

IEEE Recommended Practice for Overvoltage and Insulation Coordination of Transmission Systems at 1000 kV AC and Above

IEEE-SA Board of Governors and IEEE Power and Energy Society

Sponsored by the
Corporate Advisory Group
IEEE Substations Committee
IEEE Switchgear Committee
IEEE Transformers Committee

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IEEE Std 1862™-2014

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Abstract: The procedure for selection of insulation levels of UHV ac transmission lines and substations are specified. Also specified are reliability criterion under switching overvoltage and lightning overvoltage. Calculation methods of insulation coordination design are suggested. According to the characteristics of UHV ac systems, overvoltage mitigation measures are recommended. Some examples of insulation coordination are presented.

Keywords: atmospheric correction factor, basic lightning impulse insulation level (BIL), basic switching impulse insulation level (BSL), clearance, crest value, ground fault factor, IEEE 1862™, insulation coordination, insulation design, overvoltage, phase-to-ground insulation configuration, phase-to-phase insulation configuration, protective margin, protective ratio, shielding failures, standard withstand voltages, ultra-high voltage (UHV), voltage stresses

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Introduction

This introduction is not part of IEEE Std 1862-2014, IEEE Recommended Practice for Overvoltage and Insulation Coordination of Transmission Systems at 1000 kV AC and Above.

In order to resolve the prominent problem of the inverse distribution between energy resources and power demands, the ultra-high voltage (UHV) ac transmission, which is advantaged over long distance and large capacity, is required.

There are specifics on overvoltage and insulation coordination of UHV ac systems, such as switching overvoltages (SOV), very fast front overvoltage (VFFO), lightning overvoltage, etc. Time-to-crest of SOV on UHV lines is much longer than that of standard switching impulse (SI). For air clearance of UHV transmission lines, the switching impulse flashover voltage is non-linearly related to the distance of the clearance. Flashover voltage presents its saturation feature as clearance increase. In order to improve the economy of an UHV transmission line, air clearance test data of longer time-to-crest SI can be used for insulation coordination. In UHV ac systems, the ratio of the basic lightning impulse insulation level (BIL) to the system voltage is lower than that of EHV system, so VFFO may become the main dielectric stress to be limited. Since UHV towers are higher than EHV ones, lightning overvoltage in UHV systems needs special attention.

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1. Overview

1.1 Scope

This recommended practice applies to transmission system at 1000 kV ac and above. It defines standard insulation levels and specifies procedures for selecting insulation levels of ac transmission lines and substations. It also specifies reliability criteria under switching and lightning overvoltages. Suggestions on insulation coordination design are described. Overvoltage mitigation measures are recommended according to the characteristics of such ac systems. Some examples of insulation coordination are also presented.

1.2 Purpose

Ultra-high voltage (UHV) ac power transmission system is an effective approach to achieve efficient allocation of energy resources utilizing the advantages of large capacity with long distance, and low loss. Some countries have already carried out research on UHV technologies, and several UHV ac projects have been constructed and put into operation. This recommended practice is formulated specifically for the design and application of insulation coordination for transmission systems at 1000 kV ac and above.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

Accredited Standards Committee C2-2012, National Electrical Safety Code® (NESC®).^{1, 2}

IEEE Std 4™-1995, IEEE Standard Techniques for High-Voltage Testing (ANSI).^{3, 4}

IEEE Std 1312™-1993, IEEE Standard Preferred Voltage Ratings for Alternating-Current Electrical Systems and Equipment Operating at Voltages Above 230 kV Nominal.

IEEE Std 1313.2™-1999, IEEE Guide for the Application of Insulation Coordination.

IEC 60071-1-2011, Insulation Co-ordination—Part 1: Definitions, Principles and Rules.

IEC/TR 60071-4-2004, Insulation Co-ordination—Part 4: Computational Guide to Insulation Co-ordination and Modeling of Electrical Networks.

IEC/TS 60815-1-2008, Selection and Dimensioning of High-Voltage Insulators Intended for Use in Polluted Conditions—Part 1: Definitions, Information and General Principles.⁵

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁶

ultra-high voltage (UHV): A maximum system voltage that is equal to or greater than 1000 kV.

NOTE—This definition is taken from IEEE 1312™-1993 and is reproduced here for the convenience of the reader.⁷

shielding angle: The included angle between the plumb line from ground wire and the virtual line connecting ground wire to the most outside sub-conductor on the tower, without considering the windage yaw of the conductor.

representative overvoltage: Overvoltages assumed to produce the similar dielectric effect on the insulation system as overvoltages of a given class occurring in service due to various origins. They consist of voltages with the standard shape of the class, and may be defined by one value or a set of values or a frequency distribution of values that characterize the service conditions.

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⁷ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

3.2 Acronyms and abbreviations

σ_f	coefficient of variation
ac	alternating current
AIS	air-insulated switchgear
BFR	back-flashover rate
BIL	basic lightning impulse insulation level
BSL	basic switching impulse insulation level
CB	circuit breaker
CFO	critical flashover
CVT	capacitor voltage transformer
EGM	electrogeometric model
EHV	extra-high voltage
EMTP	Electro-Magnetic Transient Program
ESDD	equivalent salt deposit density
GIS	gas-insulated metal enclosed switchgear
LPM	leader progression model
MOSA	metal oxide surge arrester
MTBF	mean time between failures
MTS	mixed technology switchgear
NSDD	non-soluble deposit density
pu	per unit
RTV	room temperature vulcanizing (silicone)
SDD	salt deposit density
SF ₆	sulfur hexafluoride
SSFOR	shielding failure flashover rate
SOV	switching overvoltages
SSFOR	switching surge flashover rate
TOV	temporary overvoltages
UHV	ultra-high voltage
USCD	unified specific creepage distance
VFFO	very fast front overvoltage

4. Overvoltage and mitigation measures

Overvoltages include temporary overvoltages, switching overvoltages, lightning overvoltages, as well as very fast front overvoltages. Overvoltages are normally expressed in per unit (pu) with reference to $\sqrt{2} U_m / \sqrt{3}$ where U_m is the maximum system voltage, except for lightning overvoltages.

4.1 Temporary overvoltages

4.1.1 Load rejection overvoltages

Load rejection overvoltages in ultra-high voltage (UHV) systems are usually more severe than those in extra-high voltage (EHV) systems, because of the longer transmission lines and larger transmission capacity. For lines with shunt reactors, the temporary overvoltage caused by load rejection is usually less than 1.3 pu (Shu et al. [B9]; National Standard of the People's Republic of China [B7]). For lines without shunt reactors, the values of such overvoltage may be higher than 1.3 pu. The duration of such overvoltages depends on the voltage control operation and relay protection.

4.1.2 Fault overvoltages

Since in UHV systems, the ratio of zero-sequence reactance to positive-sequence reactance (X_0/X_1) is relatively smaller than that in EHV systems, the temporary overvoltage caused by fault in UHV ac system is usually less than 1.3 pu, depending on the location of the fault. Considering backup clearing, the duration of the overvoltage is generally less than 0.5 s.

The temporary overvoltage caused by the combination of ground fault with load rejection is usually higher than that of just load rejection. For the lines with application of shunt reactors, the temporary overvoltage is usually less than 1.4 pu; the duration of the temporary overvoltage depends on the fault-clearing time and is generally less than 0.1 s. For the lines without shunt reactors, the temporary overvoltage caused by load rejection followed by ground fault with self-excitation of generators connected to the UHV line via transformers directly may reach up to 1.5 pu, the duration of the overvoltage is generally 0.17 s.

4.1.3 Resonance and ferroresonance overvoltages

In UHV ac systems, the following three kinds of resonance or ferroresonance voltages are generally considered.

- Resonance overvoltage in non-successful-three-phase operations
- Resonance overvoltage caused by energizing no-load transformers
- Ferroresonance overvoltage

For a line with shunt reactors, resonance overvoltages may appear on the open phase due to unsuccessful operating of three phases. The resonance overvoltage is caused by the capacitive coupling between live phases and open phase of the line. These overvoltages can be limited by a grounding reactor installed at the neutral point of three-phase shunt reactors.

Energizing a no-load transformer may cause the transformer core magnetically saturated and may produce inrush current and periodic changes of the excitation inductance. When the frequency of some harmonic in the inrush current matches the self-oscillation frequency of the system, high resonance overvoltage may be generated.

Ferroresonance overvoltages may be developed from the interaction of capacitive and inductive elements which possess nonlinear magnetizing characteristics. In UHV systems, this kind of overvoltages is usually initiated by the resonance of gas-insulated switchgear (GIS) bus potential transformer through circuit breaker capacitance during isolating a bus bar where potential transformer is installed.

4.1.4 Mitigation of temporary overvoltages

In UHV systems, temporary overvoltages can be mitigated through the use of the following:

- Shunt reactors
- Grounding reactor installed at the neutral point of shunt reactors
- Temporary overvoltage protection relays
- Surge arresters

Shunt reactors installed on transmission lines can reduce Ferranti effect and thus reduce load rejection overvoltages, as well as the overvoltage produced by combination of earth fault and load rejection.

Grounding reactor installed at the neutral point of shunt reactor is used to control resonance overvoltages caused by non-successful-three-phase operations of a line with shunt reactors. It can also suppress secondary arc current during the time between single-phase fault clearing and single-phase reclosing.

Special temporary overvoltage protection relays can be used to trip the three-phase circuit breaker at both ends of the UHV lines immediately after load rejection, and thus limit the duration of temporary overvoltage.

Arresters are not normally sized to limit temporary overvoltages except in special cases. However, surge arresters may be applied to limit or even prevent resonant overvoltages. In this case, the thermal capability on the arresters should be investigated to determine if parallel interconnected arresters or special switched arresters are required.

4.1.5 Geomagnetic storm

A geomagnetic storm induces DC currents in a long transmission line (many kilometers in length) and increases the voltage by the factor. Sprawling power lines act like antennas, picking up the currents and spreading the problem over a wide area.

Improved infrastructure design is used to better withstand geomagnetic disturbances.

4.2 Switching overvoltages

The wave shape of switching overvoltages in UHV ac systems has longer time to crest due to the long transmission lines and application of closing resistors.

4.2.1 Line energization and single-phase reclosing overvoltages

The overvoltage produced by line energization and single-phase reclosing is one of the key factors to determine switching impulse air clearance of UHV line. With pre-insertion resistors on circuit breakers and metal oxide surge arrester (MOSA), the phase-ground overvoltages are generally less than 1.6 pu in substations and 1.7 pu on transmission lines, respectively. The phase-to-phase overvoltages are generally less than 2.9 pu.

4.2.2 Fault and fault-clearing overvoltages

During the period from line-to-ground fault initiation to clearing, overvoltages are produced on the live phases. Fault and fault clearing produce both phase-ground overvoltages and phase-to-phase overvoltages. However the phase-to-phase overvoltages can generally be neglected.

Fault and fault-clearing overvoltages are affected by both the length of lines and fault locations. Those overvoltages may cause flashover on live phases or adjacent healthy lines and lead to another fault.

The following cases are considered:

- Single-phase-ground fault and single-phase clearing
During single-phase-ground fault initiation, overvoltages are generated on live phases and adjacent lines. These overvoltages occur once again when the circuit breakers at both ends of the fault phase are opened to clear the fault. Those overvoltages are generally lower than that appearing during line energization.
- Three-phase-opening after single-phase-ground fault
When single-phase-reclosing is forbidden in case of live line working or single-phase reclosing fails due to a permanent fault, three-phase-tripping occurs. Overvoltages are produced on both the adjacent lines and the live phases of the fault line. The overvoltage on live phases is usually higher than that caused by single-phase clearing after single-phase-ground fault.
- Multi-phase fault clearing
During clearing of multi-phase-ground-fault or phase-to-phase-fault, overvoltages are produced on both the adjacent lines and live phases of fault line. The overvoltages are usually higher than the single-phase-fault clearing overvoltage and may reach up to 1.8 pu to 2.0 pu. However, the occurrence probability of such high overvoltage is very low.

4.2.3 Load rejection overvoltages

In UHV systems, transmission lines are usually longer and load is higher than that in EHV systems. Load rejection overvoltages may reach up to 1.7 pu on UHV lines. The energy dissipation capability of arresters should be examined to insure proper operation.

4.2.4 Power system out-of-step separation overvoltages

Power systems separated by system out-of-step may generate overvoltages. The energy dissipation capability of arresters for such causes should be carefully examined.

4.2.5 Mitigation of switching overvoltages

Switching overvoltages appearing on the UHV system may be limited through the use of the following:

- Surge arresters
- Closing resistors on circuit breakers
- Controlled switching of circuit breakers
- Opening resistors on circuit breakers
- Shunt reactors

Surge arresters can be used to reduce all kinds of switching overvoltages. Surge arresters can be divided into tank-type arresters and bushing-type arresters according to their structures. The rated voltage of an

arrester is determined by the power frequency temporary overvoltage at its installation location. For EHV substations, the rated voltage of the arresters on the line side of the line circuit breaker (CB) is higher than that on bus bars side. For UHV projects, however, the rated voltages of the surge arresters on both line side and bus bars are the same, since the sustaining time of the power frequency temporary overvoltage on line side is reduced to 0.2 s by using circuit breaker relaying. Since better overvoltage limitation result is achieved with lower residue voltage surge arresters, large diameter varistor elements and multi-column-in-parallel structures are generally used for UHV surge arresters (both the Chinese and Japanese UHV surge arresters are of 4-column-in-parallel structures) for higher performance. For multi-column-in-parallel surge arresters, equal sharing of current among the columns should be guaranteed.

Closing resistor of CB reduces overvoltages caused by the line energization and/or reclosing. Because the line side arresters in substations have limited switching overvoltages (SOV) protection effectiveness for long transmission lines, closing resistors are important measures in UHV systems. The value of the resistor is usually selected by considering the effect to overvoltage and its energy dissipation capability.

The controlled switching of selected pole of circuit breakers, synchronization of reclosing time, may be used to reduce overvoltage. For example, in case of line energization, each pole of the circuit breaker can be controlled to close when voltage passes through zero.

In case of the fault-clearing overvoltage being greater than fault overvoltage, it greatly increases the failure rate of the lines adjacent to the fault line, opening resistors may be used to reduce such overvoltages.

Shunt reactors installed on transmission lines can suppress temporary overvoltages (TOV), which is the fundamental component of switching overvoltage. Since the TOV can be reduced by shunt reactors, surge arresters with lower rated voltage can be used in such cases, therefore switching overvoltage level in substation is reduced due to lower rated residual voltage of the surge arresters.

4.3 Lightning overvoltages

4.3.1 The origin and characteristics of lightning overvoltages

Lightning overvoltages in UHV transmission systems with overhead lines originate from line shielding failure and back-flashover strikes to equipment in substations which subsequently bypass the ground wires and masts, and the incoming surge to substations caused by stroke on the transmission line sections adjacent to substations.

Similar to EHV transmission lines, lightning flashover caused by shielding failure is the main reason for trip-outs of UHV transmission lines, and back-flashover trip-out rate is very low.

Back-flashover rarely happens within the 2 km sections of transmission line adjacent to the substation entrance.

4.3.2 Limitation of lightning overvoltages

The key point of lightning protection for UHV transmission system is to protect the transmission lines from shielding failures, and limit the lightning incoming surge due to shielding failure of the lines section adjacent to substation. Lightning overvoltages may be limited through the use of the following:

- Overhead ground wires
- Reducing tower foot resistance
- Surge arresters

Double overhead ground wires are usually installed for the UHV transmission lines. For mountain areas and the areas with high ground flash density of lightning, the shielding angle should be further reduced, even to a negative angle according to the actual conditions of projects. It should be noted that the reduction of shielding angle may lead to a greater space between the two ground wires, the center phase conductor of single-circuit line may be stroked by relatively small lightning penetrating the space between the two ground wires. Negative shielding angle may even be adopted for the line sections adjacent to substations in order to reduce the maximum lightning shielding failure current. The lightning shielding performance for angle and tension towers should be optimized, since jumper conductors are easy to be directly struck by lightning.

The value of tower foot resistance may not be strictly limited, as trip-out rate caused by back-flashover is very low for UHV ac transmission lines, as compared to that of EHV transmission lines. The value of tower foot resistance formed by its foundation is relatively smaller for UHV ac transmission lines because of the deep tower foundation and large scale tower root span. Therefore, supplemental grounding electrodes to reduce the value of tower foot resistances are not necessary if the requirement of the designed lightning trip-out rate can be met.

Appropriate quantity of surge arresters may be installed in substations to limit the lightning overvoltages on equipment. In order to decrease the maintenance costs, the surge arresters with external series gap is preferred to be installed on UHV transmission lines in mountain ridges or where the lightning shielding failure or back-flashover occur quite often.

4.4 Very fast front overvoltages (VFFO)

4.4.1 The characteristics of VFFO

Very fast front overvoltages are caused by disconnector operations or faults within GIS. Switching of disconnectors is a normal operation in substations. During closing and opening of a disconnector, a number of pre-strikes and re-strikes occur due to the low speed of disconnectors compared to that of circuit breakers. Each strike generates VFFO. Therefore, the operation of disconnectors is the main cause of VFFO.

VFFO is characterized by a fast increase of the voltage to its peak value resulting in a time-to-crest below 0.1 μ s. This fast increase of voltage is usually followed by high frequency oscillations from 1 MHz up to 100 MHz. The amplitude and frequency characteristic of VFFO depends on the substation configurations. Characteristics of disconnectors, such as switching speed and construction, will also influence the VFFO. VFFO may damage the insulation of GIS, power transformers, and potential transformers. The maximum amplitude of VFFO is generally less than 2.5 pu and may be higher in special cases.

In UHV systems, the ratio of the BIL to the system voltage is lower than that of EHV system, and VFFO on GIS or transformer with oil-sulfur hexafluoride (SF_6) immersed bushing may become the important dielectric stress which needs special attention.

4.4.2 Mitigation of VFFO

Damping resistors on disconnectors are mainly used to reduce VFFO caused by the operation of disconnector. The value of resistance can be selected by studying its limitation effect on VFFO and its energy dissipation requirement. By adopting damping resistors, VFFO can be limited to below 1.3 pu.

The contact mechanical moving speed of disconnector has an impact on the distribution of VFFO. The operation of a slow speed disconnector generates lower trapped charge voltage, therefore the occurrence probability of high amplitude VFFO is relatively lower. However, lower speed disconnector also leads to

more strikes during operation which requires a higher energy dissipation ability of the damping resistor. By selecting the switching speed and optimizing the design of disconnectors, VFFO can be reduced. The trapped charge behavior depends on the disconnector design and could be measured during type tests or evaluated based on simulations.

5. Insulation strength

Same as in EHV systems, a number of factors influence the insulation strength in UHV systems. Switching impulse strength is primarily an important strength, sometimes clearance to the tower side for an UHV I-string insulator with swing angle is decided by insulation strength under power frequency voltage.

The standard switching impulse voltage wave, identified in IEEE Std 4-1995, is usually used to obtain the clearance discharge voltage. However for UHV systems, the time-to-crest of switching overvoltage can be much higher than 250 μ s of the standard switching impulse time-to-crest, and depend on the UHV system conditions such as transmission line lengths and the origin of overvoltage. For air clearance of UHV transmission lines, the switching impulse flashover voltage is non-linearly related to the distance of the clearance. Flashover voltage presents its saturation feature as clearance increase. Therefore, the switching impulse clearance for UHV towers is bigger than linearly extended from EHV towers. On the other hand, the switching impulse flashover voltage with longer time-to-crest is greater than that with standard switching waveform. In order to improve the economy of an UHV project, air clearance test curves of switching impulse voltage with longer time-to-crest can be used for insulation coordination of transmission lines. And considering tests can be conducted easily, the standard switching impulse voltage waveform is recommended for insulation coordination of equipment and clearances in UHV substations. The safety margin of substation is increased by adopting the standard switching impulse voltage waveform.

6. Performance reliability criterion

UHV systems are built to satisfy the requirement of large-capacity power transmission. For UHV systems, it is especially important to reduce the lightning flashover rate and ensure the reliability of power transmission. Lightning flashover rate is based on the consequence of failure and the expected life of the equipment. For UHV transmission lines, the acceptable lightning flashover rate ranges from 0.1 to 0.5 flashovers per 100 km-year, which is lower than for EHV systems. The acceptable switching flashover rate for UHV systems is specified as generally 0.1 flashovers per 100 switching operations, which is much lower than 1 flashover per 100 switching operations for EHV systems.

The desired reliability of substations for lightning is normally specified in terms of the mean time between failures (MTBF). In order to decrease significant outage and repair times of substations, the MTBF for EHV gas-insulated substations have been set as high as 800 years in IEEE Std 1313.2™-1999. Considering the importance of UHV systems, the MTBF for UHV substations due to lightning is recommended to be more than 1000 years for GIS and MTS substations.