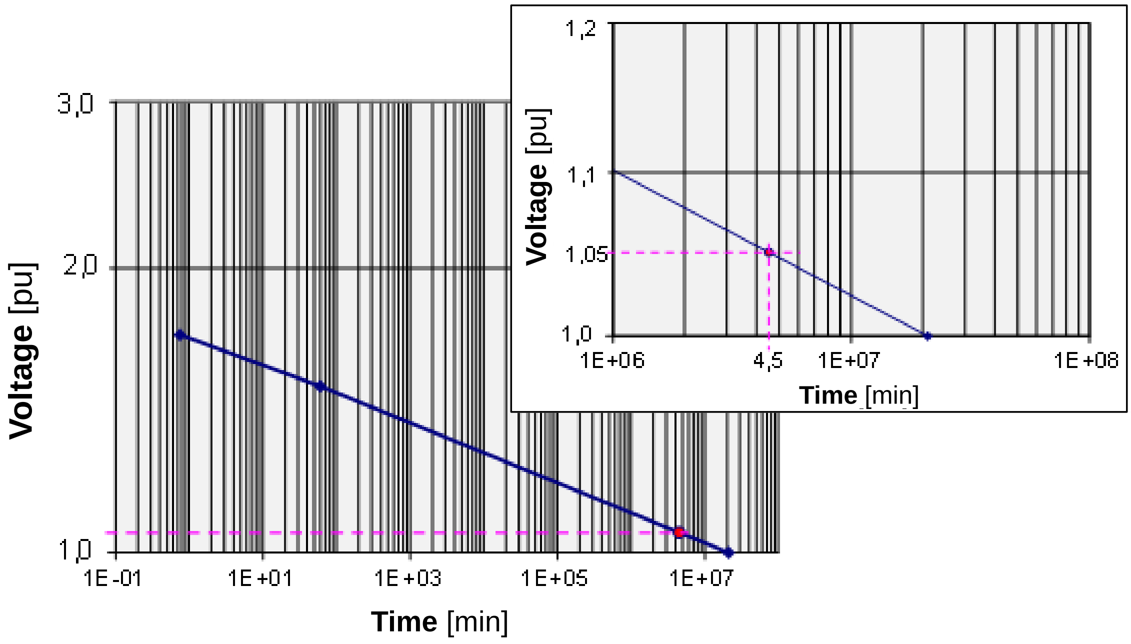


Figure 42: Lifetime characteristic for power transformers derived from the test in VDE 0532 76-3

As can be seen from Figure 42, continuous operation at 105% of the rated voltage would cause a considerable reduction of service life. If it is taken into consideration that the increased voltage only applies for a duration of 0.6% of the assumed operating time of 40 a, this stress results in a service life reduction of approximately 2 months.

In addition, the ageing performance of transformers at increased voltage should be considered based on the lifetime performance of typical insulation arrangements in transformers. The lifetime depending on the applied field strength of E is described by the life formula (6.1) [48].

$$E^N \cdot t = \text{const.} \qquad (6.1)$$

N is the ageing index and t the stress duration. For the typical insulation arrangements for the simulation of the winding insulation, the coil insulation and the oil-barrier insulation with an oil duct, the typical ageing indices given in the literature are shown in Table 10, whereby a differentiation is made between short-duration loads <1 h and long-duration loads ≥1 h [49]. Since the long-duration performance is of interest here, the ageing index for the long-duration stress is used.

Table 10: Ageing indices for different transformer insulation arrangements at long-term stress (according to [49]

		Typical value in the literature	Value used for the evaluation
N1 (<1h)	25…53	36	30
N2 (≥1 h)	60…120	83	60

6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*Um over a service life of 40 years

With an assumed service life of at least 40 a, a characteristic results as shown in Figure 43. From this lifetime characteristic, too, it can be seen that a continuous stress of the transformer increased to 105% would lead to a distinct reduction in the service life to approximately 35%. However, since this increased stress only occurs for 0.6% of the operating time, the additional service life consumption caused by this of less than a quarter of a year is negligible.

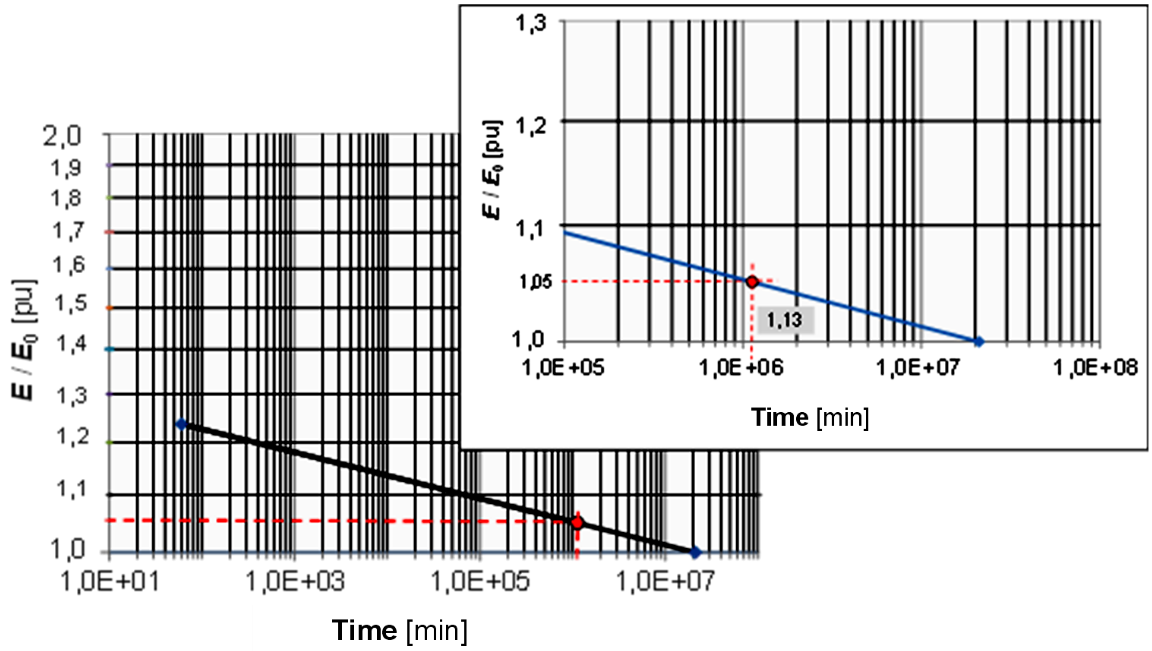


Figure 43: Lifetime characteristic *E/E*$_0$ of a transformer derived from the ageing characteristic of typical transformer insulation arrangements (according to [49])

Beside the ageing performance of the active part, the bushings are also of interest as an important component of the transformer. Figure 44 shows the results of lifetime tests on epoxy resin impregnated paper bushings (RIP bushings), as they are used in gas-insulated switchgear and transformers [50].

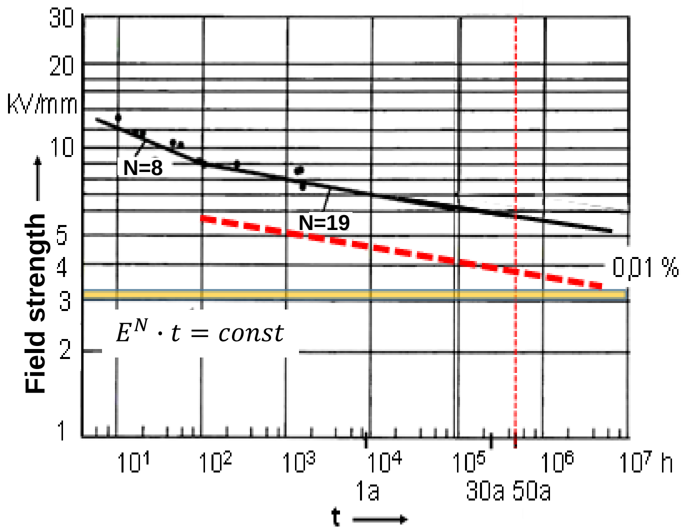


Figure 44: Lifetime characteristic of epoxy resin impregnated paper bushing (RIP bushing) (according to [50])

6.1. Scenario 1: Twice a week for 30 min each time stress with a temporary overvoltage of 1.05*Um over a service life of 40 years

An ageing index of N = 19 is given for the long-duration performance. From the breakdown values illustrated (99.99% breakdown probability), it is possible to derive the withstand values (0.01% breakdown probability) and thus the red dotted line for the lifetime characteristic (with the assumption of $E_{d99.99\%} = E_{d50\%} + 3.7\sigma$; $E_{d0.01\%} = E_{d50\%} - 3.7\sigma$; $\sigma = 6\%$).

The operating field strength is about 3 kV/mm. With these operating field strengths, due to the margins, the bushings would even withstand a continuous voltage of 1.05*U_m with an assumed operating time of 50 a. If an increased ageing is assumed and an ageing index of N = 15 is adopted, even at continuous operation with 1.05*U_m the service life would still be above the assumed operating time of 50 a (Figure 45).

:

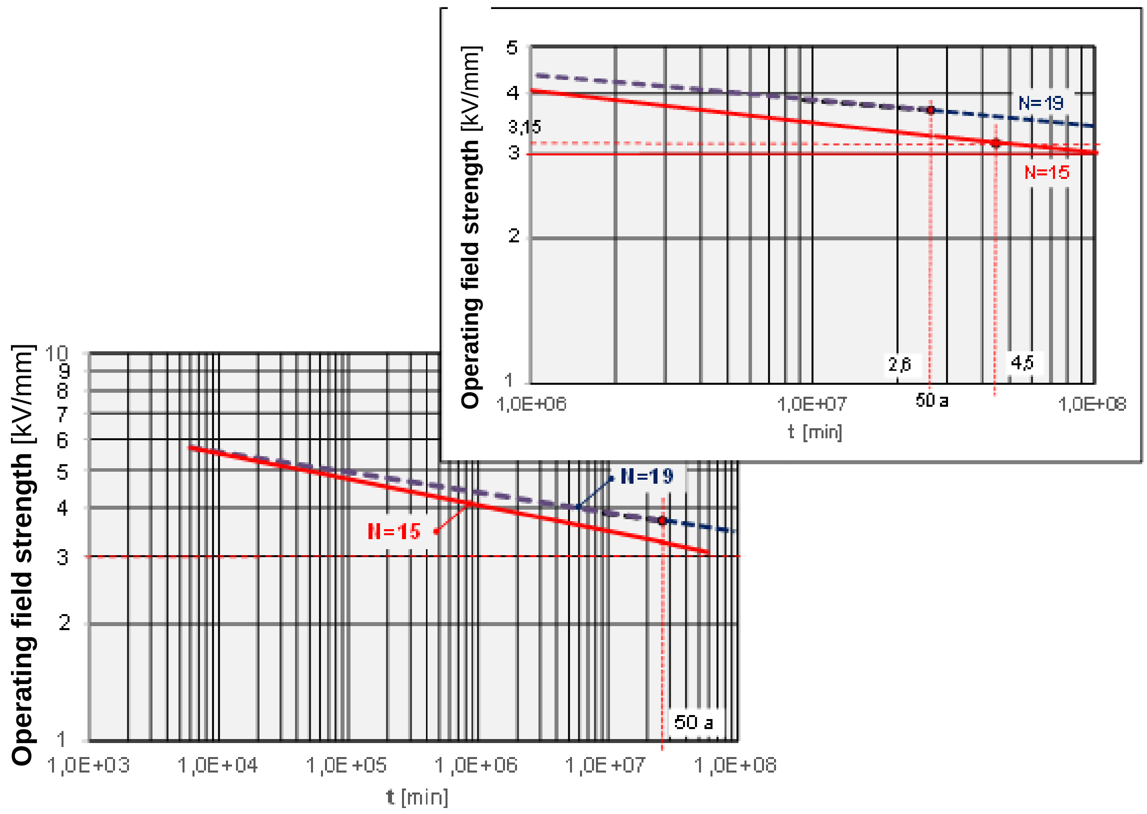


Figure 45: Lifetime consumption of a resin impregnated paper bushing (RIP bushing) with increased ageing assumed (ageing index N=15)

6.1.7. Surge arresters

As shown in Chapter 5.7, the continuous voltage of the arresters is not exceeded, even with an operating voltage of 440 kV, so that no thermal overstressing and thus no service life reduction is to be expected.

6.1.8. Cable systems

In the following, only cables with XLPE insulation will be considered. A high voltage test is carried out on these cables in accordance with VDE 0276-2067 [47] and a partial discharge test as a routine test on each cable length, as well as on the main insulation of the accessories. In the case of the high voltage test, the test voltage is 440 kV with a test duration of 60 min. In addition, a pre-qualification test is carried out on each cable system, in which a test voltage of 1.7*U_0 = 1.7*220 kV = 374 kV is used for a test duration of one year.

Furthermore, the cable length after assembly is tested with an alternating voltage of 1.7*U_0 = 374 kV, with a test duration of one hour.

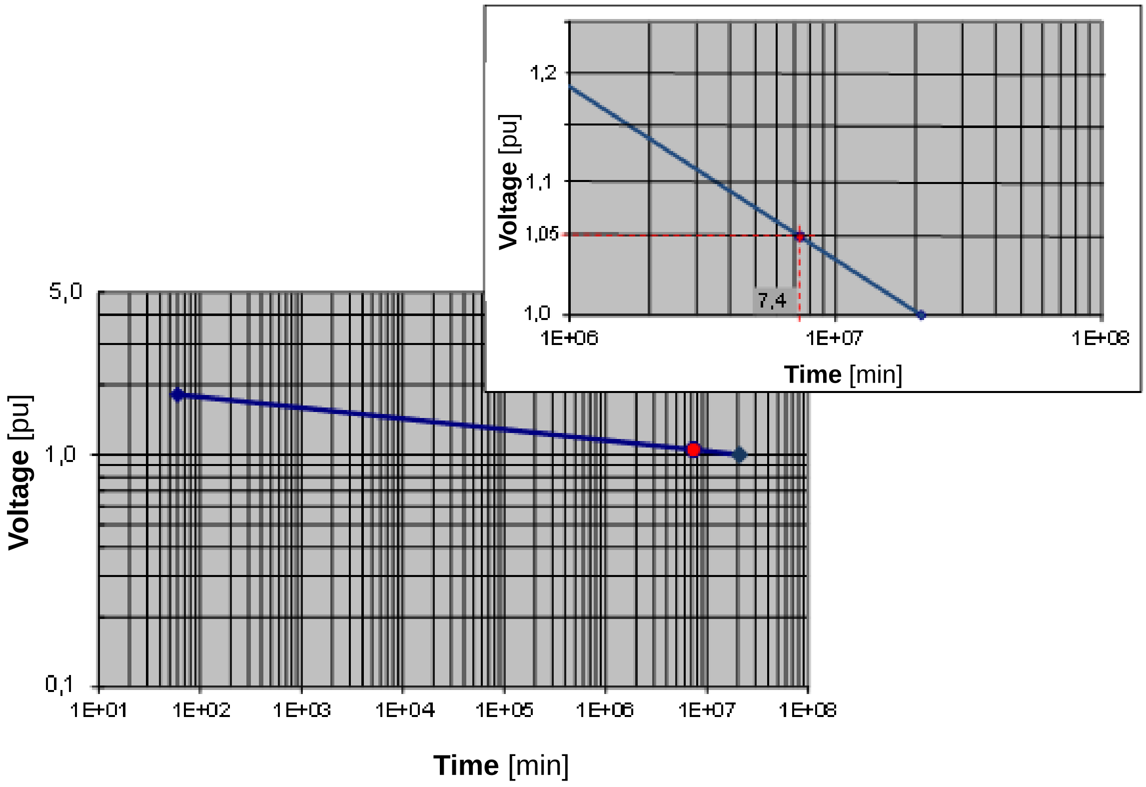


Figure 46: Lifetime characteristic of a XLPE cable system derived from the test according to VDE 0276-2067

If a service life of ≥ 40 a is assumed, the test values from the above-mentioned standard results in the characteristic shown in Figure 46. In the case of a continuous voltage stress of 1.05*U_m a distinct service life reduction of approximately 35% would result. Since this stress only occurs during 0.6% of the operating time, the service life reduction (approx. 2 months) caused by the increased voltage stress can be neglected.

The service life of the XLPE insulation of a cable in dependency on the voltage applied can also be described by the life formula (6.1) already mentioned in sections before [48]. For a XLPE cable, an ageing index N = 15 can be assumed [51], [52]. With a service life of at least 40 years, a characteristic results as shown in Figure 47.

According to this, a noticeable reduction of service life of the cable insulation is only to be expected, if the cable is continuously operated with 105% of the rated voltage. Short-duration operation with this voltage contributes only marginally to the ageing of the cable. It would not reduce the service life to any noticeable extent.

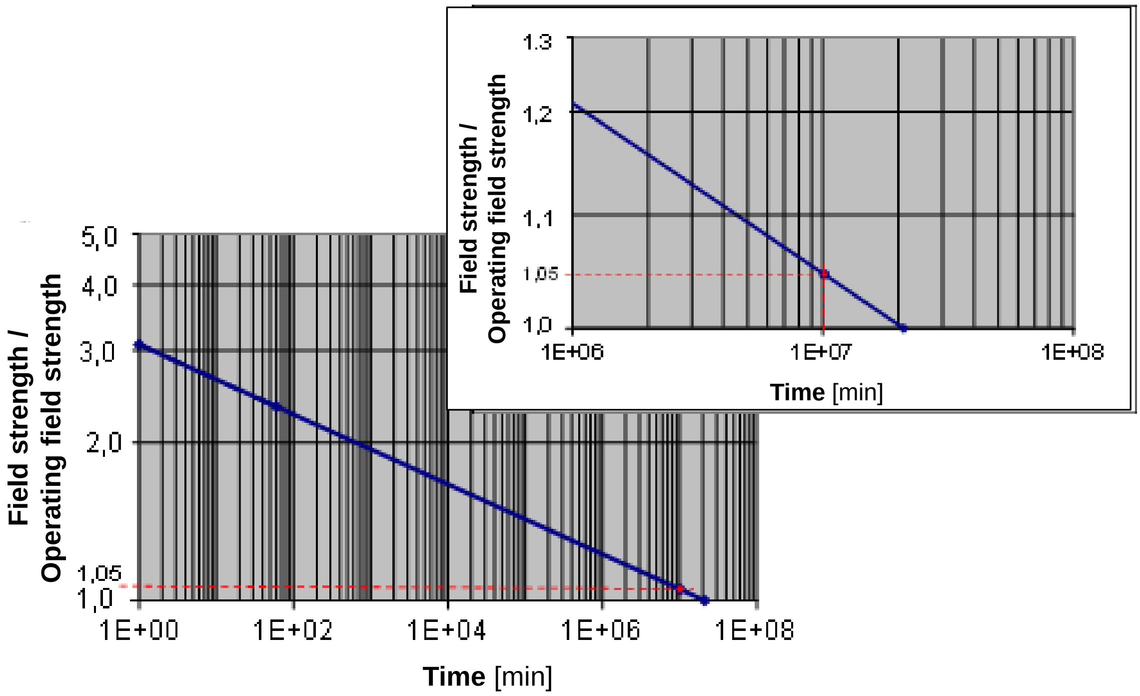


Figure 47: Lifetime characteristic of a XLPE cable insulation according to the life formula [48]

Beside XLPE cables, external gas pressure cables and oil-filled cables are in use in the German high and extra-high voltage system. The operating field strengths are comparable with those of the XLPE cable [51], yet the service life characteristics are clearly different (Figure 48) [53]. The degressive course of the service life characteristic of XLPE cables cannot be observed in the case of external gas pressure cables and oil-filled cables. Small cavities in the oil/paper insulation system are consistently re-filled by follow-on impregnating medium, whereas a comparable self-restoring effect does not occur with plastic-insulated cables. Therefore, it must be assumed that the presumed short-duration stresses do not result in a notable reduction in the service life of these cable systems. Besides the dielectric ageing observed here, the thermal ageing must also be taken into consideration, which can possibly result in a reduced service life.

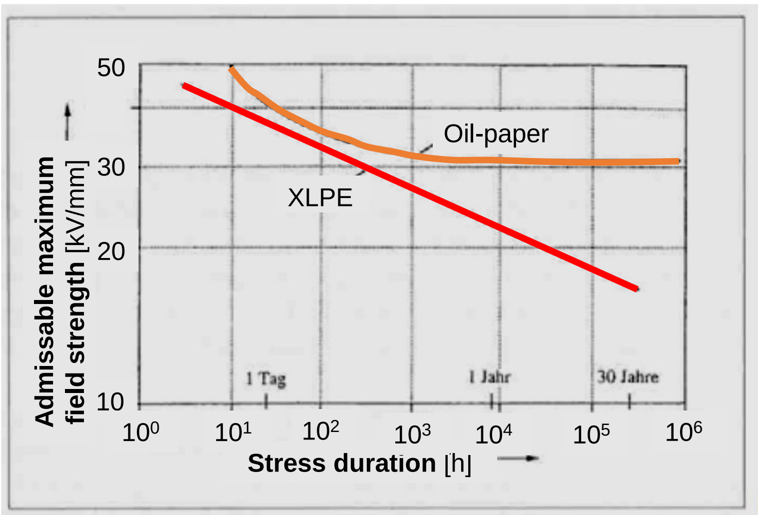


Figure 48: Comparison of lifetime characteristic of XLPE and oil-paper insulated cables

6.2. Summarized assessment of the service life of equipment in the 380 kV systems, as well as in 220 kV and 110 kV systems in the case of short-duration stress with 1.05*U_m

The assumed short duration stress of the equipment of the 380 kV system with 105% of the continuous admissible operating voltage twice per week for 30 min each time does not result in a significant reduction in service life. A continuous stress with 105% would, however, result in a marked reduction in service life for most of the equipment. Thus, such a stress could not be admitted, not only based on the valid standards, but also for physical reasons.

The findings can also be applied for the equipment in the 110 kV and 220 kV system, since the ratio of short-duration alternating voltage to rated voltage is generally greater for this equipment than that for the equipment in the 380 kV system.

6.3. Scenario 2: Possible ageing and/or reduction in service life due to temporary overvoltages of 1.025*U_m with longer stress durations

In the following, the service life performance of three types of equipment exposed to temporary overvoltages of 1.025*U_m is investigated, the insulation system ageing indices of which are known from the literature. Since the information in the literature is mostly presented depending on the operating field strength or testing field strength respectively, the following research results are shown related to the field strength. However, they can also be converted to the operating voltage.

6.3.1. GIS switchgear

For the service life of gas-insulated switchgear, the ageing performance of the insulating components made of epoxy resin is decisive. Service life characteristic with an ageing index of N = 12 can be found in the literature, e.g. [17]. Figure 49 shows an ageing characteristic calculated on this basis.

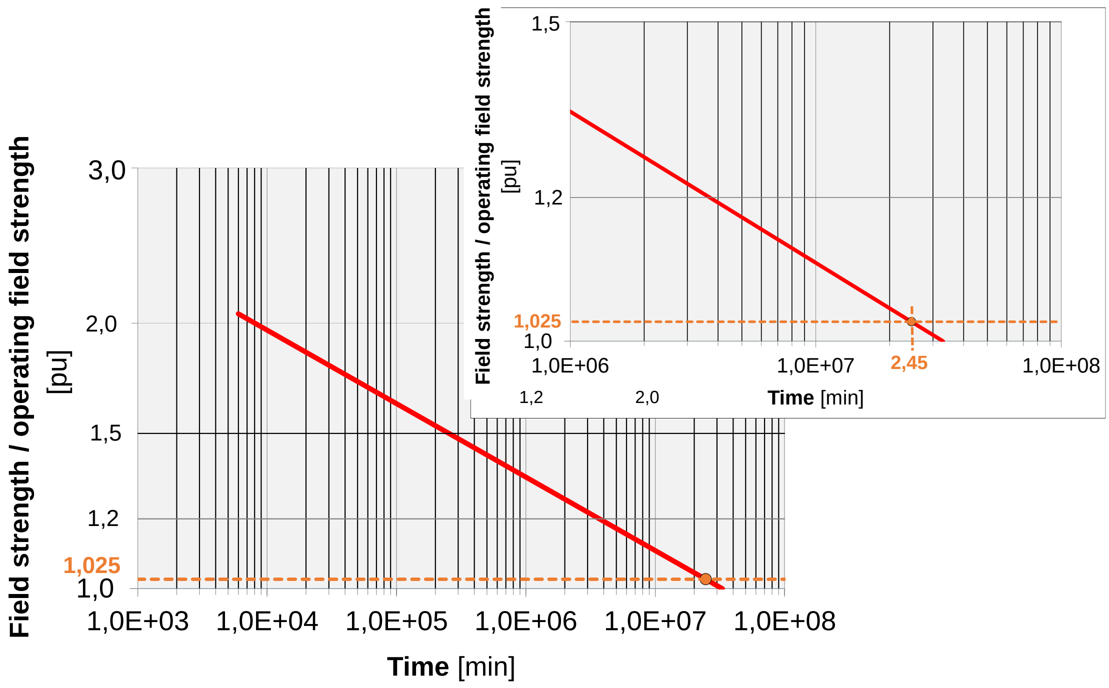


Figure 49: Ageing characteristic of the solid insulation of a GIS system, ageing coefficient N=12 according to [17]

It is to be recognised that, by raising the field strength to 1.025*operating field strength, an additional service life consumption of 26% compared to that at 1.0*U_m would result. Continuous operation at this field strength would reduce the service life of the insulation system by approx. 10 years. If it is assumed that a service life reduction of 10% at maximum is permissible, the GIS system should only be operated at a voltage of 1.025*U_m for a maximum of 40% of the operating time. Otherwise, a clear reduction in the service life would have to be taken into account.

6.3.2. Power transformers

An ageing index N = 60 for the long-term performance of insulating arrangements typical for transformers, as the winding insulation , the coil insulation and the barrier insulation with oil ducts is assumed in the literature [49]. With this ageing index and under the assumption of a service life of 40 years, an ageing characteristic according to Figure 50 is given.

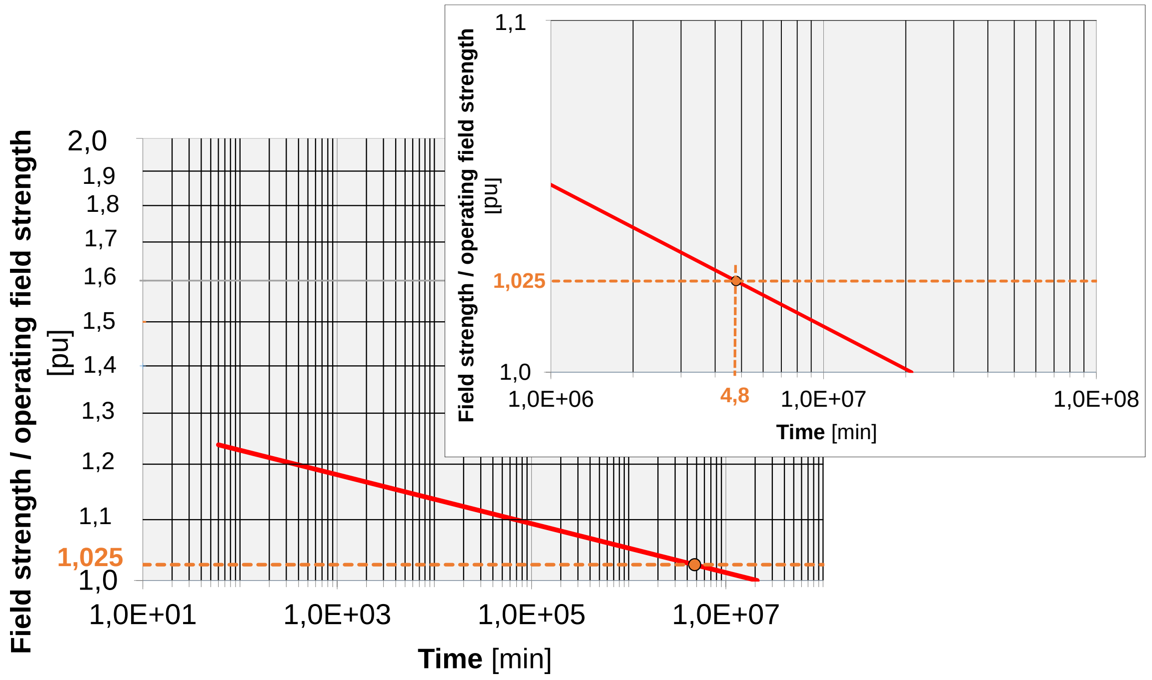


Figure 50: Ageing characteristic of typical transformer insulating arrangements, ageing index N=60

Operation with a field strength of 1.025*operating field strength would result in considerable dielectric ageing and thus to a reduction in service life of more than 70%. In order to guarantee a service life reduction of 10%, that is assumed to be permissible an accumulated operating time with the increased voltage of 1.025*U_m of 2.7 a would be permissible, in other words, for example, an operation with the increased voltage of 1.025*U_m twice a week for 8 h.

6.3.3. Cable systems

In [51], the following values for the rating insulation rating of cable systems up to 500 kV with XLPE insulation are given:

- Stress with alternating test voltage 40 kV/mm
- Stress with operating voltage 16 kV/mm
- Ageing index N 12…20

Assuming an alternating test voltage stress of 40 kV/mm for 60 min and an ageing index of N = 14 leads to a service life of 43 years (Figure 51). On the basis of this ageing characteristic a stress with 1.025* U_m is considered.

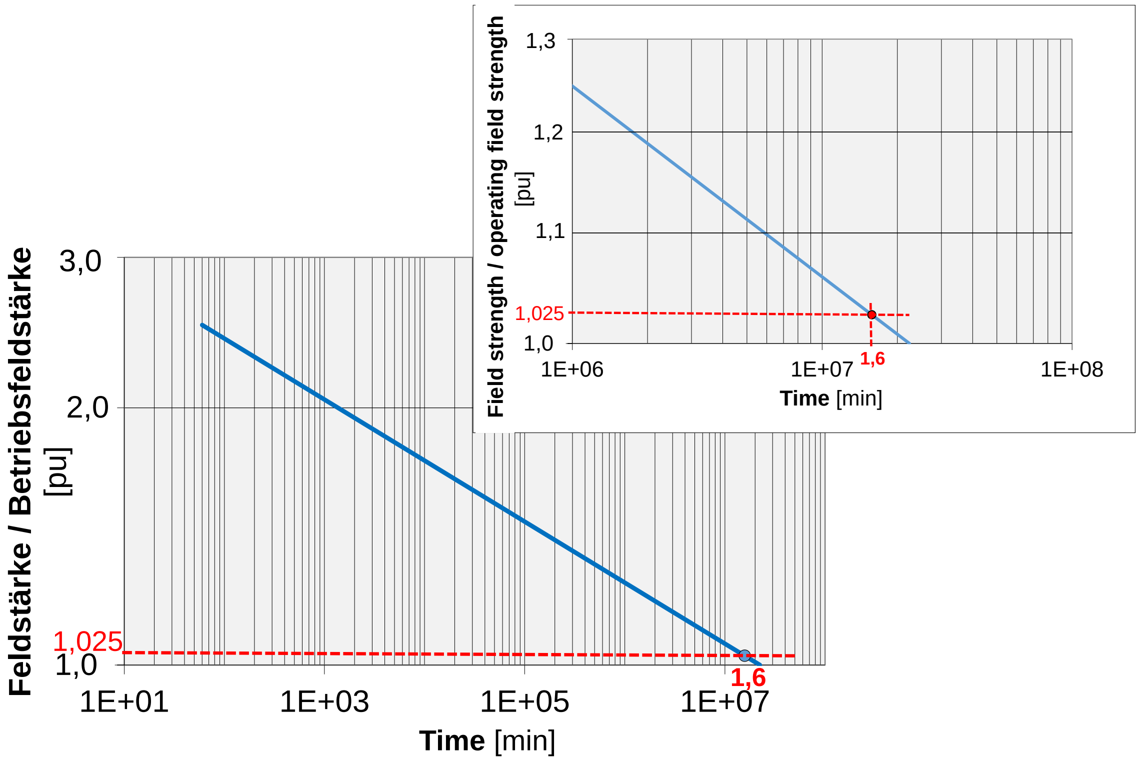


Figure 51: Ageing characteristic of a XLPE cable insulation, ageing index N= 14

From Figure 51, it can be seen that due to the continuous with 1.025*operating field strength there is an additional consumption of service life of 12 years, i.e. a distinct service life reduction. . A service life reduction of 10% that could be assumed to be permissible could be reached, if the accumulated operating time with the increased voltage of 1.025*U_m were to be at most 4 years.

6.4. Summarized assessment of the service life of 420 kV equipment in the case of longer duration stress at 102.5% of the continuous permissible operating voltage

Continuous operation at 102.5% of the permissible continuous operating voltage results in a clear reduction in service life for the insulation systems of the equipment investigated here, GIS, transformers and cables. The additional service life consumption 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 even reduced by more than two thirds. Therefore, the duration of such operating conditions must be time limited. If a service life reduction of 10% could be permitted, the accumulated operating time with a voltage of 1.025*U_m would be at most 4 years.

7. Conclusions and recommendations for action

Continuous operation of the high and extra-high voltage systems with voltages greater than U_m cannot be permitted, not only due to the relevant 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 system 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, which have been presented, are recommended.

Circuit breakers

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 system 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 interrupting transformer limited faults, transient recovery voltages not covered by the standard must be anticipated, if the transformer neutral 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*Um, 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, interruption without re-ignitions is also guaranteed even in the case of increased operating voltage.

Transformers

In the case of transformers at operation with 1.05*U_m, considerably higher audible 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 reactors at 1.05*U_m, higher copper and iron losses must be taken into account as well as increased audible 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 ferro-resonances should be generated. However, a sufficient damping behaviour at 1.05*U_m should be checked by means of tests or simulations.

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 feeding 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 of occurrence 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 used for load flow management or to avoid overload situations.

8. References

[1] Transmission Code 2007, Netz- und Systemregeln der deutschen Übertragungs-netzbetreiber. Version 1.1, August 2007

[2] GRIDCODE 2000 Netz- und Systemregeln der deutschen Übertragungsnetzbetreiber. DVG DEUTSCHE VERBUNDGESELLSCHAFT E. V.. Heidelberg, 20. April 2000

[3] EU VERORDNUNG 2016/631: Festlegung eines Netzkodex mit Netzanschluss-bestimmungen für Stromerzeuger. 14. April 2016.

[4] EU VERORDNUNG 2016/1388: Netzkodex für den Lastanschluss. 17. August 2016

[5] VDE-AR-N 4120: Technische Regeln für den Anschluss von Kundenanlagen an das Hochspannungsnetz und deren Betrieb (TAR Hochspannung). November 2018

[6] VDE-AR-N 4130: Technische Regeln für den Anschluss von Kundenanlagen an das Höchstspannungsnetz und deren Betrieb (TAR Höchstspannung). November 2018

[7] VDE 0175-1: CENELEC-Normspannungen. April 2012

[8] VDE 0111-1: Isolationskoordination, Teil 1: Begriffe, Grundsätze und Anforderungen. September 2010.

[9] M. Kizilcay, P. Malicki, S. Papenheim, M. Lösing, K. Vennemann: Influence of shunt compensated EHV transmission lines consisting of overhead line and XLPE cable sections on system performance. CIGRE Symposium Aaborg, Denmark, 4-7 June 2019. Paper 11.

[10] VDE 0210-1 (EN 50341-1): Freileitungen über AC 45 kV – Teil1: Allgemeine Anforderungen – Gemeinsame Festlegungen. April2010.

[11] P.S. Maruvada: Corona Performance of High Voltage Transmission Lines. Research Studies Press Ltd, Baldock, Hertfordshire, England, 2000.

[12] IEC 60815-2: Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions – Part 2: Ceramic and glass insulators for a.c. systems. 2008.

[13] VDE 0101-1: Starkstromanlagen mit Nennwechselspannungen über 1 kV –Teil 1: Allgemeine Bestimmungen. Dezember 2014.

[14] VDE 0671-1: Hochspannungs-Schaltgeräte und –Schaltanlagen, Teil 1: Gemeinsame Bestimmungen. Dezember 2012.

[15] VDE 0671-203: Hochspannungs-Schaltgeräte und –Schaltanlagen, Teil 203: Gasisolierte Schaltanlagen mit Bemessungsspannungen über 52 kV. November 2012.

[16] CIGRE Working Group D1.03: Very Fast Transient Overvoltages (VFTO) in Gas-Insulated UHV Substations. Technical Brochure 519, December 2012.

[17] CIGRE brochure 360: Insulation co-ordination related to internal insulation of gas-insulated systems with SF6 and N2/SF6 gas mixtures under AC condition. CIGRE WG C4.302, October 2008.

[18] VDE 0102: Kurzschlussströme in Drehstromnetzen, Dez. 2016.

[19] VDE 0671-100: Hochspannungs-Schaltgeräte und –Schaltanlagen, Teil 100: Wechselstrom-Leistungsschalter. August 2013.

[20] VDE 0671-100: Hochspannungs-Schaltgeräte und –Schaltanlagen, Teil 100: Wechselstrom-Leistungsschalter. Entwurf Nov. 2018.

[21] H. H. Schramm: Schalten im Hochspannungsnetz. VDE Verlag GmbH, Berlin, Offenbach. 2015. ISBN 978-3-8007-3879-3.

[22] FFN-Störungs- und Verfügbarkeitsstatistik, Berichtsjahr 2017.

[23] A. Braun, K.H. Hinterthür, H. Lipken, B. Stein, O. Völker.: Characteristic values of the transient recovery voltage for different types of short circuits in an extensive 420 kV system. etz-a 97, S. 489-493.

[24] G. Frind: Experimental investigation of limiting curves for current interruption of gas blast breakers. Proceedings of Symposium “Current Interruption in High-Voltage Networks”. Edited by Klaus Ragaller. Plenum Press, New York and London, 1978.

[25] G. Balzer, C. Neumann: Switching of transformer limited faults in HV and EHV Systems. Paper no. 77, CIGRE Symposium Recife, April 2011.

[26] CIGRE WG A3.11: Guide for application of IEC 62271-100 and IEC 62271-1, Part 2: Making and breaking tests. Technical Brochure 305, October 2006.

[27] C. Neumann: Manuskript zur Vorlesung Hochspannungsschaltgeräte und Anlagen an der TU Darmstadt.

[28] E. Ruoss: Überspannungen beim Einschalten von Hochspannungsleitungen. BBC-Mitteilungen Band 66, April 1979, S. 262-270.

[29] CIGRE W 13.02: Interruption of small inductive currents. Technical Brochure 50, December 1995.

[30] VDE 0671-110: Hochspannungs-Schaltgeräte und -Schaltanlagen –Teil 110: Schalten induktiver Lasten. August 2018.

[31] VDE 0671-102: Hochspannungs-Schaltgeräte und -Schaltanlagen –Teil 102: Wechselstrom-Trennschalter und –Erdungsschalter. Juni 2012.

[32] CIGRE Working Group 33/13.09: MONOGRAPH ON GIS VERY FAST TRANSIENTS. Technical Brochure 035.

[33] C. Neumann: Nichtstandardisierte betriebliche Beanspruchungen beim Schalten von Trenn- und Erdungsschaltern im Hochspannungsnetz. Dissertation Technische Hochschule Darmstadt, Juni 1992.

[34] R. Witzmann: Schnelle transiente Spannungen in metallgekapselten, SF6-isolierten Schaltanlagen. Dissertation TU München. VDI Fortschritt-Berichte Reihe 21, Nr. 55.

[35] W.J. Chen et al.: Study of the Influence of Disconnector Characteristics on Very Fast Transient Overvoltages in 1100-kV Gas-insulated Switchgear. IEEE Transactions on Power Delivery, Vol. 30, No. 4, August 2014, S. 2037-2044.

[36] VDE 0532-76-1: Leistungstransformatoren - Teil 1: Allgemeines. März 2012 [37] VDE

0532-76-3: Leistungstransformatoren, Teil 3: Isolationspegel, Spannungsprüfungen und äußere Abstände in Luft. August 2014.

[38] G. Balzer, C. Neumann: Schalt- und Ausgleichsvorgänge in elektrischen Netzen. Springer Vieweg, Springer Verlag Berlin, Heidelberg. Juni 2015. ISBN 978-3-662-44547-1.

[39] VDE 0414-9-1: Messwandler - Teil 1: Allgemeine Anforderungen. April 2010.

VDE 0414-9-2: Messwandler - Teil 2: Zusätzliche Anforderungen für Stromwandler. Juli 2013.

VDE 0414-9-3: Messwandler - Teil 3: Zusätzliche Anforderungen für induktive Spannungswandler. Mai 2012.

VDE 0414-9-4: Messwandler - Teil 4: Zusätzliche Anforderungen für kombinierte Wandler. April 2015.

[40] K. Kunde, L. Niedung, A. Umlauf, C. Neumann, H. Lipken, R. Bayer: Einphasige Kippschwingungen in Netzen mit induktiven Spannungswandlern. Elektrizitätswirtschaft. Jahrgang 95 (1996), S. 162-170.

[41] R. Bayer, J. Luhmann, J. Mentel, C. Neumann: Simulation von einphasigen Kippschwingungen in Spannungswandlern mittels EMTP/ATP. Elektrie 56 1-4 (2002); S. 79-87

[42] V. Hinrichsen: Metalloxid-Ableiter in Hochspannungsnetzen. Grundlagen. Siemens AG, Energy Sector, Power Transmission Division, High Voltage Products. 3. Auflage, Sept. 2011.

[43] VDE 0675-1: Überspannungsableiter – Überspannungsableiter mit nichtlinearen Widerständen für Wechselspannungsnetze. August 2000.

[44] VDE 0675-5: Überspannungsableiter. Empfehlung für die Auswahl und die Anwendung. September 2000.

[45] D. Oeding, B.R. Oswald: Elektrische Kraftwerke und Netze. Springer Heidelberg, Dordrecht, London, New York, 7. Auflage 2011. ISBN 978-3-642-19246-3.

[46] VDE 0276-632: Starkstromkabel mit extrudierter Isolierung und ihre Garnituren für Nennspannungen über 36 kV (U_m = 42 kV) bis 150 kV (U_m = 170 kV).

[47] VDE 0276-2067: Starkstromkabel mit extrudierter Isolierung und ihre Garnituren für Nennspannungen über 150 kV (U_m = 170 kV) bis einschließlich 500 kV (U_m = 550 kV) - Prüfverfahren und Anforderungen. August 2013.

[48] A. Küchler: Hochspannungstechnik. Grundlagen – Technologie – Anwendungen. Springer Verlag, 2004.

[49] Y. Shirasaka, H. Murase, S. Okabe, H. Okubo: Cross-sectional Comparison of Insulation Degradation Mechanisms and Lifetime Evaluation of Power Transmission Equipment. IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 2; April 2009.

[50] F. Hammer, A. Kirch: Design, manufacture and testing of RIP-bushings and their special application as components of SF6 insulated HV equipments. International conference on Sulphur hexafluoride gas filled high voltage equipments, Kerala 1978. Pp. F1-F19.

[51] CIGRE WG 21/33: Insulation Coordination for HV AC underground cable system. Cigre Brochure 189, June 2001.

[52] E. Peschke, R. von Olshausen, Cable Systems for High and Extra-High Voltage, Publicis MCD Verlag, Erlangen & Munich, 1999.

[53] R. Schwarz: Messtechnik und Diagnostik an elektrischen Betriebsmitteln. Hablitationsschrift TU Graz, 2009.

[54] VDE 0532-76-1 Beiblatt 1: Leistungstransformatoren – Teil 1: Allgemeines; Beiblatt 1: Spannungspegel oberhalb der höchsten Spannung für Betriebsmittel U_m.

Appendix: About the authors

Prof. Dr Ing. Claus Neumann worked until 2010 in different positions in the area of high voltage equipment and systems at RWE and most recently at the transmission system operator Amprion as the Head of the Operative Asset Management. He is an honorary professor at the Technical University of Darmstadt where he gives the lecture in “High-voltage switchgear and substations”. He currently works as a Senior Consultant. His specialisms are Asset Management, AC & DC System Design, Power Equipment Technology, Monitoring & Diagnosis.

Prof Neumann was the German member of the CIGRE Study Committee (SC) 33 (Insulation Coordination) for many years and Convenor of the Advisory Group “Insulation Coordination” of SC C4 (System Technical Performance). He is currently Convenor of the Joint Working Group D1/B3.57 (“Dielectric Testing of HVDC gas-insulated Systems”) and member of the WG D1.66 (“Requirements for partial discharge monitoring systems for gas insulated systems”). He is a CIGRE Distinguished Member and in 2004 he received the TC Award of SC C4.

Prof. Dr Ing Volker Hinrichsen is a university professor at Technical University of Darmstadt and head of High-Voltage Laboratories specialist area. His research specialisms are lightning and over-voltage protection, new insulation and field grading materials, high-voltage circuit breakers, new sensors, diagnosis methods and condition assessment of equipment and systems, high-voltage and high-current testing and measuring technology.

Prof. Hinrichsen works for DKE, IEC and CIGRE. Amongst other things, he is Chairman of the IEC Technical Committee TC 37 (Surge Arresters), Convenor of the TC 37 MT 4 (Surge Arresters), where he is responsible for all the test specifications for high-voltage arresters, member of the TC 28 (TC 99) MT 9 (Insulation Co-ordination – Application Guide). In 2007, he received the “IEC1906 Award”.

At the DKE/VDE, he heads up K 441 (Surge Arresters) as Chairman and he is a member of K 183 (Assessment and qualification of electrical insulating materials and insulation systems), K 451 (Insulators) and K 122 (Insulation coordination). In 2012, he was awarded the “DKE-Nadel”.

He is the Chairman of the Electrical Engineering Research Group (FE) of the ZVEI.

At CIGRE, he is currently Convenor of the working group D1.56 (Field grading in electrical insulation systems) and member of the working groups WG C4.39 (Effectiveness of line surge arresters for lightning protection of overhead transmission lines), WG D1.58 (Evaluation of dynamic hydrophobicity of polymeric insulating materials under AC and DC voltage stress). In 2018, he was appointed to a CIGRE Distinguished Member.