Comparison of Clearances Applying IEEE and IEC Standards for 230 kV Air Insulated Substation

T. Thanasaksiri†, Non-member

ABSTRACT

This paper analyzes the insulation levels and electrical air clearances of 230 kV air insulated substation (AIS). In order to get the basic lightning impulse insulation level (BIL) and clearances, the crest voltages at any equipment are required. By applying calculation method taken from IEEE Std. 1313.2, IEEE Std. 1427 and IEC 60071-2 the insulation levels and clearances have been found out and compared. The simplified calculation and simplified digital simulation via EMTP-ATPDraw have also been analyzed. The effect of elevation from sea level as well as the switching surge have been considered for insulation levels and clearances as recommended by the standards. According to IEEE Std. 1427 which taking into account the basic switching impulse insulation levels (BSL), the iterative method is inevitably required. Moreover, at this voltage level, the procedure for calculations refer to IEC 60071-2 in range I can also be applied. To compile with IEC 60071-2 for calculations the insulation levels and clearances, the iteration process accounting for BSL is not required. The clearances applying IEEE and IEC standards are closed and not significantly difference.

Keywords: BIL, BSL, AIS, EMTP, IEEE Std. 1313.2, IEEE Std. 1427, IEC 60071-2

1. INTRODUCTION

The insulation levels or withstand voltages, BIL (basic lightning impulse insulation level) and BSL (basic switching impulse insulation level) for equipment are classified by IEEE (Institute of Electrical and Electronics Engineers) and IEC (International Electrotechnical Commission). The IEEE standards involved for insulation coordination are IEEE Std. 1313.1 [1], 1313.2 [2], C62.82.1 (revision of 1313.1) [3] and 1427 [4]. The IEC standards involved for insulation coordination are IEC 60071-1 [5] and 60071-2 [6].

IEEE standard, for equipment in Class I (15 kV to 242 kV), the standard insulation withstand level include low frequency, short duration withstand voltage and BIL. For equipment in Class II (> 242 kV), the standard insulation withstand level include BIL and BSL. IEC standard, for equipment in Range I (1 kV to 245 kV), the standard insulation withstand level include low frequency, short duration withstand voltage and BIL. For equipment in Range II (> 245 kV), the standard insulation withstand level include BIL and BSL.

For 230 kV AIS, the standard insulation levels for equipment in Class I (IEEE) or Range I (IEC) of the system voltage being considered are shown in Table 1. The insulation levels, BIL may differ in the number but the minimum of 650 kV$_{peak}$ and maximum of 1,050 kV$_{peak}$ are the same for both standards. The insulation levels, short duration power frequency withstand voltage are quite the same except 480 kV$_{rms}$ for IEEE and 460 kV$_{rms}$ for IEC.

In order to get the BIL (simplified calculation or simplified digital simulation), the crest voltages at any equipment have to be found out. By applying simplified calculation method taken from IEEE Std. 1313.2 and IEEE Std. 1427 compared with simplified digital simulation, EMTP-ATPDraw [7] and also the procedure proposed by IEC 60071-2. The comparison of these standards, both the simplified calculation and digital simulation, taken into account the effect of elevations from sea level (0.5, 1.0, 1.5 and 2 km.) as well as the surge transferred originally from the switching surge have been considered in this work.

2. CALCULATIONS AND SYSTEM MODELLINGS

The purpose of this study is to compare and analyze the BIL and clearances which originated from the crest voltages obtained from simplified digital simulation using EMTP-ATPDraw and simplified calculations by applying equations from IEEE Std. 1313.2 and IEEE Std. 1427. Both standards applied the similar equations and procedures for calculating the insulation levels and air clearances [2], [4] which quite different from the procedures in IEC 60071-2 [6].

The sequence of determining the insulation levels and clearances based on the lightning surge at and above the sea levels follow IEEE Std. 1427 are summarized as shown in Fig. 1 and 2. The detail voltage calculations can be performed by applying the equations appears in the standards as shown in Fig. 2(a) or digital simulation via EMTP-ATPDraw as shown in Fig. 2(b). The part of simulation circuits in EMTP-ATPDraw is shown in Fig. 3. In this work will starting by follow the algorithms as shown in Fig. 1 and Fig. 2 respectively.

Manuscript received on July 3, 2024; revised on December 2, 2024; accepted on December 11, 2024. This paper was recommended by Associate Editor Komsan Hongesombut.

The author is with Department of Electrical Engineering, Chiang Mai University, Thailand.

†Corresponding author: tthanacmu@gmail.com

Digital Object Identifier: 10.37936/ecti-eec.2525231.254847

***Table 1**: Comparison of Standard Withstand Voltage.*

Standard	Maximum System Voltage (kV_{rms})	Standard Rated Short Duration Power Frequency Withstand Voltage (kV_{rms})	Standard Rated Lightning Impulse Withstand Voltage or BIL (kV_{peak})
*IEEE Std. C62.82.1 *IEEE Std. 1427	242	275 325 360 395 480	650 750 825 900 975 1050
+IEC 60071-1	245	(275) (325) 360 395 460	(650) (750) 850 950 1050

* IEEE Std. C62.82.1 and IEEE Std. 1427
\+ IEC 60071-1

***Table 2**: Data for BIL Calculations.*

Data description	Values
Maximum system voltage (U_s)	245 kV
Line surge impedance	488 Ω
span length	250 m
CFO	1,300 kV
SIPL (U_{ps})	410 kV
LIPL (U_{pl})	500 kV
Number of lines	2
Number of conductors/phase	2
BFR (Back flash rate)	2 FO/100 km/yr
MTBF	100 years

The circuit for digital simulation in Fig. 3 [2], [4] represented two 230 kV lines (Line 1 and Line 2). The overhead transmission line parameters for BIL and BSL calculations as shown in Table 2 and Table 3 respectively. Although for system voltage which is not greater than 242 kV (*IEEE) or 245 kV (+IEC), the clearances are mainly based on lightning surge but switching surge is involved and would affect insulation level as well [4]. To calculate the phase to ground clearance based on switching surge, the BSL required must be determined [4]. The calculations and system modeling using digital simulation are as follow.

2.1 Incoming Surge Model

For simplified calculation [2], [4], the distance to flashover is calculated using equation given in (1).

$$d_m = \frac{1}{n \times MTBF \times BFR} \tag{1}$$

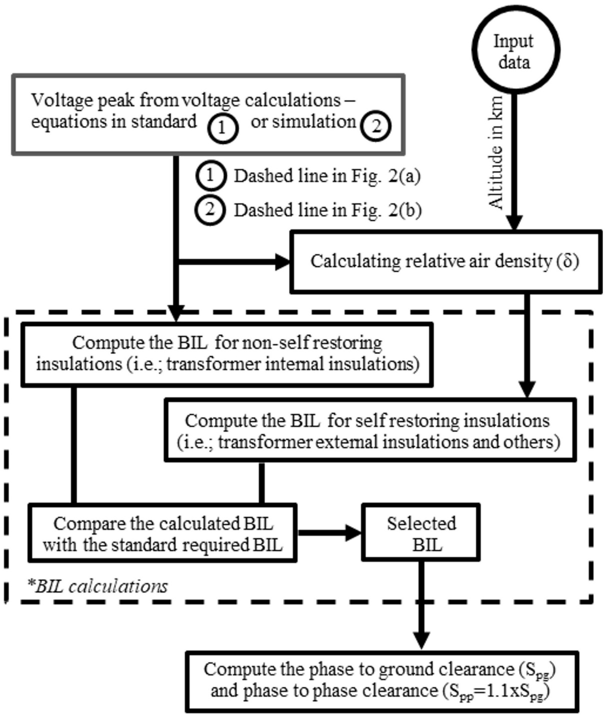

***Fig. 1**: Sequence of determining the insulation levels and electrical clearances based on lightning surge at and above the sea levels follow IEEE Std. 1427.*

***Table 3**: Data for BSL Calculations.*

Data description	Values
Maximum system voltage (U_s)	245 kV
Phase to ground withstand voltage, V_3	2.50 pu
Phase to phase withstand voltage, V_{30}	2.80 pu
SSFOR	1/100
Ratio 2% of energization (U_{p2}/U_{e2})	1.53
Ratio 2% of re-energization (U_{p2}/U_{e2})	1.5
Earth fault factor	1.5
Load rejection factor	1.4
Overvoltages originating from substation 1 (U_{e2}, U_{p2})	1.9, 2.9 pu
Overvoltages originating from substation 2 (U_{e2}, U_{p2})	3.0, 4.5 pu
α	0.50
Safety factor (K_{sf})	1.05, 1.15
σ_f/CFO	0.07
σ_{fp}/CFO_0	0.035
Gap factor	0.3
A, K_L	0.5-2.0, 0.67

where

$MTBF$ = mean time between failure, years,

BFR = back flash rate, number of flashover/100 km/yr,

n = number of lines connected to the bus.

The surge steepness for transformer and other equipment can be calculated using equation (2) which are 4,000

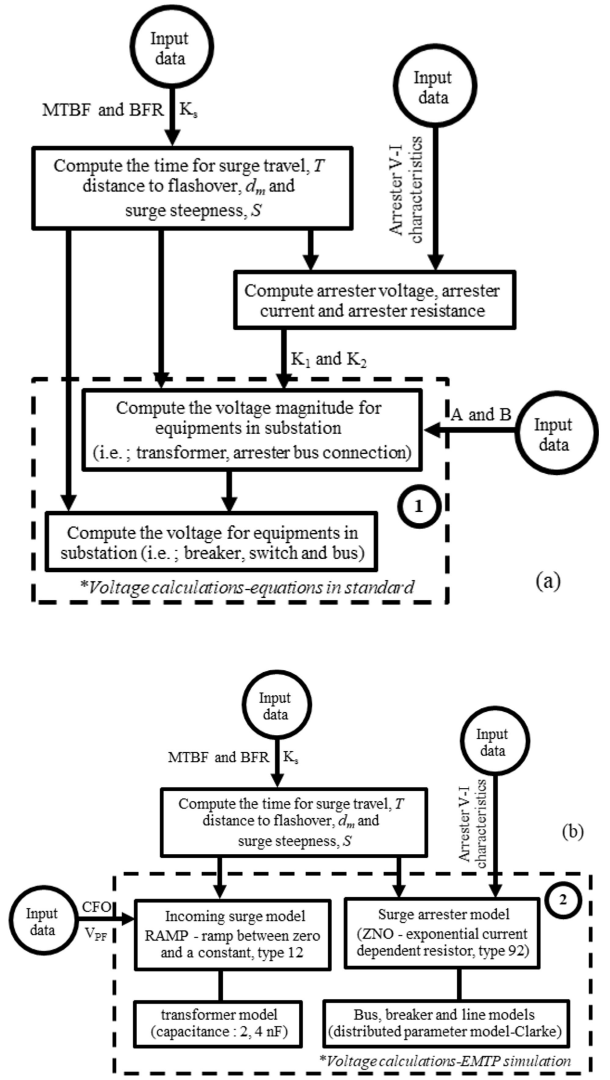

***Fig. 2**: Sequence of voltage calculations follow IEEE Std. 1427 a) equations given in standards b) EMTP simulation.*

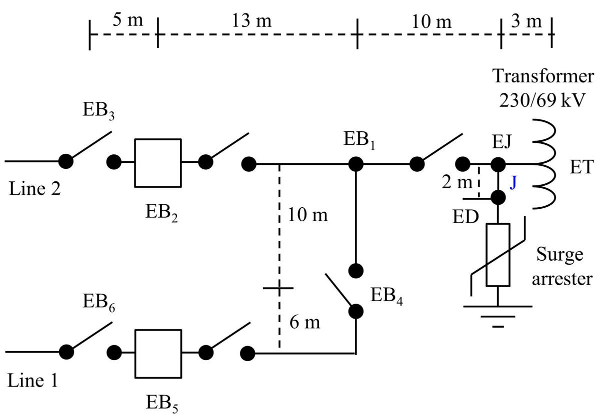

***Fig. 3**: Typical 230/69 kV line substation for EMTP simulation.*

and 2,000 kV/μs [2], [4] respectively.

$$S = \frac{K_s}{d_m} \tag{2}$$

where

K_s = corona constant,

d_m = distance to flashover point, m.

The crest voltages of incoming surge is assumed to be 1.2 times the CFO [2], which give the voltage equal to 1,560 kV. The ramp type 12 has been used for EMTP-ATPDraw simulation for 4,000 and 2,000 kV/μs as shown in Fig. 4 and Fig. 5 respectively.

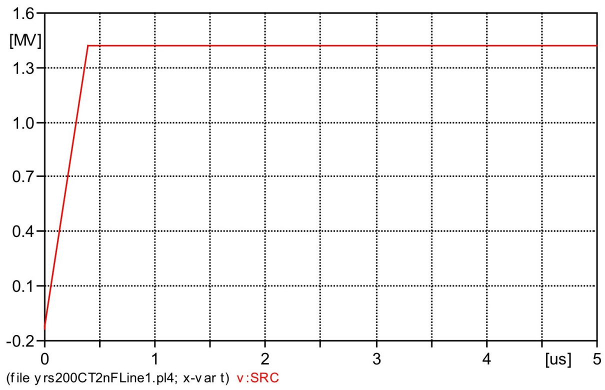

***Fig. 4**: Incoming surge of 4,000 kV/μs.*

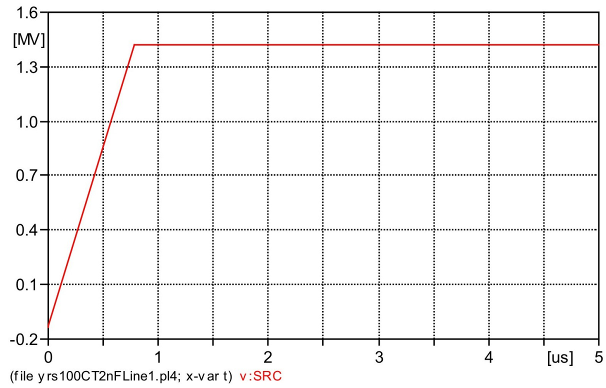

***Fig. 5**: Incoming surge of 2,000 kV/μs.*

2.2 Surge Arrester Model

MOV type 92 [8], [9] has been used for EMTP-ATPDraw simulation. Surge arrester V-I characteristics of 140 kV MCOV as shown on Fig. 6. The different V-I characteristics, rated and MCOV will give the different crest voltages as shown in this work.

2.3 Transformer Model

Transformer model when account for the lightning surge will dominated by capacitances (primary side, secondary side and across between two windings). So, transformers are modelled by single surge capacitances, which vary between 1 nF–6 nF (C_T), with 2 nF being an average value [2], [8], [9], [10]. In this work, surge capacitances of 2, 3, 4 and 6 nF have been applied.

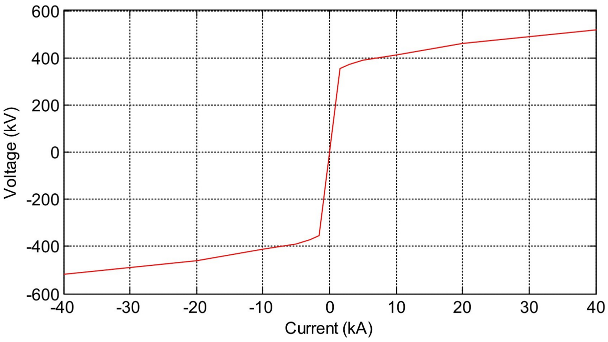

***Fig. 6**: Surge arrester V-I characteristics.*

2.4 Bus, Circuit Breaker and Line Models

The equipment besides transformer such as bus, circuit breaker and lines in substation have been represented using distributed parameter (Clarke) model [2], [8].

3. RESULTS

IEEE Std. 1313.2 [2] purposed the procedure for simplified calculation and simplified digital simulation for two lines station by dividing the system into two parts. The first part, transformer and adjacent equipment with both lines in service which can be represented by considering the incoming surge of 4,000 kV/μs or 200 years surge. The second part, other equipment not on transformer bus which can be represented by considering the incoming surge of 2,000 kV/μs or 100 years surge.

3.1 Crest Voltages from Simplified Calculation

The procedure for calculation the crest voltages which leading to BIL and BSL including phase to ground and phase to phase clearances have been taken form IEEE Std. 1313.2 and IEEE Std. 1427. The crest voltages at any point within substation obtained from simplified calculation are summarized in Table 4-7. The calculation including digital simulation start with equation (1), (2) and the crest voltages for simplified calculation at transformer, surge arrester, junction point, breakers, disconnecting switches and bus insulator can be calculated [2], [4].

For incoming surge on line 1, line entrance equipment (disconnecting switches and breaker) on line 1 (EB_6, EB_5, EB_4) will receive surge directly and get higher voltage than line entrance equipment on line 2 (EB_3, EB_2). Certainly for incoming surge on line 2, line entrance equipment on line 2 will get higher voltage than line entrance equipment on line 1 as shown in Table 4 and Table 5 (E_{b1}, E_{b2}, E_{b3}, E_{b4}, E_{b5}, E_{b6}). Because of the voltage calculations from the bus junction point (EB_1), junction point (EJ), surge arrester (ED) through transformer (ET) depends on the V-I characteristics of surge arrester so these locations will receive the same crest voltage (E_{b1}, E_j, E_d, E_t) as shown in Table 6 and Table 7.

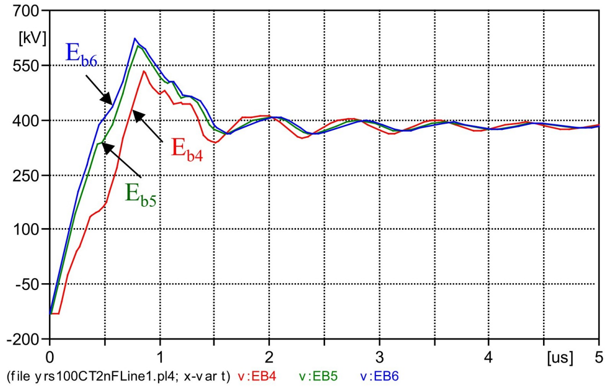

***Fig. 7**: Crest voltage from simulation at disconnecting switches and breaker on line 1 for 100 years surge, surge on line 1.*

3.2 Crest Voltages from Simplified Digital Simulation

Fig. 7 shows the crest voltages of disconnecting switches and circuit breaker on line 1 for incoming surge of 2,000 kV/μs (100 years surge) which originated on line 1. Fig. 8 shows the crest voltages of disconnecting switches and circuit breaker on line 2 for incoming surge of 2,000 kV/μs which originated on line 2. Fig. 9 shows the crest voltages at the junction point, surge arrester and transformer for incoming surge of 4,000 kV/μs (200 years surge) which originated on line 1. Fig. 10 shows the crest voltages at the junction point, surge arrester and transformer for incoming surge of 4,000 kV/μs which originated on line 2. Fig. 11 shows the arrester current for incoming surge of 4,000 kV/μs which originated on line 1. Fig. 12 shows the arrester current for incoming surge of 4,000 kV/μs which originated on line 2. The crest voltages obtained from EMTP-ATPDraw simulation are also summarized in Table 4-7.

For 100 years surge, both for incoming surge on line 1 and line 2, increasing the transformer surge capacitances (2, 3, 4 and 6 nF) will reduce the crest voltages. The same for 200 years surge, both for incoming surge on line 1 and line 2, increasing the transformer surge capacitances will also reduce the crest voltages as shown in Table 4-7. Based on the voltages from the EMTP-ATPDraw simulation at 2 nF (average value as mentioned in IEEE Std. 1313.2), the simplified calculations for the system being studied show that the minimum and maximum difference crest voltages are approximately 2% and 37% respectively.

3.3 BIL Calculations

To calculate the BIL, the crest voltages from simplified calculation and EMTP-ATPDraw simulation with the transformer surge capacitances of 2 nF have been selected [2], [10]. To cover for the 2 km elevation above sea level (the maximum height above the sea level from *IEEE and +IEC standards), the external insulation will

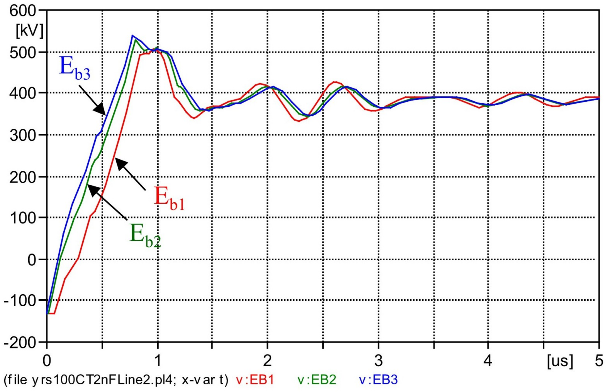

Fig. 8: *Crest voltage from simulation at disconnecting switches and breaker on line 2 for 100 years surge, surge on line 2.*

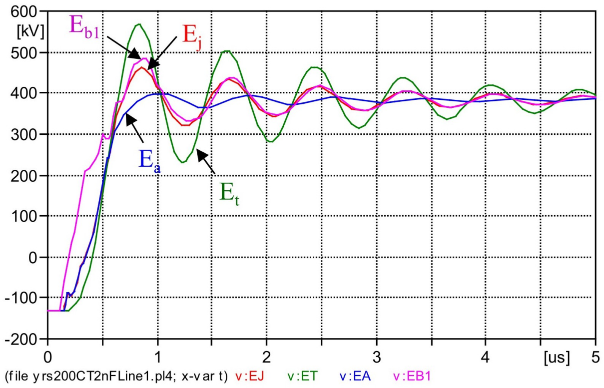

Fig. 9: *Crest voltage from simulation at junction point, surge arrester and transformer for 200 years surge, surge on line 1.*

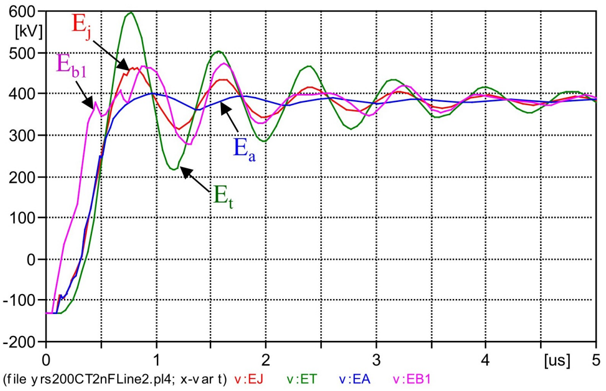

Fig. 10: *Crest voltage from simulation at junction point, surge arrester and transformer for 200 years surge, surge on line 2.*

have a higher BIL than the internal insulation [2], [4] by applying equation given in (3), the required BIL at elevation A above sea level can be calculated.

$$BIL_\delta = \frac{BIL}{e^{\left(\frac{-A}{8.6}\right)}} \tag{3}$$

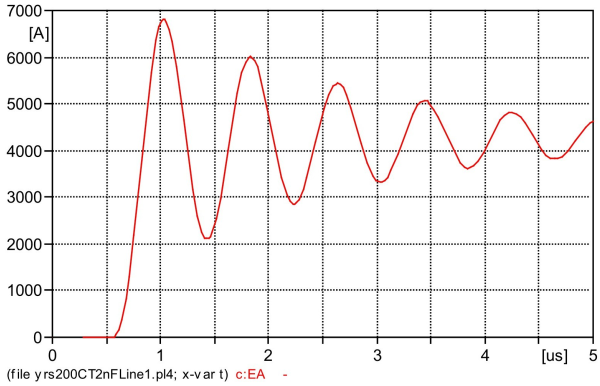

Fig. 11: *Arrester current from simulation for 200 years surge, surge on line 1.*

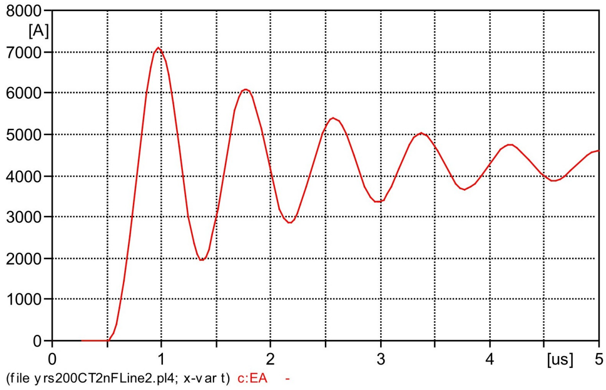

Fig. 12: *Arrester current from simulation for 200 years surge, surge on line 2.*

Table 4: *Comparison of Surge on Line 1, 100 year Surge.*

Voltage (kV)	Simplified calculation	C_T in EMTP-ATPDraw			
		2 nF	3 nF	4 nF	6 nF
E_{b4}	679	626	533	443	429
E_{b5}	931	725	603	509	473
E_{b6}	995	733	621	544	512
E_{b1}	543	553	518	455	450
E_{b2}	543	553	518	455	450
E_{b3}	543	553	518	455	450

Table 5: *Comparison of Surge on Line 2, 100 year Surge.*

Voltage (kV)	Simplified calculation	C_T in EMTP-ATPDraw			
		2 nF	3 nF	4 nF	6 nF
E_{b4}	543	578	505	455	450
E_{b5}	543	578	505	455	450
E_{b6}	543	578	505	455	450
E_{b1}	543	578	505	455	450
E_{b2}	715	655	528	443	432
E_{b3}	784	667	538	441	431

where

BIL_δ = the required BIL at sea level, kV,

A = elevation above sea level, km.

***Table 6**: Comparison of Crest Voltages and Current for Surge on Line 1, 200 year Surge.*

Voltage (kV), Current (kA)	Simplified calculation	C_T in EMTP-ATPDraw			
		2 nF	3 nF	4 nF	6 nF
E_t	558	590	567	527	503
E_j	462	474	461	442	432
E_d	341	395	399	401	400
E_{b1}	726	547	485	446	427
I_A	7	6.1	6.8	7.1	7.1

***Table 7**: Comparison of Crest Voltages and Current for Surge on Line 2, 200 year Surge.*

Voltage (kV), Current (kA)	Simplified calculation	C_T in EMTP-ATPDraw			
		2 nF	3 nF	4 nF	6 nF
E_t	558	613	596	529	499
E_j	462	482	464	449	424
E_d	341	398	400	401	400
E_{b1}	726	532	473	499	455
I_A	7	6.6	7.1	7.2	7

From the system being studied, the required BIL at sea level and at 2 km elevation are summarized in Table 9-12. The standard BIL as shown in the Table 9-12 are considered from the set of the list of standard rated impulse withstand voltages both IEEE Std. 1313.1, C62.82.1 [1], [3] and IEC 60071-1 [5]. For examples, the standard BIL 550/650 of external bushing of transformer from simplified calculation as shown in the Table 9 means the standard BIL of 550 kV can cover insulation at the sea level but at the 2 km above sea level, the insulation level should be 650 kV.

The standard BIL in Table 9-12 have been compared with the standard insulation levels in Table 1 which bring to the selected BIL. The standard BIL as well as the selected BIL at the elevation of 2 km from the simplified calculation for bus insulators are not in the range of Table 1, both for IEEE and IEC as shown in the Table 9 and 10.

The BIL selected which is coming from the EMTP-ATPDraw simulation give all the insulation levels in the range as shown in Table 8, 11 and 12, both for *IEEE and +IEC insulation levels have been justified. The selected BIL from Table 11 and 12 will lead to the phase to ground and phase to phase clearances calculations and compared with the insulation levels and clearances from Table 8.

Based on BIL at 2 km elevation from sea level. To calculate phase to ground and phase to phase clearances follow the IEEE Std. 1313.2, the highest crest voltage in the substation from Table 8 is 733 kV (crest voltage from digital simulation), and therefore, the required clearance is calculated by using a gradient of 605 kV/m [2] (phase-ground and phase-phase clearances are equal = 733/605 = 1.21 m.). To calculate phase to ground and phase to phase

***Table 8**: Crest Voltages.*

Equipment	Simplified Calculation	EMTP Simulation
Transformer	558	613
Transformer bushing -internal -external	 558 558	 613 613
Circuit breaker	931	725
Disconnecting switch	931	725
Bus insulators	995	733

***Table 9**: BIL Based on Simplified Calculations (* IEEE).*

Equipment	Required BIL (kV)		Standard BIL (kV)	Selected BIL (kV)
	Sea level	2 km		
Transformer	586	586	650/650	650
Transformer bushing -internal -external	 586 486	 586 615	 650/650 550/650	 650 650
Circuit breaker	809	1024	825/1050	1050
Disconnecting switch	809	1024	825/1050	1050
Bus insulators	865	1092	900/-	-

***Table 10**: BIL Based on Simplified Calculations (+ IEC).*

Equipment	Required BIL (kV)		Standard BIL (kV)	Selected BIL (kV)
	Sea level	2 km		
Transformer	586	586	650/650	650
Transformer bushing -internal -external	 586 486	 586 615	 650/650 550/650	 650 650
Circuit breaker	809	1024	850/1050	1050
Disconnecting switch	809	1024	850/1050	1050
Bus insulators	865	1092	950/-	-

clearances follow the IEEE Std. 1427, the selected BIL in the substation from Table 11 is 825 kV and from Table 12 is 850 kV. The required phase to ground clearance is calculated by using a gradient of 526 kV/m [4] (*IEEE : phase-ground clearance = 825/526 = 1.57 m. and *IEC : phase-ground clearance = 850/526 = 1.62 m.) and the phase to phase clearance = 1.73 and 1.78 m. respectively. For the highest crest voltage in the substation is 995 kV (crest voltage from simplified calculation), the clearances can also be calculated. From the system being studied

Table 11: *BIL Based on EMTP Simulations (* IEEE).*

Equipment	Required BIL (kV)		Standard BIL (kV)	Selected BIL (kV)
	Sea level	2 km		
Transformer	644	644	650/650	750
Transformer bushing -internal -external	 644 533	 644 675	 650/650 550/750	 750 750
Circuit breaker	630	798	650/825	825
Disconnecting switch	630	798	650/825	825
Bus insulators	637	806	650/825	825

Table 12: *BIL Based on EMTP Simulations (+ IEC).*

Equipment	Required BIL (kV)		Standard BIL (kV)	Selected BIL (kV)
	Sea level	2 km		
Transformer	644	644	650/650	750
Transformer bushing -internal -external	 644 533	 644 675	 650/650 550/750	 750 750
Circuit breaker	630	798	650/850	850
Disconnecting switch	630	798	650/850	850
Bus insulators	637	806	650/850	850

Table 13: *Calculated Clearances Based on BIL.*

Method	Phase to ground clearance (m)		Phase to phase clearance (m)	
	*IEEE	+IEC	*IEEE	+IEC
Simulation (IEEE Std. 1313.2)	1.21	1.21	1.21	1.21
Calculation (IEEE Std. 1313.2)	1.64	1.64	1.81	1.81
Calculation (IEEE Std. 1427)	1.57	1.62	1.73	1.78

as explained, the comparison of phase to ground and phase to phase clearances are summarized and is shown in Table 13. The clearances from IEEE Std. 1427 are closed to the clearances from IEEE Std. 1313.2 by mean of simplified calculation, 4.4-4.6% differences but 30-34% differences by simplified digital simulation.

3.4 Critical Withstand Voltage

The critical phase to ground and phase to phase withstand voltages (V_{3crit}, V_{30crit}) from switching surge can be determined. Besides the critical withstand voltages, the insulation levels and clearances can be calculated as shown in sequences of Fig. 13. The critical withstand voltages including BSLs and clearances at the sea level can be calculated, follow the flow chart as shown in Fig. 13(a) but when consider all these values above the sea level the iterative process is required as shown in Fig. 13(b).

Calculations the insulation levels and clearances above the sea level need to take some numbers which is performed from the calculations at the sea level. Selection of the phase to phase clearances which account for switching surge conditions will follow the same concepts and equations used in the selection of phase to ground clearances with the substitution of appropriate phase to phase factors are required [4]. The detail calculations correspond to Fig. 13 can be found in [2], [4] and [9], [11].

From Fig. 13(a), at the sea level, the phase to ground clearance can be calculated by applying equation given in (4).

$$S_{pg} = \frac{8}{\left(\frac{3400\times k_g}{CFO}\right) - 1} \tag{4}$$

where

$$CFO = \left(\frac{V_3}{1-3\left(\frac{\sigma_f}{CFO}\right)}\right)\times V_{base}$$

And the phase to ground BSL can also be calculated by applying equation given in (5).

$$BSL_{pg} = CFO\left(1-1.28\left(\frac{\sigma_f}{CFO}\right)\right) \tag{5}$$

The phase to phase clearance can be calculated by applying equation given in (6).

$$S_{pp} = \frac{8}{\left(\frac{3400\times k_g}{CFO_p}\right) - 1} \tag{6}$$

where

$$CFO_p = \frac{CFO_0}{1-\propto\left(1-K_L\right)}$$

and

$$CFO_0 = \left(\frac{V_{30}}{1-3\left(\frac{\sigma_{fp}}{CFO}\right)}\right)\times V_{base}$$

And the phase to ground BSL can also be calculated by applying equation given in (7).

$$BSL_{pp} = CFO_p\left(1-1.28\left(\frac{\sigma_{fp}}{CFO}\right)\right) \tag{7}$$

From Fig. 13(b), the insulation levels and clearances above the sea levels can be calculated as follow, starting with the altitude adjustments by applying equation given in (8), the relative air density, δcan be calculated.

$$\delta = 0.997 - 0.106\times A \tag{8}$$

where

A = altitude above the sea level, km.

The phase to ground clearance (S_{pg}) can be calculated by applying equation given in (9) and phase to phase

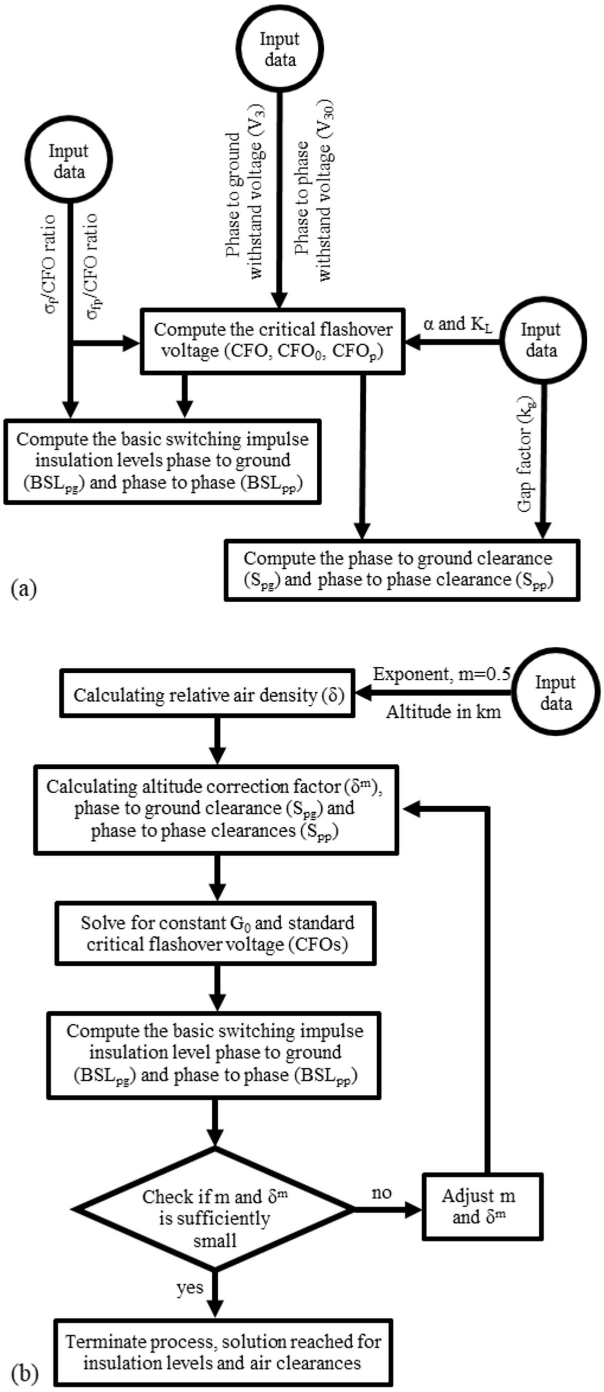

***Fig. 13**: Sequence of determining the insulation levels and electrical clearances based on the switching surge follow IEEE Std. 1427 (a) at the sea level (b) above the sea levels.*

clearance (S_{pp}) can also be calculated by applying equation given in (10).

$$S_{pg} = \frac{8}{\left(\frac{3400 \times k_g \times \delta^m}{CFO}\right) - 1} \tag{9}$$

$$S_{pp} = \frac{8}{\left(\frac{3400 \times k_g \times \delta^m}{CFO_p}\right) - 1} \tag{10}$$

***Table 14**: Critical Withstand Voltage Based on BSL.*

Critical phase-ground voltage (V_{3crit})		Critical phase-phase voltage (V_{30crit})	
*IEEE	+IEC	*IEEE	+IEC
Clearance : 1.57 m	Clearance : 1.62 m	Clearance : 1.73 m	Clearance : 1.78 m
V_{3crit} : 2.37 pu	V_{3crit} : 2.43 pu	V_{30crit} : 2.50 pu	V_{30crit} : 2.56 pu

The phase to ground BSL can be calculated by applying equation given in (11).

$$BSL_{pg} = \frac{CFO_{spg}}{1.0471} \tag{11}$$

where

$$CFO_{spg} = G_o \times 500 \times S_{pg}$$

and by solving the quadratic equation given in (12), the constant G_o can be found.

$$m = 1.25 G_o \left(G_o - 0.2\right) \tag{12}$$

The phase to phase BSL can also be calculated by applying equation similar to equation (11). Recalculating m and δ^m until the solutions are within the tolerance.

The critical withstand voltages (V_{3crit}, V_{30crit}) in per unit from switching surge correspond to phase to ground and phase to phase clearances based on BSL both for *IEEE and +IEC standard insulation levels are shown in Table 14. From the Table 14, to follow the *IEEE insulation level, the critical phase to ground and phase to phase withstand voltages are 2.37 and 2.50 pu respectively. To follow the +IEC insulation level, the critical phase to ground and phase to phase withstand voltages are 2.43 and 2.56 pu respectively. The critical phase to phase withstand voltage is higher than the phase to ground withstand voltage at least by approximately 5.5%.

3.5 Clearances Based on Switching Surge

From Table 14, the critical voltages for *IEEE are V_{3crit} = 2.37 pu and V_{30crit} = 2.50 pu (2.43 and 2.56 pu for +IEC) have been found out as the minimum voltage. To calculate the phase to ground (S_{pg}) and phase to phase clearances (S_{pp}) based on switching surge at the sea level, the critical flashover voltages (CFO, CFO_0, CFO_p) must be determined. The required data and steps for BSLs calculations are given in Table 3 and in Fig. 13(a) respectively. By assuming that the phase to phase withstand voltage (V_{30} = 2.8 pu) is higher than the phase to ground withstand voltage (V_3 = 2.5 pu) by 30% [4]. The procedure for calculation of the required phase to ground and phase to phase BSLs (BSL_{pg} and BSL_{pp}) has been applied with constants as shown in Fig. 13(a).

To calculate the phase to ground and phase to phase clearances and BSLs above the sea level, the solutions require an iterative process as shown in Fig. 13(b). The sea level and the altitude of 0.5, 1, 1.5 and 2 km above the

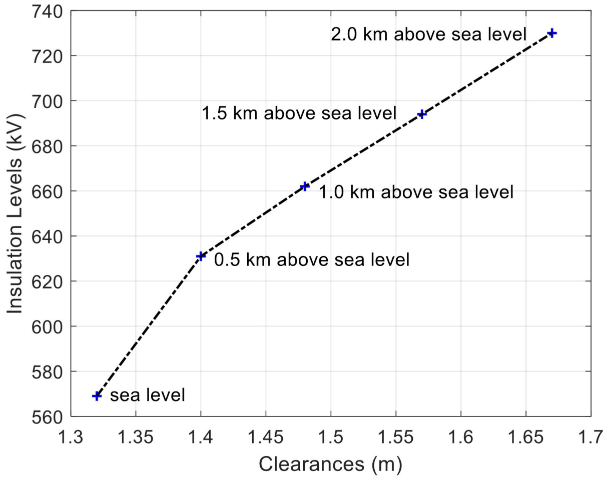

***Fig. 14**: The relation between phase to ground clearances and insulation levels at different sea levels.*

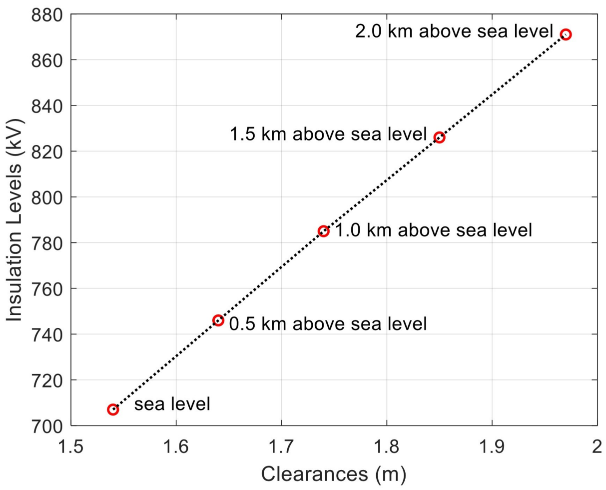

***Fig. 15**: The relation between phase to phase clearances and insulation levels at different sea levels.*

sea level have been considered and the results are shown in Fig. 14 for phase to ground clearances and Fig. 15 for phase to phase clearances. Based on BSL, the minimum clearance at sea level should be 1.32 m phase to ground and 1.54 m phase to phase. The minimum clearance at 2 km elevation from sea level should be 1.67 m phase to ground and 1.97 m phase to phase (not include the safety clearances).

Refer to both IEEE Std. 1427, the recommended insulation levels and electrical clearances at the sea level based on BIL are shown in Fig. 16 [13]. For example, at the selected insulation level of 650 kV, the minimum electrical clearances phase to ground and phase to phase should be 1.235 and 1.360 m respectively. At the selected insulation level of 825 kV, the minimum electrical clearances phase to ground and phase to phase should be 1.570 and 1.725 m respectively. Again the phase to phase clearance is greater than the phase to ground clearance approximately by 10%. The insulation

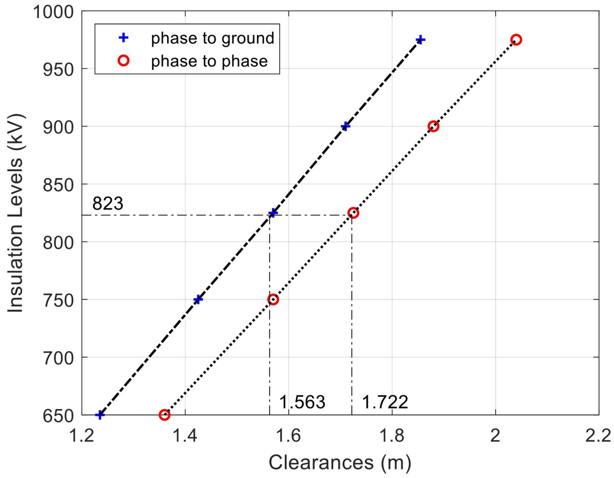

***Fig. 16**: The relation between minimum insulation levels, BIL and clearances recommended by IEEE Std. 1427.*

***Table 15**: Insulation Levels Applied IEC 60071-2.*

Insulation types	Calculated insulation levels (kV)		Selected insulation levels (kV)	
	Phase to ground	Phase to phase	Phase to ground	Phase to phase
External insulation	803	1,046	850	1,050
Internal insulation	705	798	750	850

strength decreases as a linear function of the relative air density [1] which means at the altitude of 2 km above the sea level, the BIL and clearances must be divided by the relative air density (0.79).

From Fig. 16, the insulation level of 650 kV can be applied at the sea level with the clearances of 1.235 m phase to ground and 1.360 m phase to phase but at the altitude of 2 km above the sea level the insulation should be 650/0.79 = 823 kV with the clearances of 1.235/0.79 = 1.563 (< 1.57 *IEEE and 1.62 $^{+}$IEC) m phase to ground and 1.36/0.79 = 1.722 (< 1.73 *IEEE and 1.78 $^{+}$IEC) m phase to phase. From these numbers, they show that the BIL and clearances are well within the values as recommended.

3.6 Insulation Levels Based on IEC 60071-2

When refer to IEC 60071-2 [4], follow the sequence of finding the insulation levels. The recommended insulation levels and electrical clearances based on BIL are calculated [11] and has been shown in Fig. 17 [12], [13]. The calculated and selected insulation levels at the altitude of 2 km above sea level are summarized in Table 15 and the relation between minimum insulation levels and clearances at the altitude of 2 km above the sea level are given in Fig. 18 [13]. At the altitude of 2 km above sea level. For external insulation, the selected BIL should be 850 kV phase to ground and 1,050

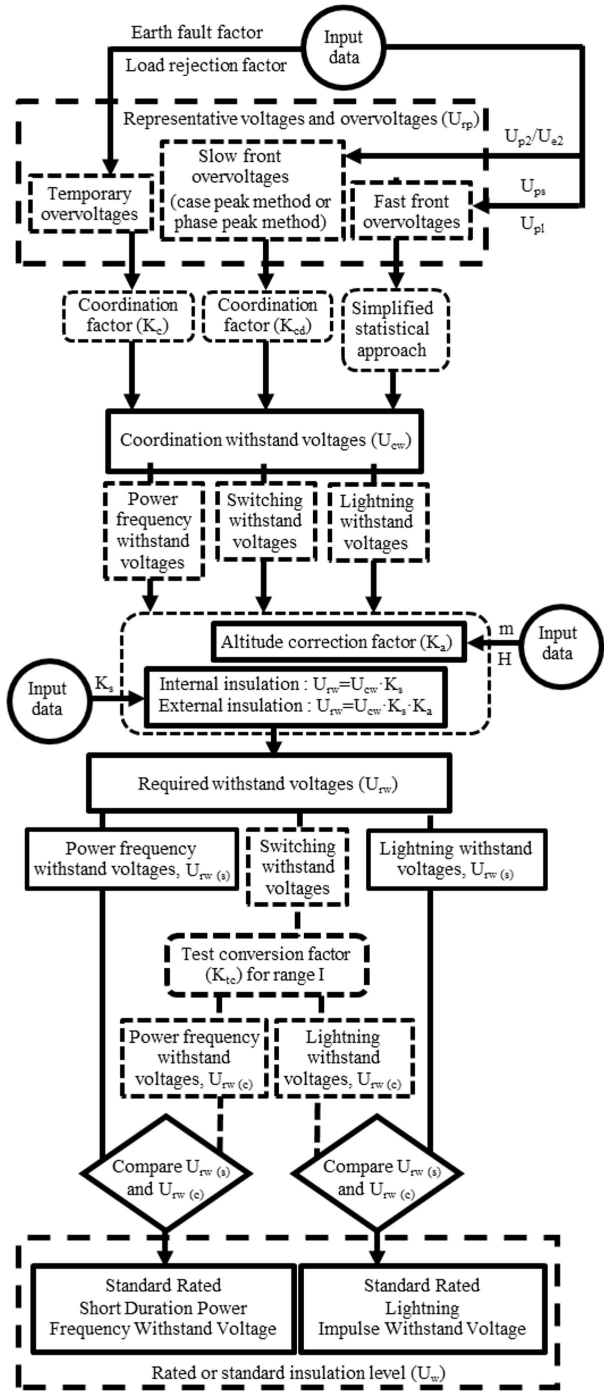

Fig. 17: Sequence of determining the insulation levels (BIL and BSL) and electrical clearances (phase to ground and phase to phase clearances) at and above the sea levels follow IEC 60071-2.

kV phase to phase and the required clearances should be at minimum of 1.6 m phase to ground and 2.1 m phase to phase. For internal insulation, the selected BIL should be 750 kV phase to ground and 850 kV phase to phase and the required clearances should be at minimum of 1.5 m phase to ground and 1.7 m phase to phase. The clearances from *IEEE and +IEC standards, both for

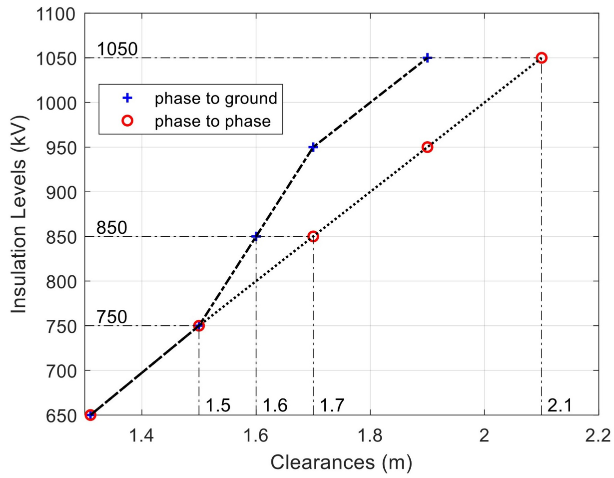

Fig. 18: The relation between minimum insulation levels, BIL and clearances applied IEC 60071-2.

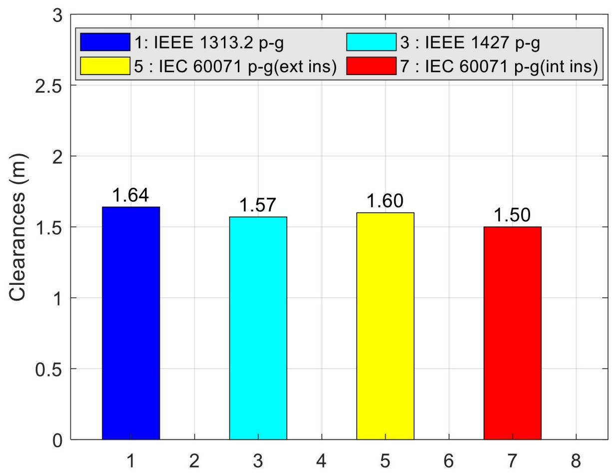

Fig. 19: Comparison of phase to ground clearances between IEEE 1313.2, 1427 and IEC 60071-2.

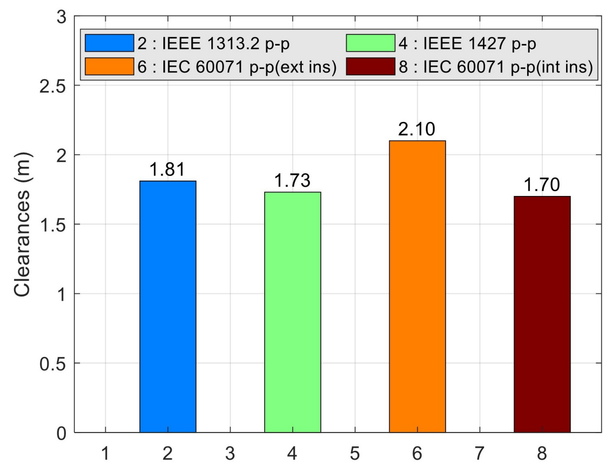

Fig. 20: Comparison of phase to phase clearances between IEEE 1313.2, 1427 and IEC 60071-2.

phase to ground and phase to phase clearances, are closed and not significantly difference as shown in Fig. 19 and Fig. 20 respectively.

4. CONCLUSIONS

This paper compares the insulation levels and electrical clearances in 230 kV air insulated substation applying IEEE Std. 1313.2, IEEE Std. 1427 and IEC 60071-2. For the voltage level being considered, the low frequency, short duration withstand voltage and BIL are mainly factors which can be leading to the final insulation levels and electrical clearances of all equipment in substation but the effect of switching impulse, BSL to insulation levels can also dominated the insulation levels and clearances which received from BIL and short duration withstand voltage.

For the voltage level, both for IEEE (class I) and IEC (range I) standards, BIL calculation is much more complicated. Especially when taking into account the effect of switching impulse. According to IEEE Std. 1427 which taking into account the BSL, the simplified by means of the iterative method is required. Besides calculations, the simulations may be the other choice which has been implemented using simplified models via EMTP-ATPDraw. To compile with IEC 60071-2 for calculations the insulation levels and electrical clearances, the iteration process accounting for the standard rated switching impulse withstand voltage or BSL is not required. The electrical clearances applying *IEEE and $^{+}$IEC standards are closed and not significantly difference.

REFERENCES

[1] "IEEE Standard for Insulation Coordination - Definitions, Principles, and Rules," in *IEEE Std 1313.1-1996*, pp.1-18, 1996.

[2] "IEEE Guide for the Application of Insulation Coordination," in *IEEE Std 1313.2-1999*, pp.1-66, 1999.

[3] "IEEE Standard for Insulation Coordination– Definitions, Principles, and Rules," in *IEEE Std C62.82.1-2010 (Revision of IEEE Std 1313.1-1996)*, pp.1-22, 2011.

[4] "IEEE Guide for Recommended Electrical Clearances and Insulation Levels in Air Insulated Electrical Power Substations," in *IEEE Std 1427-2020 (Revision of IEEE Std 1427-2006)*, pp.1-51, 2021.

[5] "IEC *Insulation Coordination-Part 1: Definitions, Principles, and Rules"* in *IEC 60071-1*, pp.1-78, 2006.

[6] "IEC *Insulation Coordination-Part 2: Application guide"* in *IEC 60071-2,* pp.1-260, 1996.

[7] Hans Kristian HØidalen, László Prikler, Francisco Peñaloza, *ATPDraw version 7.5p6*, 2024.

[8] IEEE Modeling and Analysis of System Transients Working Group, "Modeling Guidelines for Fast Front Transients," *IEEE Transactions on Power Delivery*, vol. 11, no. 1, pp. 493-506, January 1996.

[9] Andrew R. Hileman, *Insulation Coordination for Power Systems*, Marcel Dekker, 1999.

[10] Juan A. Martinez-Velasco, *Power System Transients*, CRC Press, 2010.

[11] T. Thanasaksiri, "Insulation level and clearances for 230 kV air insulated substation," *2014 11th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Nakhon Ratchasima, Thailand, 2014, pp. 1-6.

[12] T. Thanasaksiri, "Iterative method for clearances and insulation levels based on switching surge," *2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Hua Hin, Thailand, 2015, pp. 1-4.

[13] T. Thanasaksiri, "Comparison of IEEE and IEC standards for calculations of insulation levels and electrical clearances for 230 kV air insulated substation," *2016 13th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*, Chiang Mai, Thailand, 2016, pp. 1-6,

T. Thanasaksiri was born in 1971. He received the B.Eng. degree in electrical engineering from King's Mongkut Institute of Technology, Ladkrabang, Thailand and M.S. degree in the field of power system from Clemson University, Clemson, USA, in 1994 and 1997, respectively. Since 1994, he is with Chiang Mai University, Thailand. His current research interests include lightning modeling and simulation, relay and protective devices simulation and analysis, high voltage and hvdc simulations.