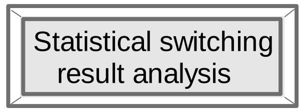
Statistical Switching Result Analysis



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Henry Gras, 6/2/2023 3:24 PM

1 Introduction

This device is an option device processing results of statistical simulations where random numbers are applied to switching closing times. It provides parameters which are required to apply insulation coordination standards such as IEC 60071 and IEEE Std 1313.2.

2 Get started.

The steps to perform the Statistical Switching Analysis are:

1. **Insulation coordination voltage probes** of the Switching Toolbox library must be included in the design at buses or across devices where the analysis is to be performed.
    - *Insulation coordination voltage probes* are placed at buses where phase-to-ground and phase-to-phase overvoltages are monitored (see Figure 2). Standard Insulator characteristics may be entered in the Insulation Coordination Data tab (see Figure 1) to allow the determination of the rate of failures (see 3.2). The study outcomes described in 3 are determined to all buses connected to such probes.
    These probes may also be placed at locations to represent several insulators in parallel which are assumed to have similar voltage waveforms during the transient events simulated. For example, a probe may be placed along a transmission line to study the insulation coordination of a section of few kilometers. The assumption is the voltage at the location where the probe is connected is the same for every insulator.
    - *Insulation coordination longitudinal voltage probes* are placed across devices where longitudinal overvoltages are monitored (i.e. Open circuit breakers) (see Figure 2). The + sign must be placed on the side where the transients are studied. Standard Insulator characteristics may be entered in the Insulation Coordination Data tab (see Figure 1) to allow the determination of the rate of failures (see 3.2). The study outcomes described in 3 are determined to all buses connected to such probes.

See 3.2.2 for more information on how to setup the probes data for the analysis. Details tooltips are also available in the device mask by placing the mouse cursor over parameter names.

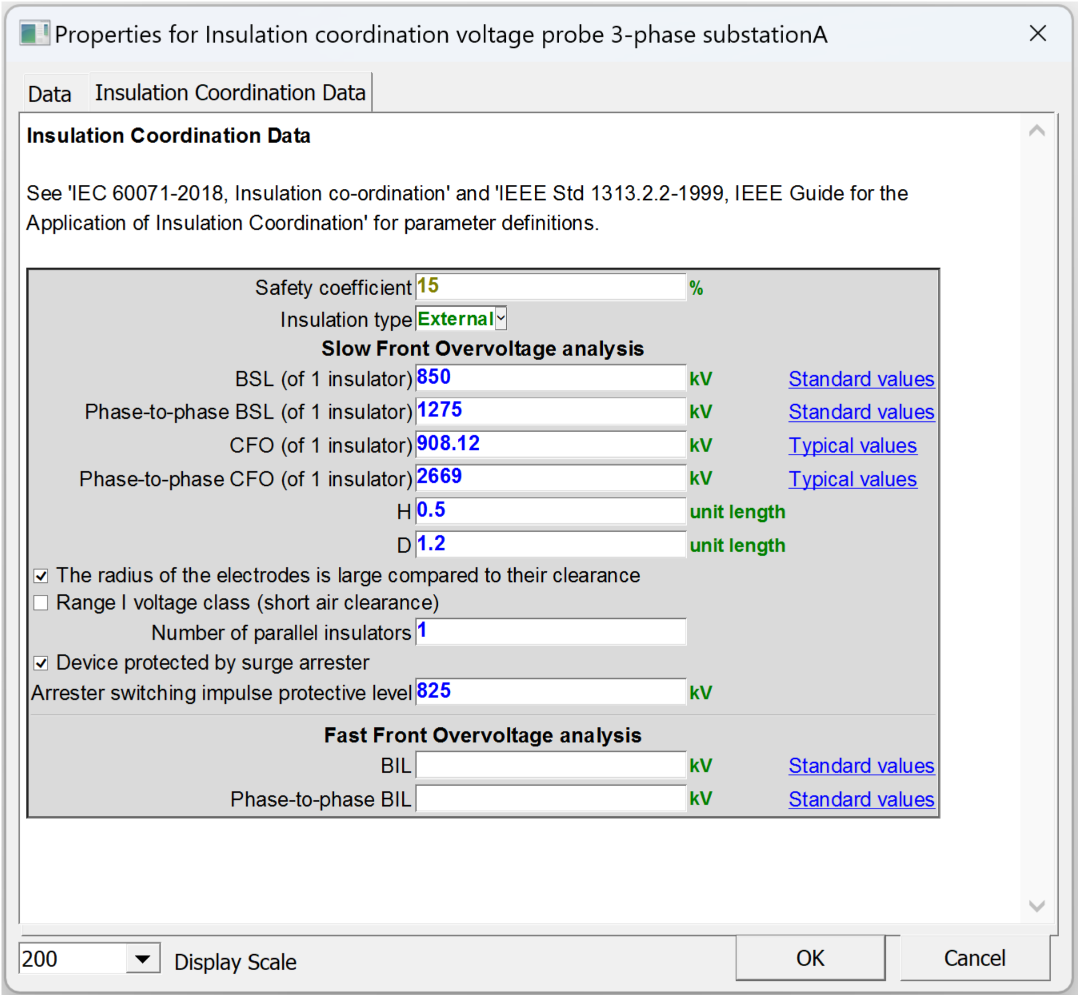


Figure 1: Insulation Coordination Data of an Insulation coordination voltage probes

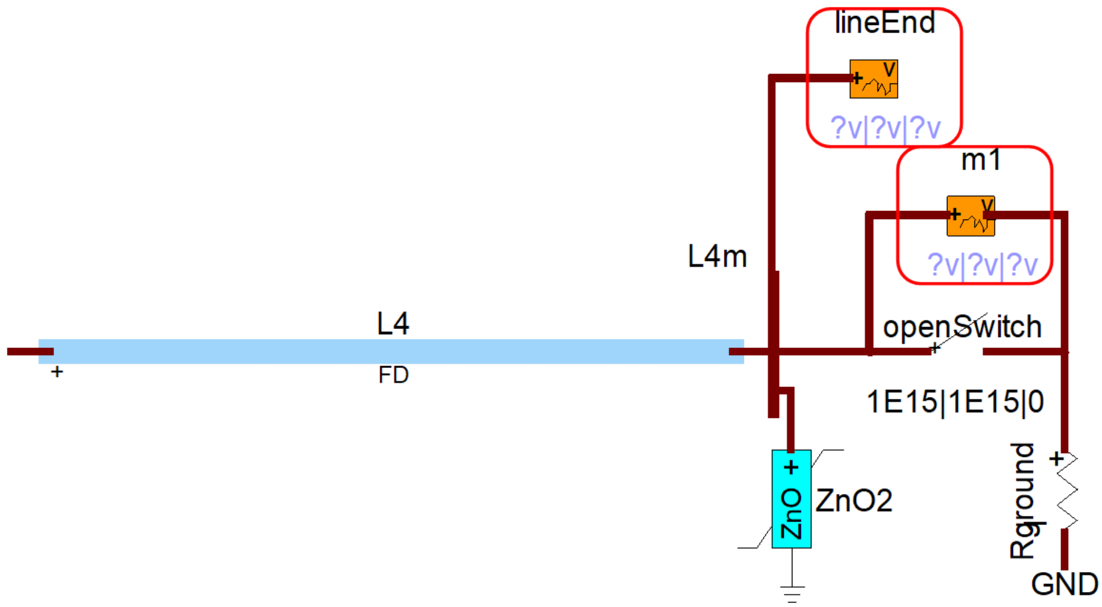


Figure 2: Example of an Insulation coordination voltage probe connected to a line end bus and an Insulation coordination longitudinal voltage probe connected across an open switch.

2. **A statistical study must be performed prior to starting the analysis**. To perform such studies, a Statistical option device (from Options library) (see Figure 3) must be included in the design and set for Statistical. See the Statistical option device documentation for more information on how to set it up. Figure 4 shows a typical configuration of the Statistical option device for switching analysis.

Figure 3: Statistical option device (from the Options library) required to run the statistical studies prior to the Statistical Switching Result Analysis

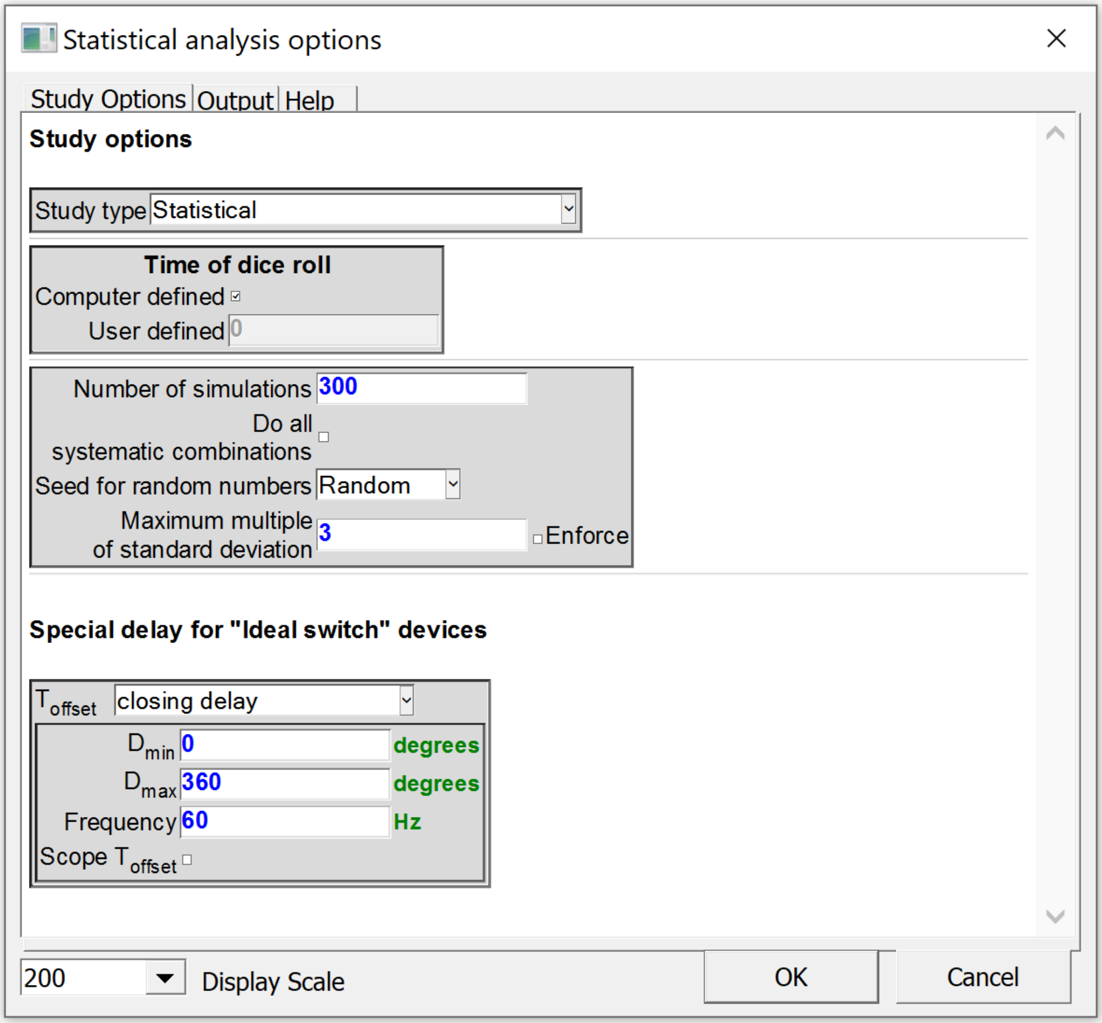


Figure 4: Typical configuration of the Statistical option device for switching analysis.

The **'Save both min and max values for all scope variables' must be enabled** in the Output tab of the Statistical Option device before starting the statistical simulation.

3. **The Random data tab** must be set up for all switches and breakers whose switching operations are being analyzed.
   For example, if an energization is performed by only one breaker, the Random data tab of this device must be set up.
   If the energization is performed by several breakers, for example, by an auxiliary breaker energizing through a pre-insertion resistance and a main breaker completing the energization, the Random data of both breakers must be configured. In this case, the pre-insertion resistance breaker is a Master and the main breaker is a slave with a delay with the Master.
   More information may be found in the ideal switch documentation.
   A typical configuration may be found in Figure 5.

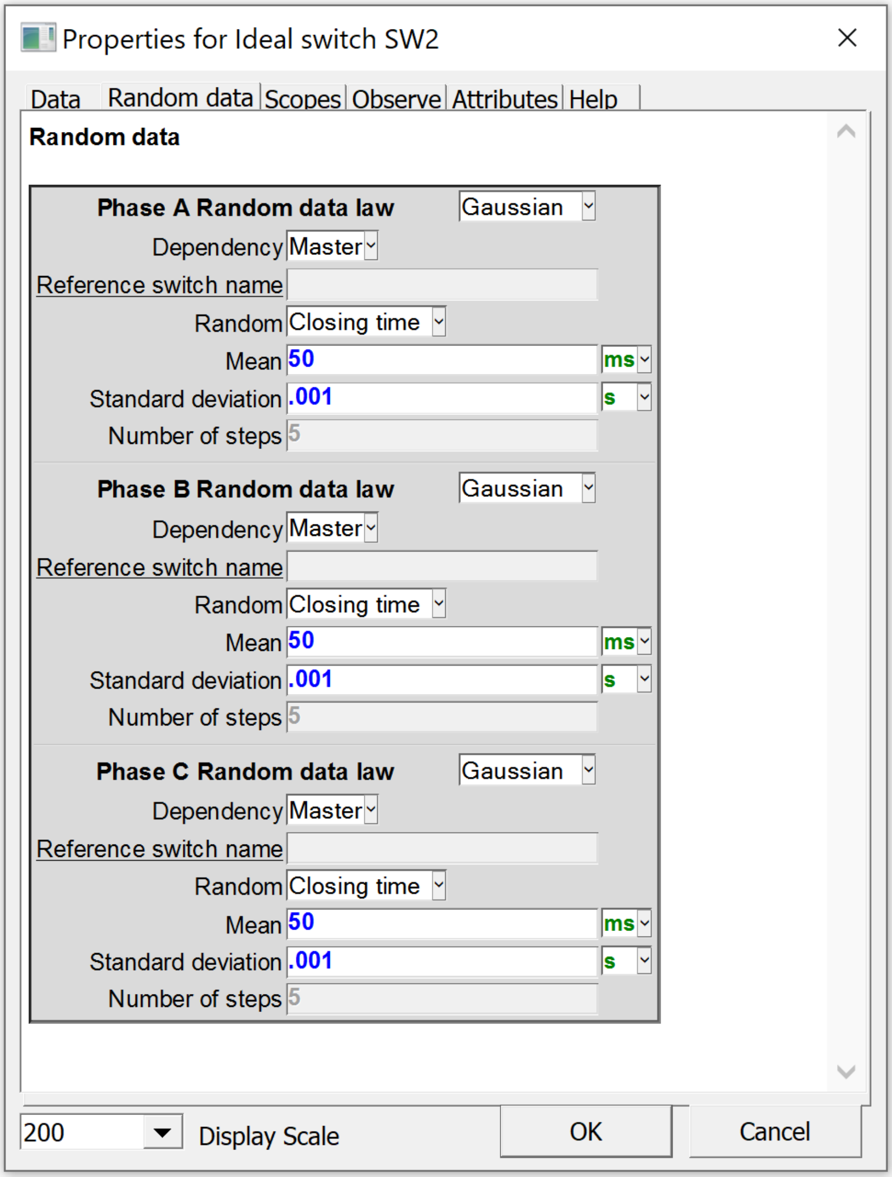


Figure 5: Typical configuration of the Random data tab of a breaker for an energization performed by one switching device.

4. The Random switching times of all switches or breakers with Random data setup must be checked in the Scopes tab (see Figure 6).

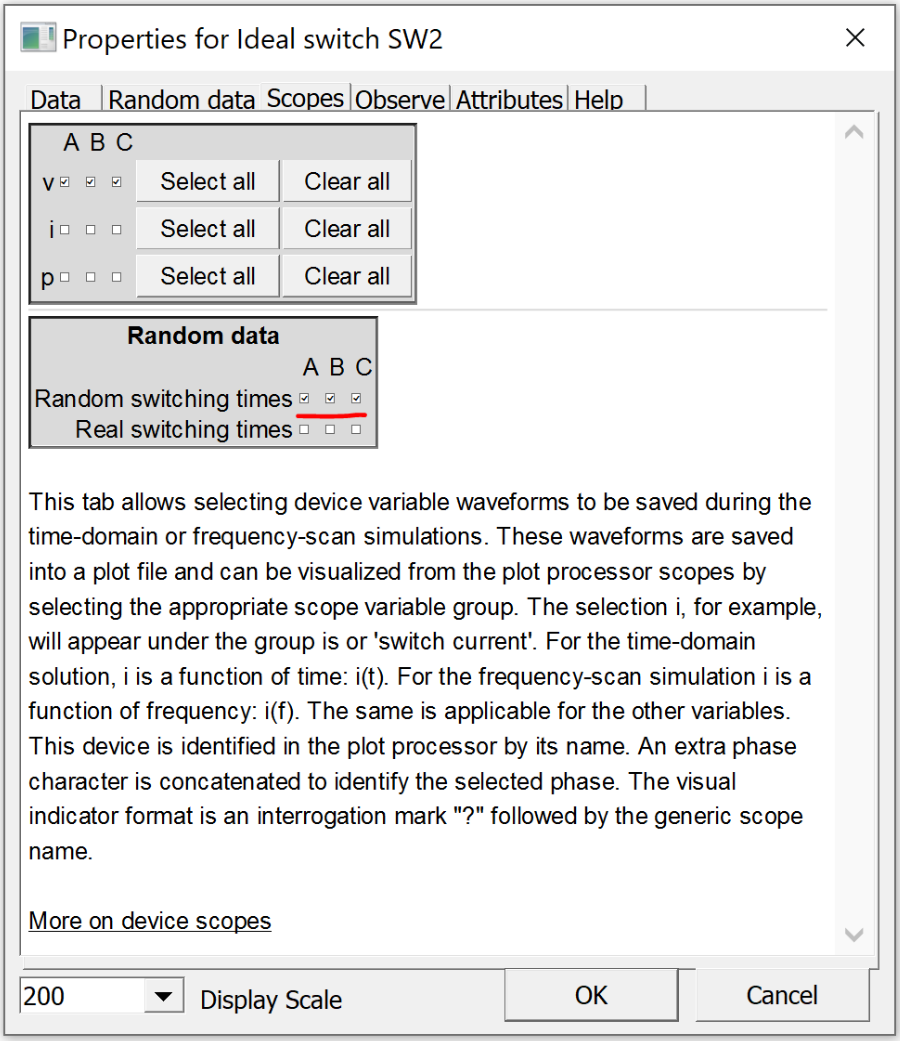
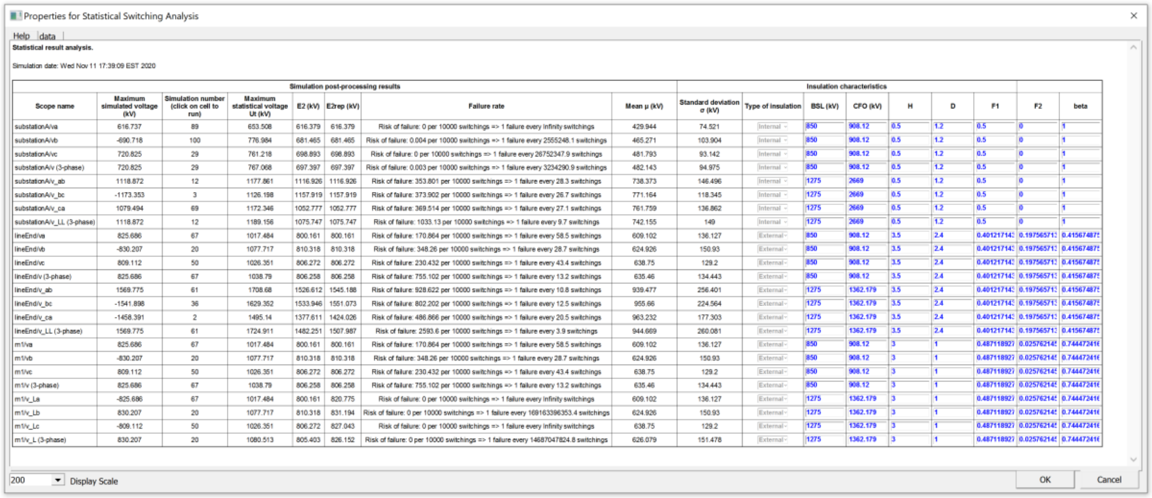


Figure 6: Random switching times of all switches or breakers with Random data setup must be checked.

5. Start a time-domain simulation the regular way to start the statistical analysis. Multiple simulations will be performed.
6. Place the Statistical Switching Analysis device into the design and double click on it to start the analysis. A table with all outcomes defined in 3.
   Figure 7 shows an example of results.



Simulation post-processing results									Insulation characteristics							
Scope name	Maximum simulated voltage (kV)	Simulation number (click on cell to run)	Maximum statistical voltage Ut (kV)	E2 (kV)	E2rep (kV)	Failure rate	Mean μ (kV)	Standard deviation σ (kV)	Type of insulation	BSL (kV)	CFO (kV)	H	D	F1	F2	beta
substationA/va	616.737	89	653.508	616.379	616.379	Risk of failure: 0 per 10000 switchings => 1 failure every Infinity switchings	429.944	74.521	Internal	850	908.12	0.5	1.2	0.5	0	1
substationA/vb	-690.718	100	776.984	681.465	681.465	Risk of failure: 0.004 per 10000 switchings => 1 failure every 2555248.1 switchings	465.271	103.904	Internal	850	908.12	0.5	1.2	0.5	0	1
substationA/vc	720.825	29	761.218	698.893	698.893	Risk of failure: 0 per 10000 switchings => 1 failure every 26752347.9 switchings	481.793	93.142	Internal	850	908.12	0.5	1.2	0.5	0	1
substationA/v (3-phase)	720.825	29	767.068	697.397	697.397	Risk of failure: 0.003 per 10000 switchings => 1 failure every 3234290.9 switchings	482.143	94.975	Internal	850	908.12	0.5	1.2	0.5	0	1
substationA/v_ab	1118.872	12	1177.861	1116.926	1116.926	Risk of failure: 353.801 per 10000 switchings => 1 failure every 28.3 switchings	738.373	146.496	Internal	1275	2669	0.5	1.2	0.5	0	1
substationA/v_bc	-1173.353	3	1126.198	1157.919	1157.919	Risk of failure: 373.902 per 10000 switchings => 1 failure every 26.7 switchings	771.164	118.345	Internal	1275	2669	0.5	1.2	0.5	0	1
substationA/v_ca	1079.494	69	1172.346	1052.777	1052.777	Risk of failure: 369.514 per 10000 switchings => 1 failure every 27.1 switchings	761.759	136.862	Internal	1275	2669	0.5	1.2	0.5	0	1
substationA/v_LL (3-phase)	1118.872	12	1189.156	1075.747	1075.747	Risk of failure: 1033.13 per 10000 switchings => 1 failure every 9.7 switchings	742.155	149	Internal	1275	2669	0.5	1.2	0.5	0	1
lineEnd/va	825.686	67	1017.484	800.161	800.161	Risk of failure: 170.864 per 10000 switchings => 1 failure every 58.5 switchings	609.102	136.127	External	850	908.12	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/vb	-830.207	20	1077.717	810.318	810.318	Risk of failure: 348.26 per 10000 switchings => 1 failure every 28.7 switchings	624.926	150.93	External	850	908.12	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/vc	809.112	50	1026.351	806.272	806.272	Risk of failure: 230.432 per 10000 switchings => 1 failure every 43.4 switchings	638.75	129.2	External	850	908.12	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/v (3-phase)	825.686	67	1038.79	806.258	806.258	Risk of failure: 755.102 per 10000 switchings => 1 failure every 13.2 switchings	635.46	134.443	External	850	908.12	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/v_ab	1569.775	61	1708.68	1526.612	1545.188	Risk of failure: 928.622 per 10000 switchings => 1 failure every 10.8 switchings	939.477	256.401	External	1275	1362.179	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/v_bc	-1541.898	36	1629.352	1533.946	1551.073	Risk of failure: 802.202 per 10000 switchings => 1 failure every 12.5 switchings	955.66	224.564	External	1275	1362.179	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/v_ca	-1458.391	2	1495.14	1377.611	1424.026	Risk of failure: 486.866 per 10000 switchings => 1 failure every 20.5 switchings	963.232	177.303	External	1275	1362.179	3.5	2.4	0.40121714	0.19756571	0.41567487
lineEnd/v_LL (3-phase)	1569.775	61	1724.911	1482.251	1507.987	Risk of failure: 2593.6 per 10000 switchings => 1 failure every 3.9 switchings	944.669	260.081	External	1275	1362.179	3.5	2.4	0.40121714	0.19756571	0.41567487
m1/va	825.686	67	1017.484	800.161	800.161	Risk of failure: 170.864 per 10000 switchings => 1 failure every 58.5 switchings	609.102	136.127	External	850	908.12	3	1	0.48711892	0.02576214	0.74447241
m1/vb	-830.207	20	1077.717	810.318	810.318	Risk of failure: 348.26 per 10000 switchings => 1 failure every 28.7 switchings	624.926	150.93	External	850	908.12	3	1	0.48711892	0.02576214	0.74447241
m1/vc	809.112	50	1026.351	806.272	806.272	Risk of failure: 230.432 per 10000 switchings => 1 failure every 43.4 switchings	638.75	129.2	External	850	908.12	3	1	0.48711892	0.02576214	0.74447241
m1/v (3-phase)	825.686	67	1038.79	806.258	806.258	Risk of failure: 755.102 per 10000 switchings => 1 failure every 13.2 switchings	635.46	134.443	External	850	908.12	3	1	0.48711892	0.02576214	0.74447241
m1/v_La	-825.686	67	1017.484	800.161	820.775	Risk of failure: 0 per 10000 switchings => 1 failure every Infinity switchings	609.102	136.127	External	1275	1362.179	3	1	0.48711892	0.02576214	0.74447241
m1/v_Lb	830.207	20	1077.717	810.318	831.194	Risk of failure: 0 per 10000 switchings => 1 failure every 169163396353.4 switchings	624.926	150.93	External	1275	1362.179	3	1	0.48711892	0.02576214	0.74447241
m1/v_Lc	-809.112	50	1026.351	806.272	827.043	Risk of failure: 0 per 10000 switchings => 1 failure every Infinity switchings	638.75	129.2	External	1275	1362.179	3	1	0.48711892	0.02576214	0.74447241
m1/v_L (3-phase)	830.207	20	1080.513	805.403	826.152	Risk of failure: 0 per 10000 switchings => 1 failure every 14687047824.8 switchings	626.079	151.478	External	1275	1362.179	3	1	0.48711892	0.02576214	0.74447241

Figure 7: Example of Statistical Switching Analysis

3 Statistical result analysis and study outcomes

3.1 Overvoltage distribution determination

For each probe, the tool returns the following representative overvoltages:

- **The Max simulated voltage**: The voltage with the maximum absolute value which was reached during all statistical simulations for this scope. It may be either phase-to-ground, phase-to-phase or longitudinal, according to the type of probes.
- **Max statistical voltage** U_T: Maximum voltage estimated with the parameters of the overvoltage statistical distribution.

  $$U_T = E2 + 3\sigma$$

  In IEEE, this is called the **truncated overvoltage**.
- **E2**: Overvoltage with 2% chance of being exceed in the maximum voltage statistical distribution of the statistical simulation results. This value is obtained using a cumulative distribution function of the maximum voltages obtained at each statistical run.

and:

- **Simulation number**: Number of the statistical run where the maximum voltage was reached for this scope.
  This run may be automatically replayed (see 5).
- **Mean**: Mean of the overvoltage statistical distribution of the current statistical simulation results. The mean is defined as:

  $$\mu = \frac{\sum |Vmax_i|}{N}$$

  Where $Vmax_i$ is the maximum voltage obtained at each statistical run for this scope and N is the total number of statistical runs.
- **Standard deviation** σ: Standard deviation of the overvoltage statistical distribution of the current statistical simulation results. The standard deviation is defined as:

  $$\mu = \frac{\sum (\mu - Vmax_i)^2}{N-1}$$

  Where $Vmax_i$ is the maximum voltage obtained at each statistical run for this scope, N is the total number of statistical runs and μ is the mean.

For phase-to-phase or longitudinal overvoltages, the representative overvoltages are calculated using the $F_1$and F_2 coefficients as explained in annex C of [1]:

$$F_1 = \frac{1}{2-\sqrt{2}}\left[1 - \frac{\sqrt{1+\beta^2}}{1+\beta}\right] \qquad F_2 = \frac{1}{2-\sqrt{2}}\left[2\frac{\sqrt{1+\beta^2}}{1+\beta} - \sqrt{2}\right]$$

Where $\beta = tan\left(\left(\left((10-50) * \frac{D}{H_t} + 50\right) * \frac{\pi}{180}\right)\right)$ (See figure C-5 of [1].)

β may be simplified in the following conditions:

- Short air clearances with inhomogeneous electric field (The air clearances in range I of IEC 71-1), $\beta = 1$
- If the radius of the electrodes is large compared to their clearance (ex: Three-phase power transformers, GIS) the discharge depends on the total voltage between electrodes ($\beta = 1$)

The representative overvoltages are:

- $E_2 = 2\left(F_1 E_{p2} + F_2 E_{e2}\right)$
- $S_{pre} = 2(F_1 S_P + F_2 S_e)$
- $U_{ptre} = 2(F_1 U_{Pt} + F_2 U_{et})$

Where:

- E_{p2} and $E_{e2}$are, respectively, the overvoltages with 2% chance of being exceed in the maximum phase-to-phase and phase-to-ground voltage statistical distributions of the statistical simulation results.
- S_P and S_e are, respectively, the standard deviations of the phase-to-phase and phase-to-ground overvoltage statistical distributions.
- U_{Pt} and U_{et} are, respectively, the maximum phase-to-phase and phase-to-ground voltages estimated with the parameters of the overvoltage statistical distributions.

For 3-phase voltage scopes, in addition to the analysis performed on each phase, one is done on the 3-phase combined. The statistical parameters are calculated based on the maximum voltages obtained on the 3 phases at each statistical run.
If the 'Case-Peak Method' of the insulation coordination procedure (see [1] and [2]) is applied, the 3-phase combined statistical parameters should be used.
If the 'Phase-Peak Method' of the insulation coordination procedure (see [1] and [2]) is applied, the statistical parameters of each phase should be used independently. The rate of failures of each phase must then be combined to obtain the 3-phase rate of failure.

3.2 Rate of failure determination

3.2.1 Definition

- IEEE definition of external (self-restoring) insulation: insulation which, after a short time, completely recovers its insulating properties after a disruptive discharge during test.
  For such insulation, the number of disruptive discharges tolerated is related to a specified withstand probability.
  Therefore, for external insulation, the **BSL** (Basic Switching Level) is defined as the voltage having a 10% probability of leading to a flashover (90% probability of withstand)
  Another important parameter for external insulation is the **CFO** (Critical Flashover Overvoltage) which is the voltage having a 50% probability of leading to a flashover.

- IEEE definition of internal (non-self-restoring) insulation: insulation which loses its insulating properties, or does not recover them completely, after a disruptive discharge during test.
  For internal insulation, the **BSL** (Basic Switching Level) is defined as the voltage having a 100% probability of leading to a flashover or a damage if overpassed.
  As a rule of thumb, for low voltage application, the BSL may be assumed 85% of the BIL (Basic Insulation Level)

3.2.2 Analysis

3.2.2.1 Probes monitoring the voltage of an internal insulation.

For probes monitoring the voltage of an internal insulation, enter the BSL value. Because the BSL for such insulation is defined as a 100% probability of failure, the rate of failure is not calculated. Instead, the BSL must be larger than the Max simulated Voltage and the Max statistical voltage both multiplied by the safety coefficient.
Example of safety coefficients:

- safety coefficient: typical values in IEC 60071-2 or IEEE Std 1313.2-1999.
  For internal insulation: 15%
  For external insulation: 5%
- Coordination Factor
- etc.

3.2.2.2 Probes monitoring the voltage of an external insulation.

For external insulations, both the **BSL** and **CFO** parameters must be provided.
The number of parallel insulators is used to automatically calculate the probability of flashover all insulator combined using the voltage measured at the probe bus:

$$P_{N_{insulators}} = 1 - \left(1 - P_{1_{insulator}}\right)^{N_{insulators}}$$

Where $P_{1_{insulator}}$ is the probability of flashover of one insulator for the statistical distribution of overvoltages obtained during the statistical simulation and $N_{insulators}$ is the number of insulators. It is assumed all the insulators have voltage peaks of same magnitudes during switching transients. If several insulators are considered, CFO and BSL must be entered for only one.

For phase-to-phase insulation coordination (see 3.1), the following parameters are also required:

- H_t: Conductor height above earth. May be any unit as long as it is the same as the one used for D.
- D: Phase-to-phase clearance. May be any unit as long as the same is used for H.
- The radius of the electrodes is large compared to their clearance: used to simplified $\beta = 1$.
- Range I voltage class (short air clearance): used to simplified $\beta = 1$.

The Rate of Failure (R) is calculated using two methods:

1. IEC method based on Weibull parameters:

$$R = \int_{CFO-4Z}^{U_T} f(U)P(U)$$

Where:

- $f(U)$ is the probability density of overvoltage. **Peaks other than the highest one are disregarded, which may lead to error.**

$$f(U) = \frac{e^{-\frac{1}{2}\left(\frac{U-\mu}{\sigma}\right)^2}}{\sigma\sqrt{2\pi}}$$

  with:
  - μ: Mean of simulated overvoltage distribution
  - σ : Standard deviation of simulated overvoltage distribution
  - U_T: Maximum statistical overvoltage

  These parameters are identified using the statistical distribution of overvoltages obtained during the statistical simulation.
- $P(U)$ is the probability of flashover of the insulation under an impulse of value U

$$P(U) = 1 - 0.5^{\left(1+\frac{\frac{U-CFO}{Z}}{4}\right)^5}$$

With:

- Z: standard deviation of insulator withstand voltage distribution.
  Z: is estimated as:
  $$Z = \frac{CFO - BSL}{1.3}$$
  This estimation may lead to slight errors in the rate of failure determination.

For calculation, CFO and BSL are divided by the safety coefficient.
The IEEE standard does not consider the truncation $CFO - 4Z$. For typical cases, this may lead to an underestimation of risk of less than 0.01%.
This method is not valid when devices are protected by surge arresters, since the surge arrester clamping voltage produce a skewing which male the Weibull identification inaccurate.

2. Risk of failure based on simulated cases.

For this method, the same calculation as the IEC method is used, but the probability density of overvoltage is calculated using the statistical simulation results without Weibull identification. The maximum overvoltages obtained by each simulation is assumed to have a probability of occurrence of one over the number of statistical simulations performed. The method provides reliable results only if the number of simulations is large enough. More than 500 is recommended. This method is valid for devices protected by surge arresters.

For three-phase devices, and when following the standard 'Phase-Peak Method' of the insulation coordination procedure (see [1] and [2]), the total risk of failure is:

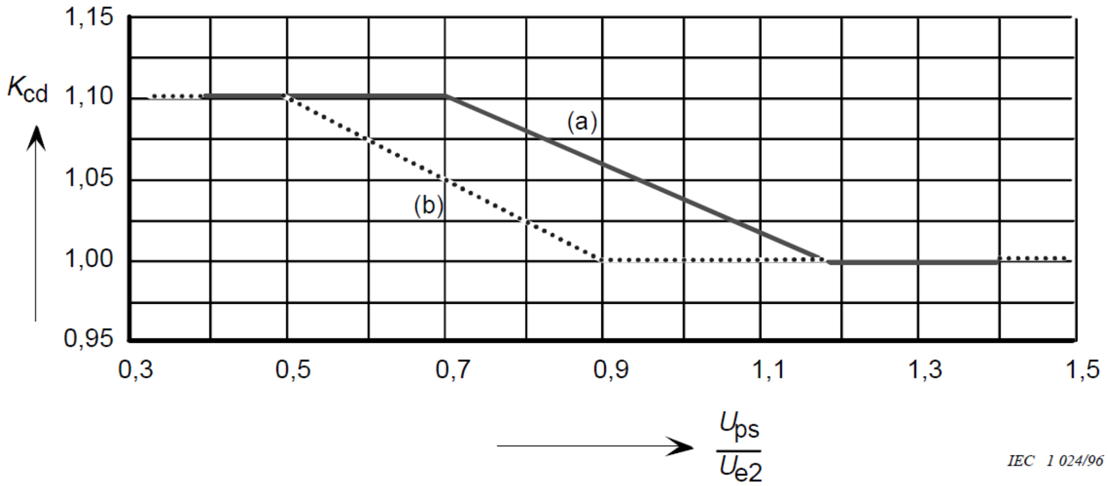
$$R_{total} = 1 - \left(1 - R_{phaseA}\right) * \left(1 - R_{phaseB}\right) * (1 - R_{phaseC})$$

When following the 'Case-Peak Method' of the insulation coordination procedure (see [1] and [2]), the total risk of failure is the one displayed on the line where the scope name appears with (3-phase):

m2/v (3-phase)

3.2.3 Case of external insulation with surge arrester

Surge arresters have a skewing effect on the statistical distribution of overvoltages. Therefore, the risk of failure calculation based on Weibull approximation is not valid. In the case, the risk of failure is only calculated using simulated cases (see 2 in 3.2.2.2).
The BSL may also be determined using the coordination factor provided by the following IEC 60071 figure:



Where K_{cd} is the coordination factor, U_{ps} is the surge arrester switching impulse voltage and U_{e2} is the overvoltage value having 2% of chance of being exceeding during the considered switching operation.

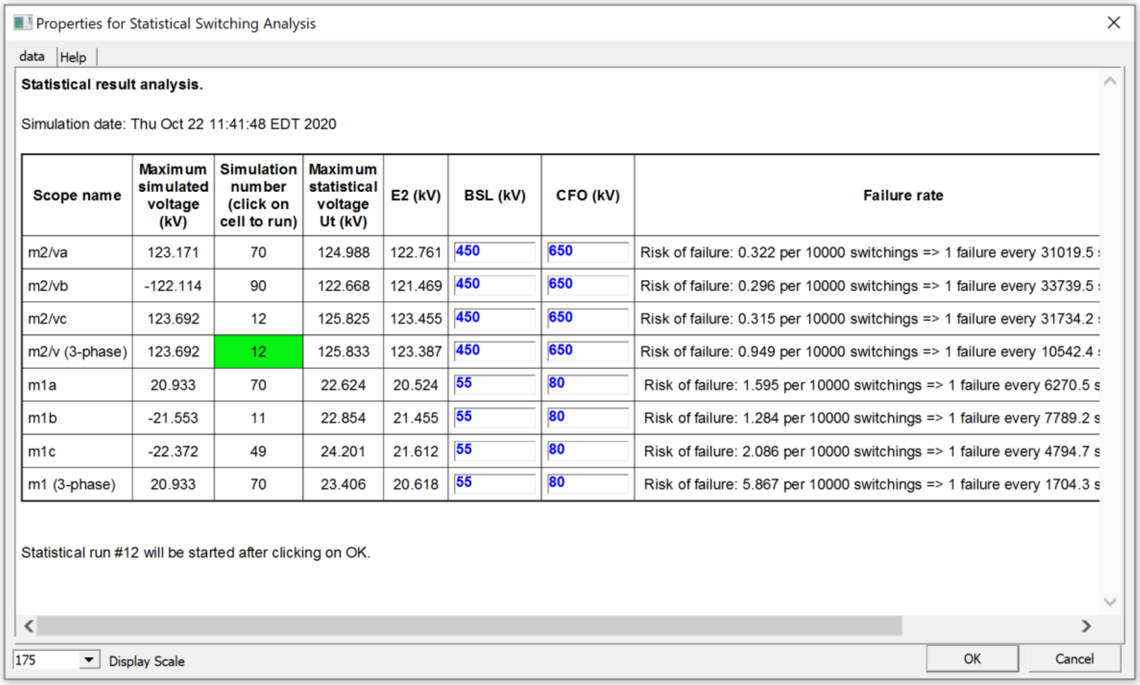
4 Files created during analysis.

During the result analysis, MPLOT is used to process results and several files are created. Users must ensure files with same names are not being used already.
All these files are saved in the project file (folder which has the same name as the design with the extension _pj and which is located in the same folder of the EMTP design).
Once the process is completed, these files may be deleted by users.
The files are:

- **filedata_switchingOptions.txt**: MPLOT scripting file.
- **MinMax_switchingOptions.txt**: ASCII file with the simulation numbers and the min max value of each Node Voltage scope.
- **MinMax_switchingOptions_labels.txt**: labels of the scopes of the previous file.
- **t_stat_switchingOptions.txt**: ASCII file with the simulation numbers and the switching times of switches which had Random data defined during the statistical simulation and which had the scopes Random switching times enabled.
- **t_stat_switchingOptions_labels.txt**: labels of the scopes of the previous file
- **FixedRandomData_switchingOptions.dat**: This file is the one used by the Fixed Random Data device to run a user specified run number.

5 Run a specific case.

Once the analysis is performed and the device mask is open, a specific statistical run number may be selected by clicking on it:



Scope name	Maximum simulated voltage (kV)	Simulation number (click on cell to run)	Maximum statistical voltage Ut (kV)	E2 (kV)	BSL (kV)	CFO (kV)	Failure rate
m2/va	123.171	70	124.988	122.761	450	650	Risk of failure: 0.322 per 10000 switchings => 1 failure every 31019.5 s
m2/vb	-122.114	90	122.668	121.469	450	650	Risk of failure: 0.296 per 10000 switchings => 1 failure every 33739.5 s
m2/vc	123.692	12	125.825	123.455	450	650	Risk of failure: 0.315 per 10000 switchings => 1 failure every 31734.2 s
m2/v (3-phase)	123.692	12	125.833	123.387	450	650	Risk of failure: 0.949 per 10000 switchings => 1 failure every 10542.4 s
m1a	20.933	70	22.624	20.524	55	80	Risk of failure: 1.595 per 10000 switchings => 1 failure every 6270.5 s
m1b	-21.553	11	22.854	21.455	55	80	Risk of failure: 1.284 per 10000 switchings => 1 failure every 7789.2 s
m1c	-22.372	49	24.201	21.612	55	80	Risk of failure: 2.086 per 10000 switchings => 1 failure every 4794.7 s
m1 (3-phase)	20.933	70	23.406	20.618	55	80	Risk of failure: 5.867 per 10000 switchings => 1 failure every 1704.3 s

Once a simulation number is selected, click on OK. This will start the time-domain simulation with the switching times of the selected run.
A Fixed Random Data device will be added to start this simulation and then immediately remove. All other Fixed Random Data devices must be removed prior to this operation.

6 References

[1]. IEC 60071-2018, Insulation co-ordination
[2]. IEEE Std 1313.2.2-1999, IEEE Guide for the Application of Insulation Coordination