# Lightning Effects on Overhead Distribution Lines – Mitigation Strategies and Optimal Solutions

Nagananthini Ravichandran

**Tutor:** Prof. Amedeo Andreotti
**co-Tutor:** Prof. Daniela Proto
**Cycle:** XXXVII
**Year:** Third

# MY BACKGROUND

Master of Engineering in Power Electronics and Drives – Anna University, Tamil Nadu (India)

Research group - Power System (IIND-08/B)

PhD start date - 01/11/2021 (Academic Year: 2021-2022)

Scholarship type – UNINA

Period Abroad - École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland

September 11, 2023 – March 31, 2024

# STUDY ACTIVITIES

| Courses | PhD Schools | Period Abroad Research Activities |
|---|---|---|
| • Matrix Analysis for Signal Processing with MATLAB Examples<br>• Big Data Architecture and Analysis<br>• Machine Learning for Science and Engineering Research<br>• Sustainable ship for the energy transition of maritime transport .<br>• Operational Research: Mathematical Modelling, Methods and Software Tools for Optimization Problems.<br>• Wave propagation along transmission lines : Wave Propagation – Electromagnetic compatibility | • Lectures on Computational Linguistics 2022<br>• 2023 Spring School on Transferrable Skills | An EMTP - Compatible Frequency-Dependent Model for Vertical Grounding Rods for Transient Studies.<br><br>Single-Sensor Machine-Learning-Based Lightning Localization using Lightning-Induced Voltages |

# RESEARCH FIELD OF INTEREST

Power Quality Issues

Overhead Distribution  Line

Lightning-Overvoltages : Direct and Indirect Events

Improvement of Lightning Performance Analysis

Optimal Strategies for Surge Protection

# RESEARCH RESULTS

EMTP-based modelling of an actual distribution network

Optimal protection strategy (generation of events): a new tool to statistically characterize lightning events based on Futures and Design of Experiments (DOE)

Optimal protection strategy (choice of the optimal device allocation): Single-Objective and Multi-objective approaches for optimal location of Surge Arresters (SAs) and Decision Theory

# RESEARCH PRODUCTS

- **International journal papers**

1. Cao, J., Andreotti, A., Du, Y., **Ravichandran, N.** and Ding, Y., **Selection of the Lateral Distance for the Assessment Area in a Monte Carlo Procedure Under Indirect Lightning for Overhead Distribution Lines**, *IEEE Transactions on Electromagnetic Compatibility, 65(3), pp.935-939.*, DOI: 10.1109/TEMC.2023.3257361.
2. Stracqualursi, E., Araneo, **R., Ravichandran, N.,** Andreotti, A. and Celozzi, S., 2023. **Modeling of conductor's catenary in power lines: Effects on the surge propagation due to direct and indirect lightning.** *IEEE Transactions on Electromagnetic Compatibility*. DOI: 10.1109/TEMC.2023.3288029.
3. Cao, J., Du, Y., Wang, J., Andreotti, A., Ding, Y., **Ravichandran, N.,** Zhang, Y. and Cai, L., 2024. **Novel Probabilistic Lightning Performance Evaluation Considering Multi-objective for Differentiated Protection in a Distribution Network**. *Electric Power Systems Research*, *230*, p.110153. DOI: 10.1016/j.epsr.2024.110153.
4. **Ravichandran,** N., Proto, D. and Andreotti, A., 2024. **Surge arrester optimal placement in distribution networks: A decision theory-based approach.** *Electric Power Systems Research*, *234*, p.110744. DOI: 10.1016/j.epsr.2024.110744.
5. **Ravichandran,** N., Proto, D., Mottola. F and Andreotti, A., 2024. **Multi-Objective Optimization for Lightning Protection in Distribution Networks: A Novel Approach Based on Design of Experiments** in *IEEE Access* ***[Submitted].***
6. Asadi. M, **Ravichandran. N,** Rajabi. S, Miki. T, Karami. H, Rubinstein, M, Rachidi.F, and Andreotti. A. **Single-Sensor Machine-Learning-Based Lightning Localization using Lightning-Induced Voltages** ***[Submitted].***
7. **Ravichandran,** N., Proto, D., Mottola. F and Andreotti, A., 2024 Multiobjective Optimal Placement of Surge Arresters in Distribution Networks based on Decision Theory, ***[To be Submitted].***

# International Conference papers

1. **Ravichandran, N.,** Andreotti, A., Pagano, M., Di Pasquale, A., Volpe, F. Interconnection Topologies for Floating Photovoltaic System to Enhance the Power Output by Reducing the Mismatch Losses (2022). Asia-Pacific Power and Energy Engineering Conference, APPEEC. Melbourne, Australia. November,2022. DOI: 10.1109/APPEEC53445.2022.10072079.

2. Andreotti, A., Di Pasquale, A., Pagano, M., **Ravichandran,** N., Volpe, F. Analysis of Lightning Transients in 2 × 25 kV 50 Hz Railway Traction System using EMTP (2022) 2022 AEIT International Annual Conference, AEIT 2022. Rome, Italy. October 2022. DOI: 10.23919/AEIT56783.2022.9951858.

3. Andreotti, A., Pasquale, A.D., Pagano, M., **Ravichandran,** N., Volpe, F. An Optimal Centralized Control Strategy for Regenerative Braking Energy Flow Exchanges in DC Railway Traction Systems (2022) 2022. International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2022, pp. 436-441. Sorrento, Italy. June, 2022. DOI: 10.1109/SPEEDAM53979.2022.9841998.

4. Andreotti, A., **Ravichandran, N**., D'Orazio, L., Villacci, D., Cerretti, A., Araneo, R. and Stracqualursi, E., Assessment of the indirect lightning performance of a distribution line. In 2023 IEEE International Conference on Environment and Electrical Engineering and 2023 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). Rome, Italy. June, 2023.DOI: 10.1109/EEEIC/ICPSEurope57605.2023.10194859

5. D'Orazio, L., Andreotti, A., Frain, J.B., Gentilini, I., **Ravichandran, N.,** Greco, A., Di Felice, G., Proto, D. and Spitilli, L., 2023. Analysis of the application of LLPDs on a MV feeder of E-Distribuzione. 27th International Conference on Electricity Distribution (CIRED 2023), 2023 p. 633 – 637. Rome, Italy. June 2023.DOI: 10.1049/icp.2023.0438

6. **Ravichandran, N.,** Andreotti, A., Araneo, R., Cao, J., D'Orazio, L., Du, Y., Proto, D. and Stracqualursi, E., 2023, October. Improvement of the Lightning Performance of Overhead Distribution Lines: Possible Solutions. In 2023 International Symposium on Lightning Protection (XVII SIPDA) (pp. 1-6). IEEE. Suzhou, China. September, 2023.DOI: 10.1109/SIPDA59763.2023.10349161.

7. **Ravichandran, N.,** Andreotti, A., Di Pasquale, A., Pagano, M., Proto, D., Stracqualursi, E., Araneo, R., D'Orazio, L. Selection of Viable Distribution Line Surge Arrester for Prospective Optimal Protection (2023) 2023 AEIT International Annual Conference, AEIT 2023. Rome, Italy, October 2023.

8. Asadi. M, **Ravichandran. N,** Rajabi. S, Miki. T, Karami. H, Rubinstein.M, Rachidi.F, and Andreotti.A. Single-Sensor Machine-Learning-Based Lightning Localization using Lightning-Induced Voltages. 37th International Conference on Lightning Protection. Dresden, Germany. September 2024. [Presented].

9. Alipio. R , Duarte. N, **Ravichandran. N,** Andreotti. A, and Rachidi. F. An EMTP-Compatible Frequency-Dependent Model for Vertical Grounding Rods for Transient Studies; 37th International Conference on Lightning Protection. Dresden, Germany. September 2024. [Presented].

10. Ghimire. B, **Ravichandran. N,** Andreotti. A, Narayan Poudyal. N Khem, Sharma. S, Karki. R,Ground Flash Density Mapping in Nepal: Enhancing Lightning Performance and Resilience of Distribution Lines. Australasian Universities Power Engineering Conference (AUPEC). Sydney, Australia. November 2024. [Submitted].

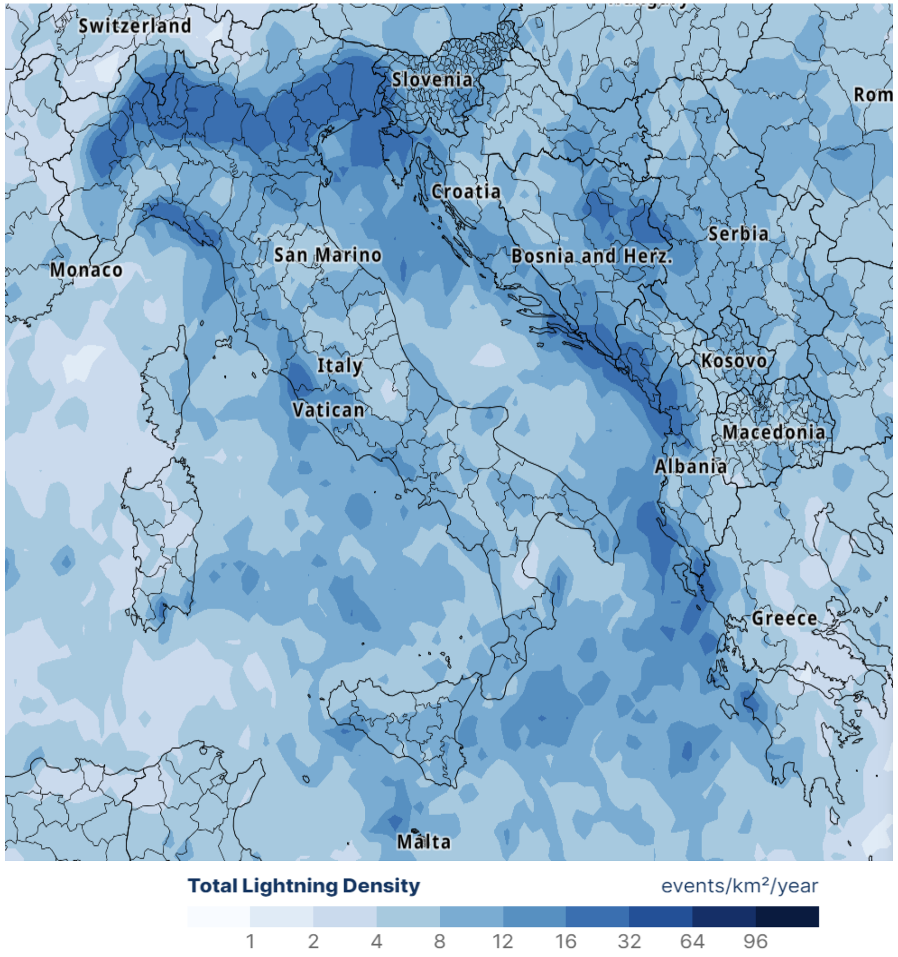
# PhD Thesis Overview

## Lightning Effects on Overhead Distribution Lines – Mitigation Strategies and Optimal Solutions

# PROBLEM STATEMENT

## Enhancing Lightning  Protection in Power Infrastructures

1. Increased lightning activity  (growing frequency of events)
2. High ground flash density  (percentage of faults related to lightning)
   2.1 Equipment damage, overvoltages and surges, power quality issues, grounding issues, fire hazard
3. Vulnerability of distribution areas  (regions prone to lightning-related failures)
   3.1 Damage assessment, isolation and safety measures, equipment repair or replacement, power restoration
4. Need for protection mechanisms  (strategies to improve performance)
   4.1 Lightning arresters, grounding and bonding, shielding and insulation, lightning detection and monitoring systems, regular maintenance and inspections.



# RESEARCH OBJECTIVE

## Modelling of an actual distribution network

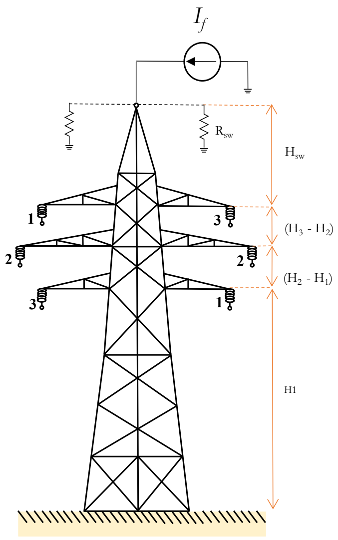
## Unified lightning attraction model-based direct/indirect lightning assessment

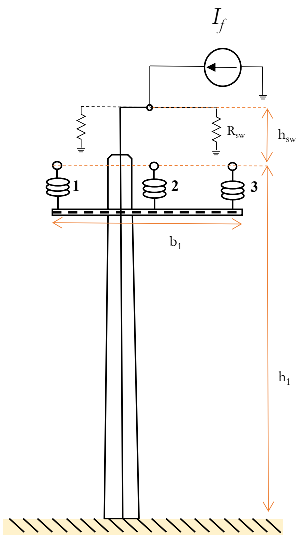
## Protection devices analysis

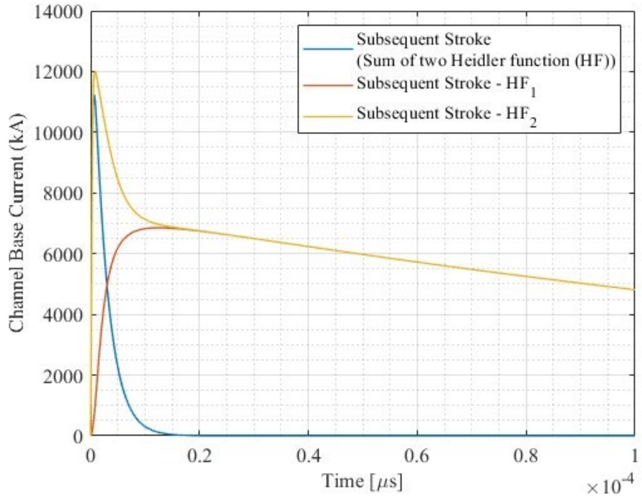
## Protection strategy

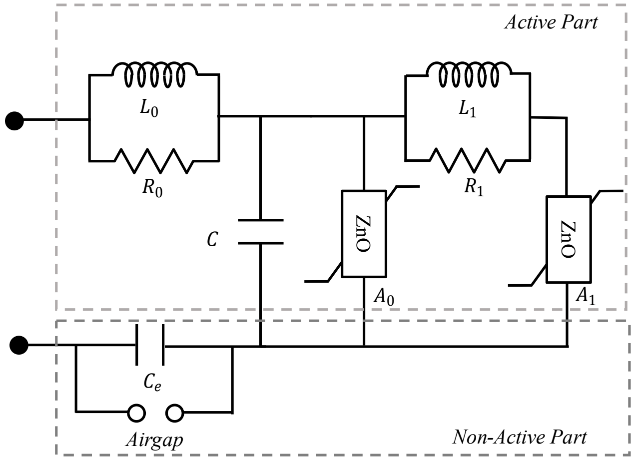
- Single-objective and multi-objective optimization for the allocation of the arresters
- Scenario-based approach - Design of Experiments techniques – comparison to Monte Carlo approach to generate random lightning events (computational time)
- Decision theory approach for choice of protection alternative

# NETWORK MODELLING




$$\frac{\partial}{\partial x}V(x,t) = -RI(x,t) - L\frac{\partial}{\partial t}I(x,t)$$
$$\frac{\partial}{\partial x}I(x,t) = -GV(x,t) - C\frac{\partial}{\partial t}V(x,t)$$

*Geometry: Height, Cross arm Length*
*Parameters: Conductor(R,L,C), footing resistance, & OHGW*

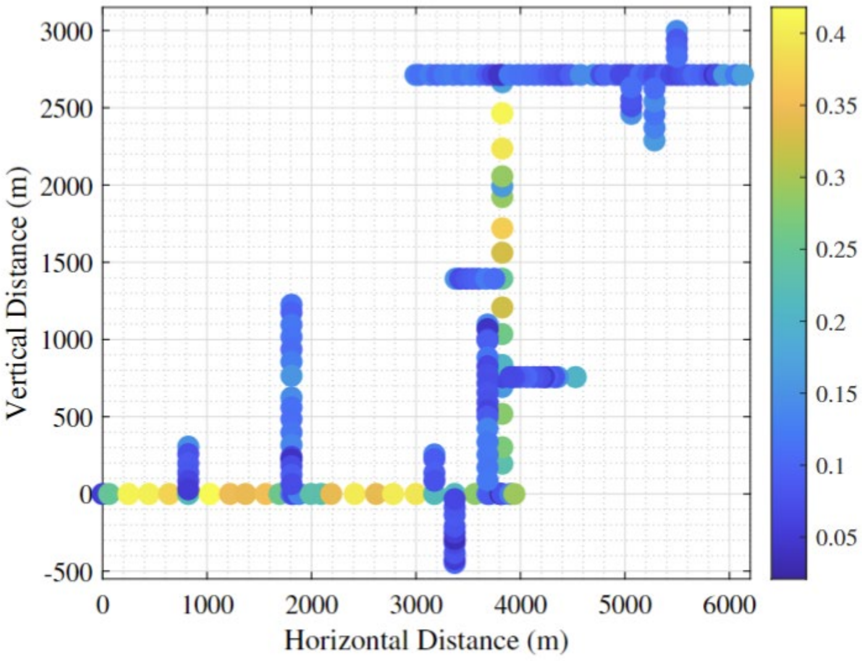
$$i_0(t) = \frac{I_0}{\eta}\frac{(t/\tau_1)^n}{1+(t/\tau_1)^n}exp(-t/\tau_2)$$
$$\eta = exp\left[-\left(\frac{\tau_1}{\tau_2}\right)\left(n\frac{\tau_2}{\tau_1}\right)^{\frac{1}{n}}\right]$$

*Type: First or Subsequent*
*Parameters: Current peak, rise time and decay time*

$$D(t) = \int_{t_0}^{t}(|V_{ins}(t)| - V_0)^k\,dt$$

*Parameters: Minimum threshold voltage*

# UNIFIED LIGHTNING ATTRACTION MODEL



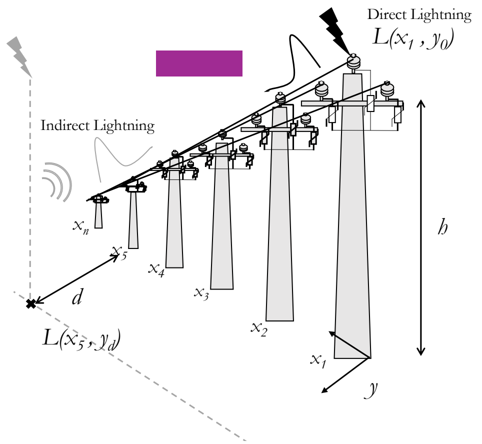

$$Striking\ Distance,\ r = a\,.\,I^{b}$$

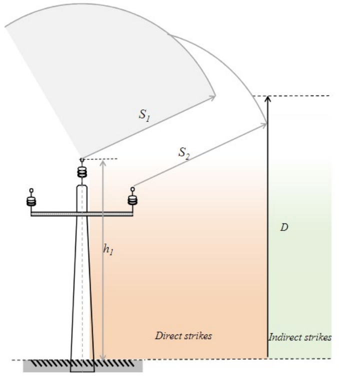
$$Attractive\ Radius,\ S = (28 \cdot h_t)^{0.6}$$

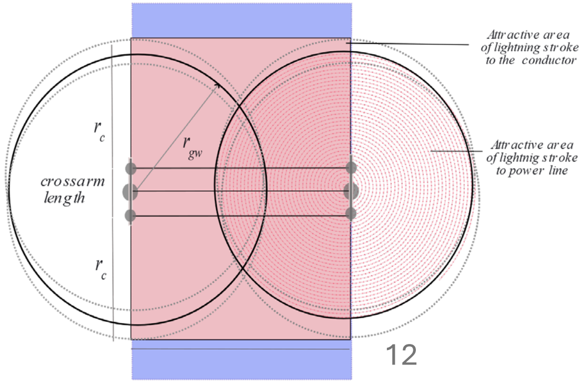
$$R_{egm} = \begin{cases} \sqrt{S_{egm}^2 - \left(S_{egm} - h\right)^2} & for\ \ S_{egm} > h \\ S_{egm} & for\ \ S_{egm} < h \end{cases}$$

$$R_a = I^{a} \cdot 0.84 \cdot h^{0.6} [m, kA]$$

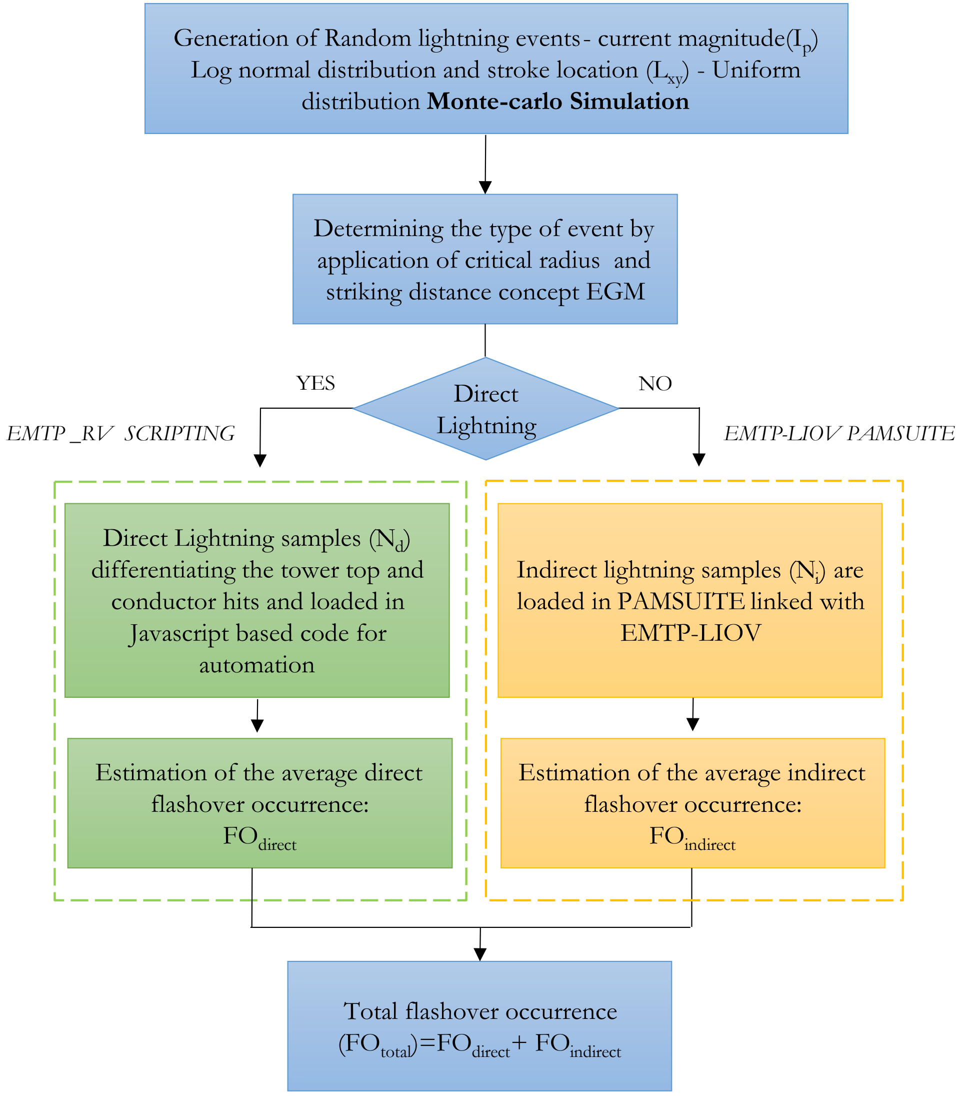
$$D_{ra} = 1.57 \cdot I^{0.69} \cdot h^{0.45} [m, kA]$$



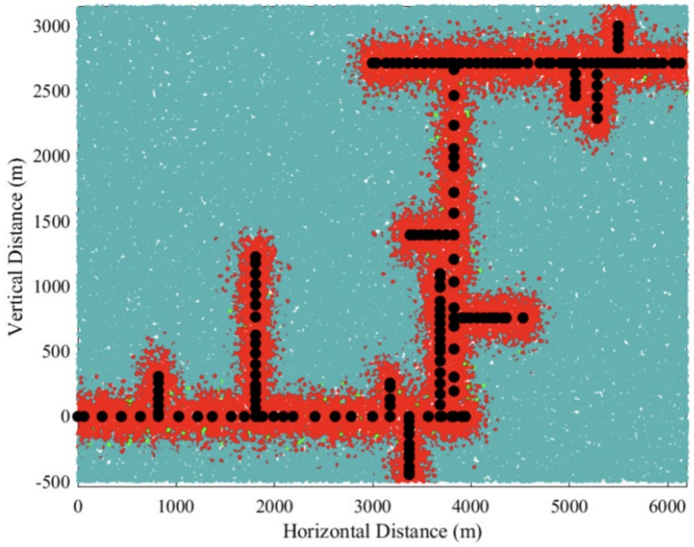



# FLASHOVER ESTIMATION




| Parameters | First Stroke | | Subsequent Stroke | |
|---|---|---|---|---|
| | Average | Standard Deviation | Average | Standard Deviation |
| Current Amplitude [kA] | 31 | 0.46 | 13 | 0.641 |
| Front Time [µs] | 5 | 0.54 | 0.31 | 0.66 |
| half Time [µs] | 70 | 0.56 | 20 | 0.67 |



# SINGLE AND MULTI-OBJECTIVE PROBLEM FORMULATION

$$Minimize\ F = \sum_{i=1}^{n} [(1 - x_i)FOR_i + x_i AFOR_{i,j}]$$

$$\mathrm{FOR} = \frac{N_{FO}}{N_{TOT}} \cdot A \cdot N_g$$

$$Minimize\ F = \sum_{i=1}^{n} C_T$$

$$C_T = N_{sa} \cdot (C_{init} + C_{maint} + C_{short} + C_{long}) + C_{sw}$$

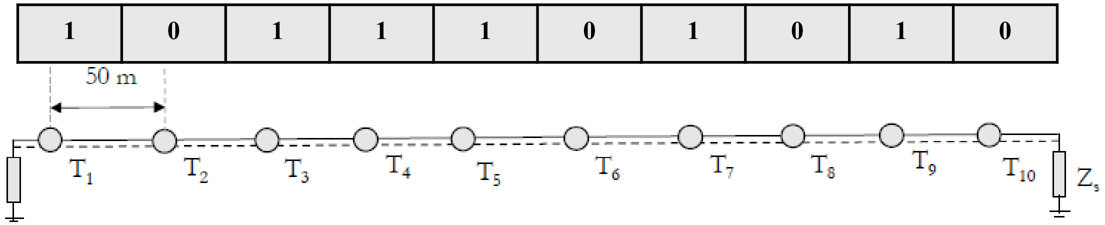
$$Minimize\ F = \sum_{i=1}^{n} R_T$$

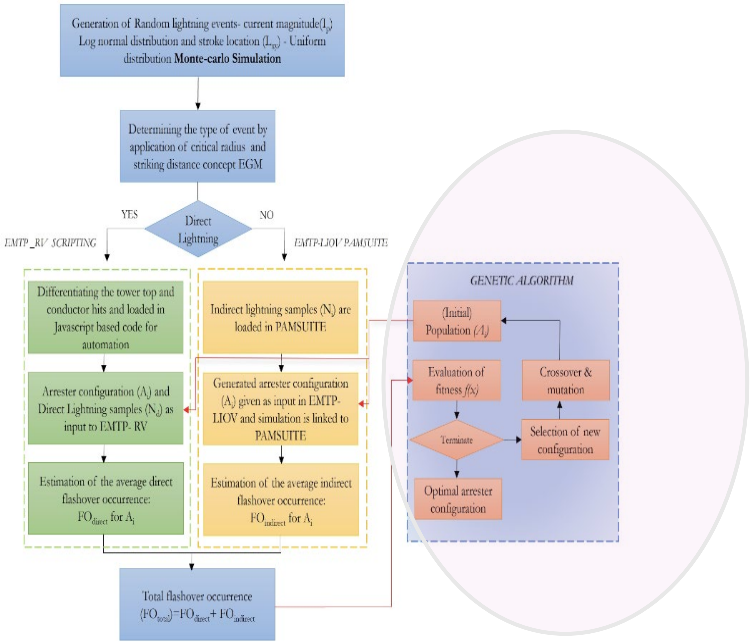
$$R_T = \int_0^{\infty} P(I_p, T_i) \cdot P(FA)dE + \int_0^{\infty} f(V) \cdot D(V)dV$$

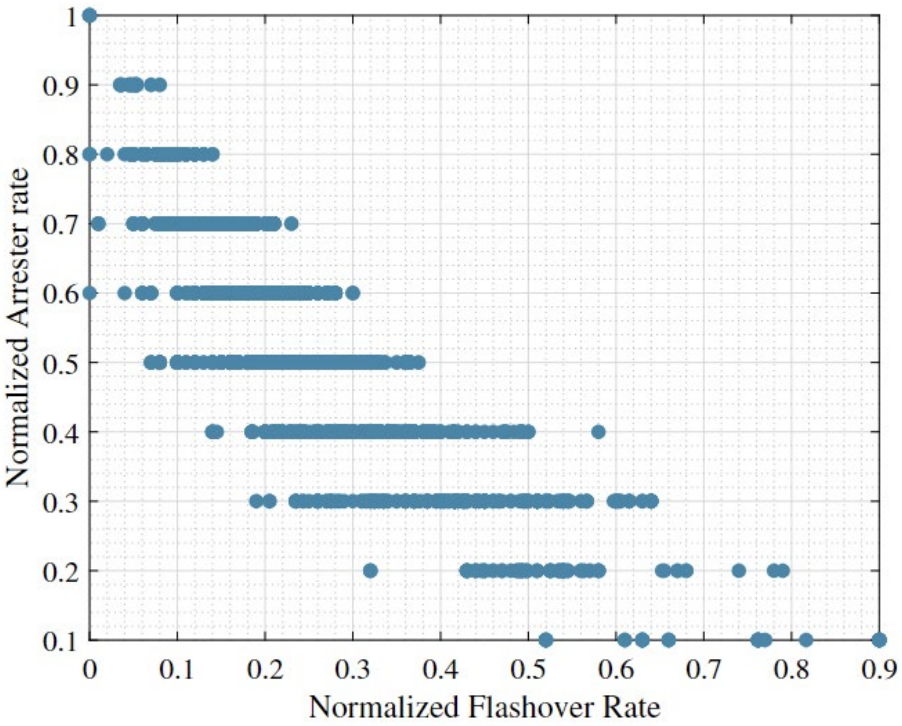
$$Minimize\ F = \sum_{i=1}^{n} \left[ w_1 \frac{FOI_i}{FOI_{max}} + w_2 \frac{R_{i,total}}{R_{risk,max}} + w_3 \frac{C_{i,total}}{C_{max}} \right]$$

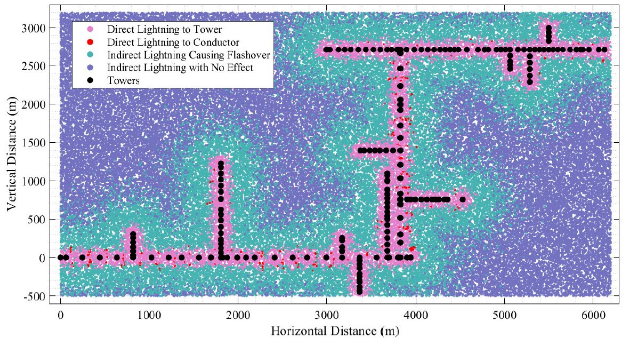
- *Tower Criticality Index: Always protected.* $(x = 1\ for\ C_{FOR} > C_{limit})$
- *Adjacent tower Overvoltage Transfer* $(AFOR_{i,j} < AFOR_{i\_max,j\_max})$
- *Network Intersection* $(x = 1\ T_{i,tower} = T_{critical})$
- *Surge Travel* $(x = 1\ d \le r_{ti} + r_{tj})$
- *Consecutive Arrester Arrangement : High – Risk Zones*
- *Top Phase Protection*
- *Shield wire Presence*

# PROTECTION STRATEGY: TRADITIONAL APPROACH




| Type of Stroke | Numerical simulation |
|---|---|
| Direct | 2405 (12.03 %) |
| Indirect with Flashover | 5385 (26.92 %) |
| Indirect w/o flashover | 13210 (61.05 %) |

Number of Lightning Events : 10000
Length of the line : 500 m
Population:50
Time:8.2 hrs

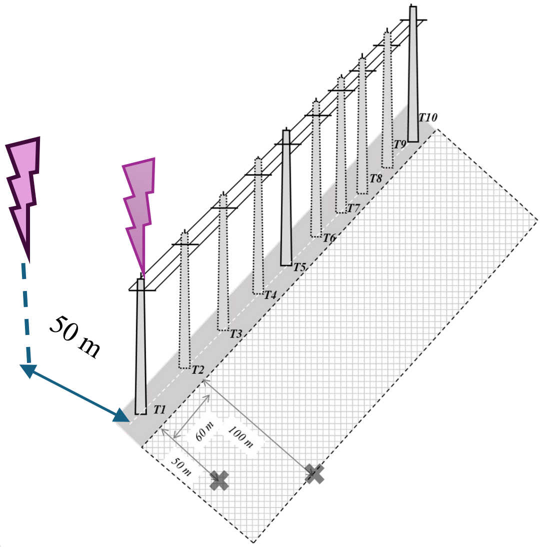
# PROTECTION STRATEGY: SCENARIO-BASED APPROACHES – FUTURES & ALTERNATIVES

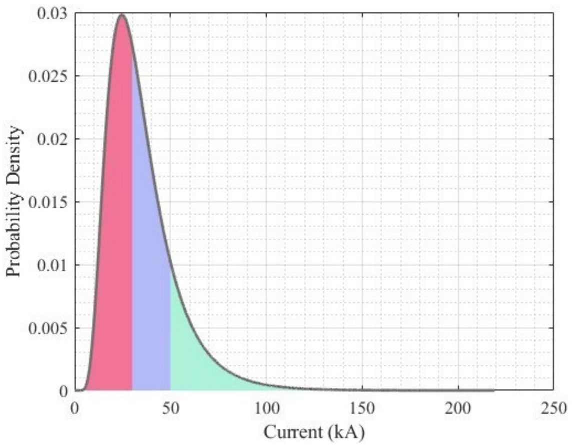
Location (Indirect)

- The lightning return stroke locations $f_q = L(x_q, y_q)$ are considered with a uniform distribution probability.
- $x_{\hat{q}} = (\hat{q} - 1) \cdot 30$, for $\hat{q} \in N, 1 \leq \hat{q} \leq N_T$ where $N_T$ represents the total number of towers

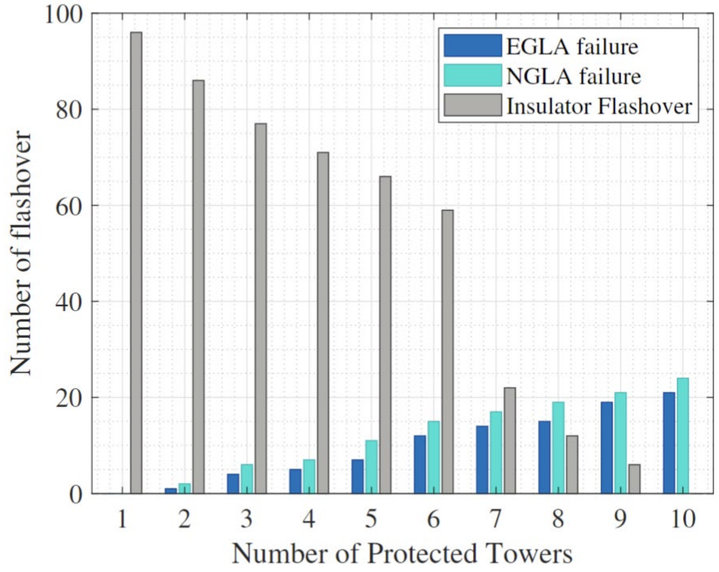
current magnitude

- ($1.2/50\ \mu s$ lightning waveform)
- probability distribution of current amplitude denoted as $f_q$ where $q = 1, \ldots, 3$, is considered.
- The occurrence rates for amplitudes of 30 kA, 50 kA, and 80 kA are specified as 0.6, 0.3, and 0.1, respectively.




| Alternatives | Type | coverage | Shielding Nature |
|---|---|---|---|
| $A_1$ | NGLA | Every 4 Towers | Unshielded line |
| $A_2$ | EGLA | Every 2 Towers | Shielded line |
| $A_3$ | NGLA | Every 4 Towers | Unshielded line |
| $A_4$ | EGLA | Every 2 Towers | Shielded line |
| $A_5$ | NGLA | Every 4 Towers | Unshielded line |
| $A_6$ | EGLA | Every 2 Towers | Shielded line |
| $A_7$ | NGLA | Every 4 Towers | Unshielded line |
| $A_8$ | EGLA | Every 2 Towers | Shielded line |



# PROTECTION STRATEGY: DECISION THEORY

**CRITERION –I - Expected total FOR minimization over the set of futures considered**

$$EF_T(A_p) = \sum_{q=1}^{n_f} \omega_q F_T(A_p, F_q) \quad p = 1, \dots, n_a$$

The best alternative $A_{best}$, among all the $na$ alternatives - lowest value of the $EF_T$.

**CRITERION –II: Minimization of the Maximum Weighted Regrets**

$$F_T^{opt}(F_q) = \min_{p} F_T(A_p, F_q) \quad q = 1, \dots, n_f$$

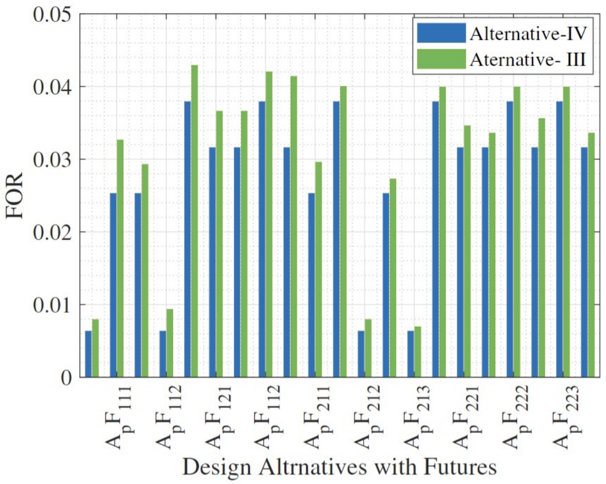
$$R(A_p, F_q) = F_T(A_p, F_q) - F_T^{opt} F_q \qquad p = 1, \dots, n_a, \quad q = 1, \dots, n_f$$

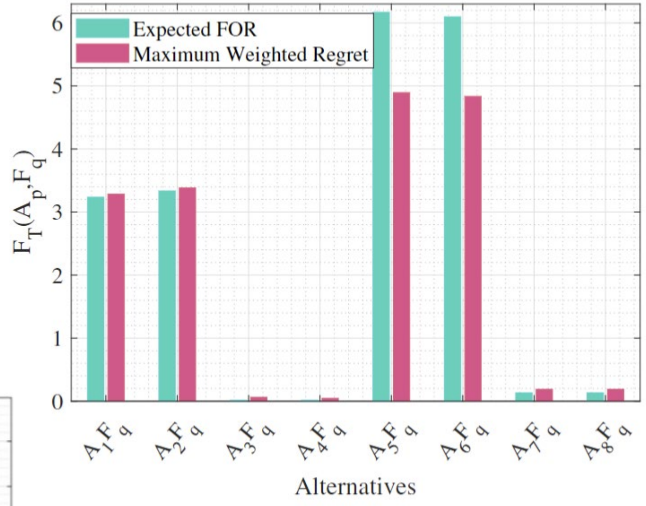
$$R_w(A_p, F_q) = \omega_q R(A_p, F_q) \quad p = 1, \dots, n_a, \quad q = 1, \dots, n_f$$

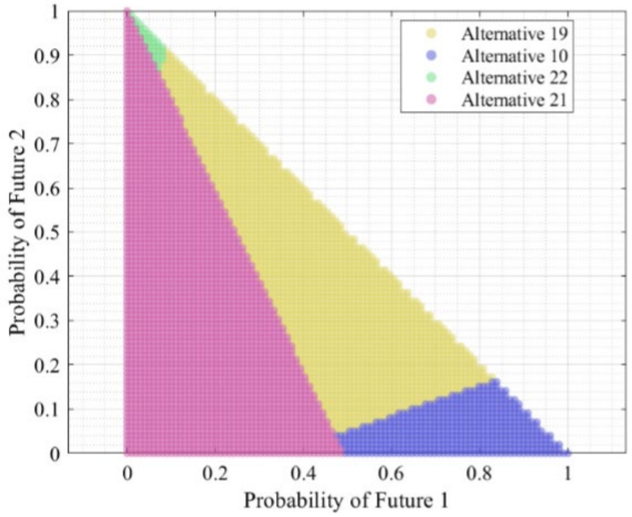
$$R_w^{max}(A_p) = \max_{q} R_w\{A_p, F_q\} \; p = 1, \dots, n_a$$

the best alternative $A_{opt}$ is the one associated with the minimum among the maximum weighted regrets.

**CRITERION III: Maximum Stability Areas:** For each set of future probabilities (s = 1,…,ns), only those solutions that fulfil both the expected cost minimization and the min-max weighted regret criteria will be considered. All other solutions will be discarded. The Decision Maker can select the best design alternative as the one that is more frequently provided as the optimal solution.



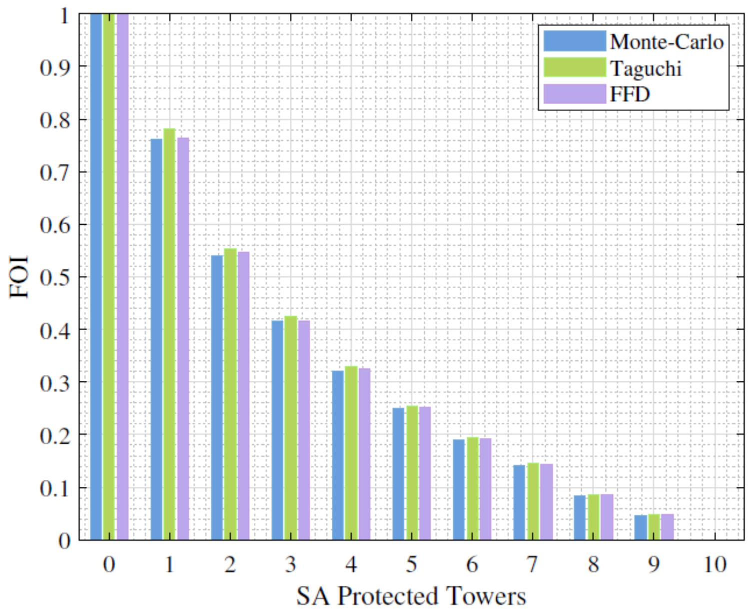



# Multi objective Optimization

# PROTECTION STRATEGY: DESIGN OF EXPERIMENT TECHNIQUES FOR GENERATION OF LIGHTNING EVENTS - FULL FACTORIAL DESIGN

- **DoE techniques** assess system responses based on various input combinations. Responses are influenced by factors, which directly affect outputs.
- **Factors** are data points with varying **levels** that impact system outputs.
- **Full Factorial Design (FFD):** FFD considers all possible combinations of selected factors and levels.
- For m factors, each with n levels, the total number of experimental runs is $n^m$.

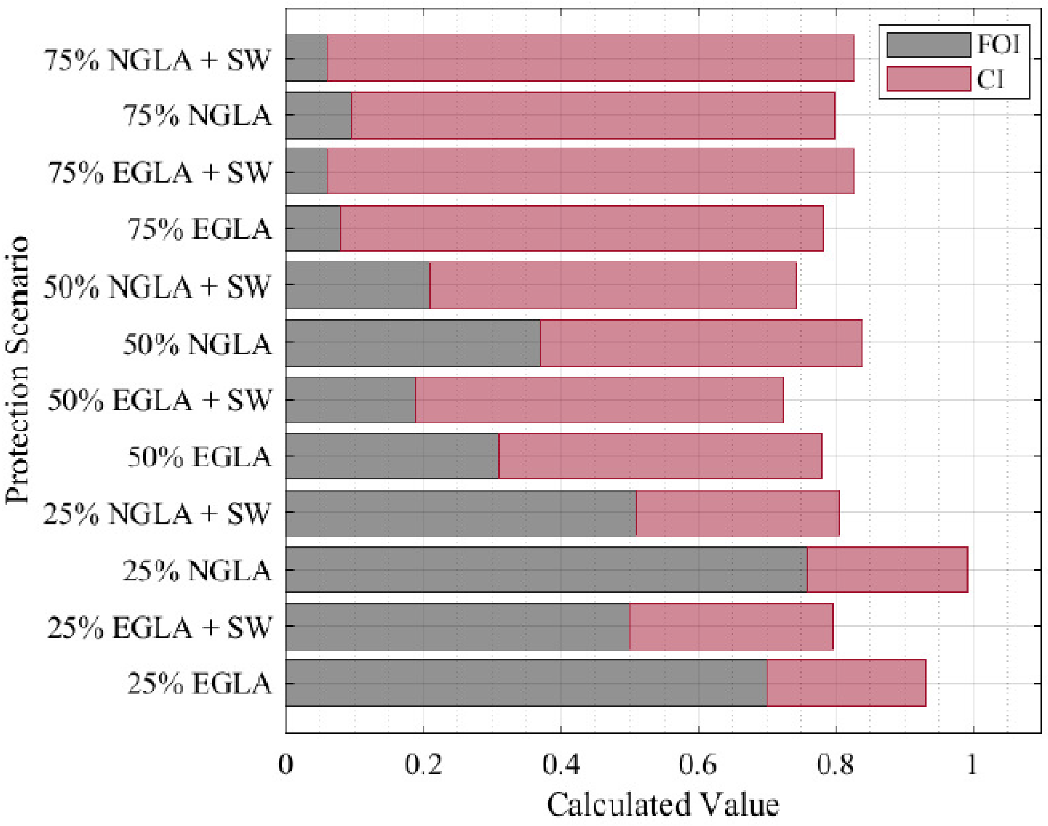


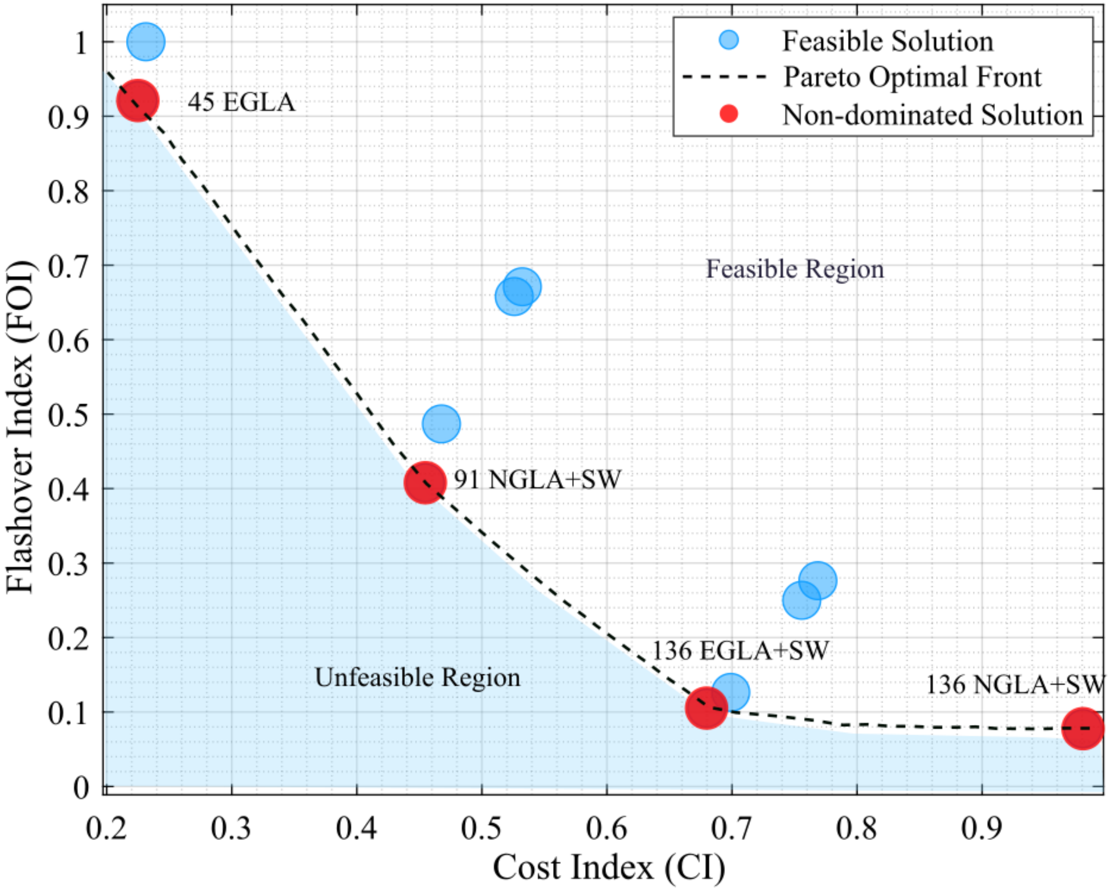

| Factors | Mean | Std. Dev |
|---|---|---|
| Lightning peak current | $\mu_1$ | $\sigma_1$ |
| Return stroke front time | $\mu_2$ | $\sigma_2$ |
| Location- y (Vertical axis) | $\mu_3$ | $\sigma_3$ |
| Location – x (Horizontal axis) | $\mu_4$ | $\sigma_4$ |

*Level 2:* $\mu_i \pm \sigma_i$

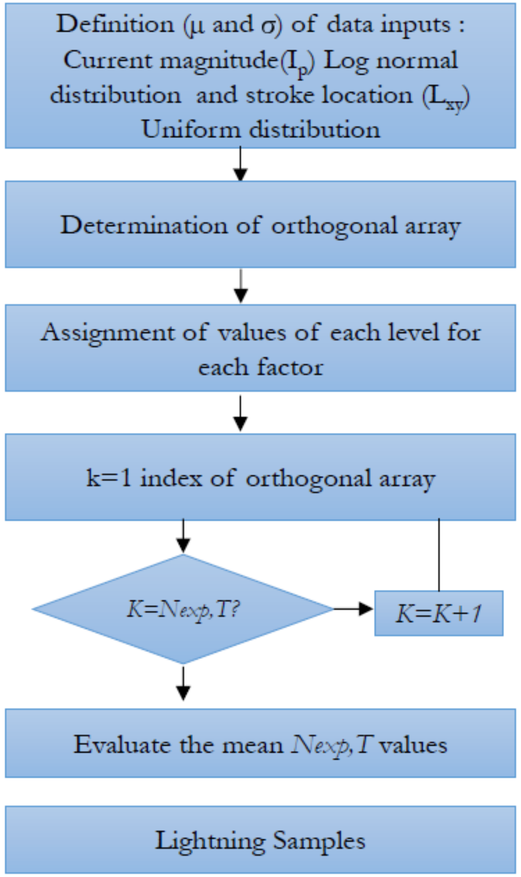
*Level 3:* $\mu_i, \mu_i \pm \sqrt{3/2}\sigma_i$

# PROTECTION STRATEGY: PROTECTION ALTERNATIVES AND VALUES OF THE OBJECTIVES



# PROTECTION STRATEGY: DESIGN OF EXPERIMENT TECHNIQUES FOR GENERATION OF LIGHTNING EVENTS – TAGUCHI MULTI-AREA

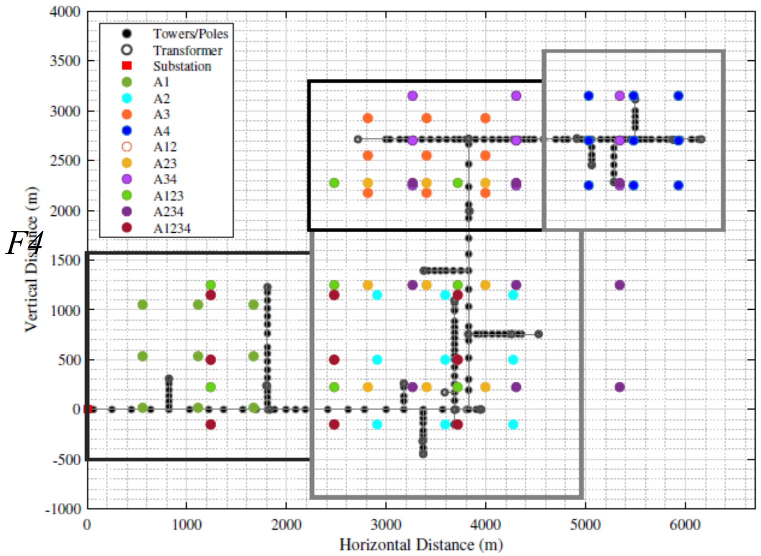



| Exp No. | Factor A | Factor B | Factor C | Factor D |
|---|---|---|---|---|
| 1 | $\mu_A - \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B - \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C - \sqrt{\frac{3}{2}}\sigma_C$ | $\mu_D - \sqrt{\frac{3}{2}}\sigma_D$ |
| 2 | $\mu_A - \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B$ | $\mu_C$ | $\mu_D$ |
| 3 | $\mu_A - \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B + \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C + \sqrt{\frac{3}{2}}\sigma_C$ | $\mu_D$ |
| 4 | $\mu_A$ | $\mu_B - \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C$ | $\mu_D + \sqrt{\frac{3}{2}}\sigma_D$ |
| 5 | $\mu_A$ | $\mu_B$ | $\mu_C + \sqrt{\frac{3}{2}}\sigma_C$ | $\mu_D$ |
| 6 | $\mu_A$ | $\mu_B + \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C$ | $\mu_D - \sqrt{\frac{3}{2}}\sigma_D$ |
| 7 | $\mu_A + \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B - \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C + \sqrt{\frac{3}{2}}\sigma_C$ | $\mu_D$ |
| 8 | $\mu_A + \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B$ | $\mu_C$ | $\mu_D - \sqrt{\frac{3}{2}}\sigma_D$ |
| 9 | $\mu_A + \sqrt{\frac{3}{2}}\sigma_A$ | $\mu_B + \sqrt{\frac{3}{2}}\sigma_B$ | $\mu_C$ | $\mu_D$ |

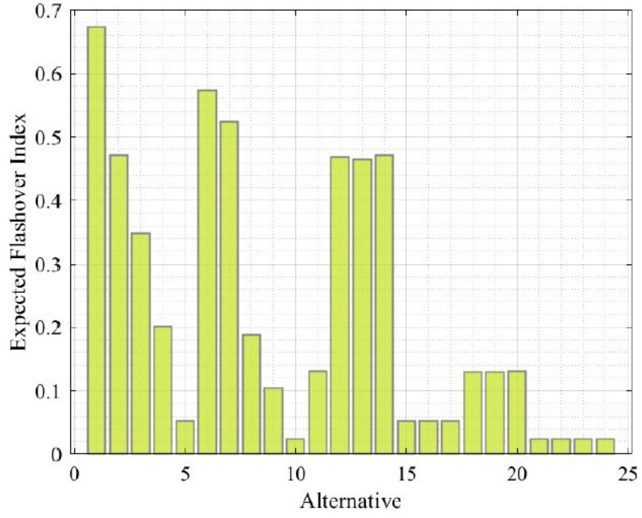
$$n_{col} = \frac{(n^J - 1)}{(n - 1)}$$

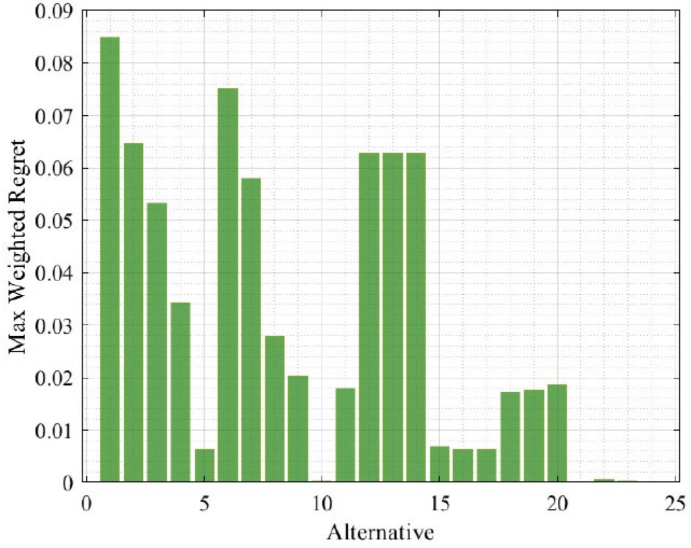
*Single area : F1, F2, F3, F4*
*Double area : F5,F6,F7*
*Triple areas : F8, F9*
*The Quad : F10*

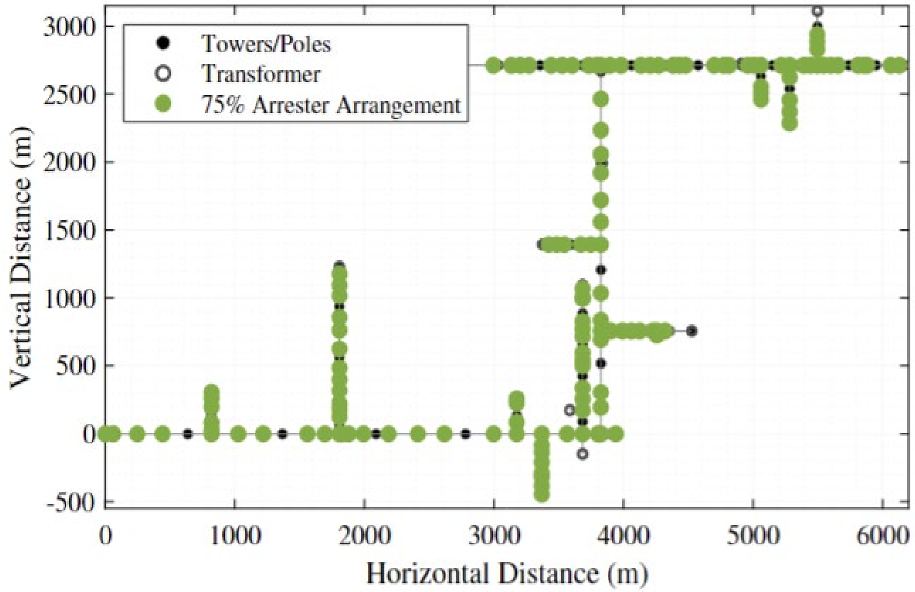
| | F1 | F2 | Fn |
|---|---|---|---|
| A1 | $\begin{pmatrix} T1a & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tma & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1b & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmb & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1z & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmz & \cdots & Tmn \end{pmatrix}$ |
| A2 | $\begin{pmatrix} T1a & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tma & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1b & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmb & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1z & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmz & \cdots & Tmn \end{pmatrix}$ |
| An | $\begin{pmatrix} T1a & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tma & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1b & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmb & \cdots & Tmn \end{pmatrix}$ | $\begin{pmatrix} T1z & \cdots & Tnn \\ \vdots & \ddots & \vdots \\ Tmz & \cdots & Tmn \end{pmatrix}$ |

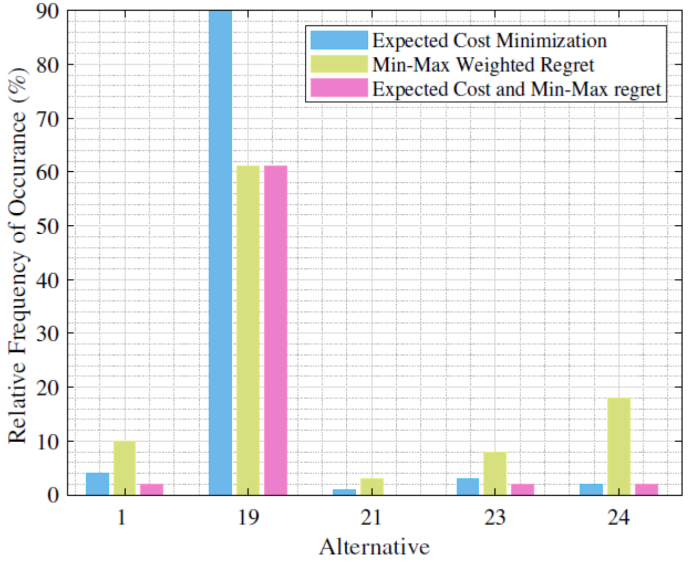


# PROTECTION STRATEGY: DESIGN OF EXPERIMENT TECHNIQUES FOR GENERATION OF LIGHTNING EVENTS – TAGUCHI MULTI-AREA



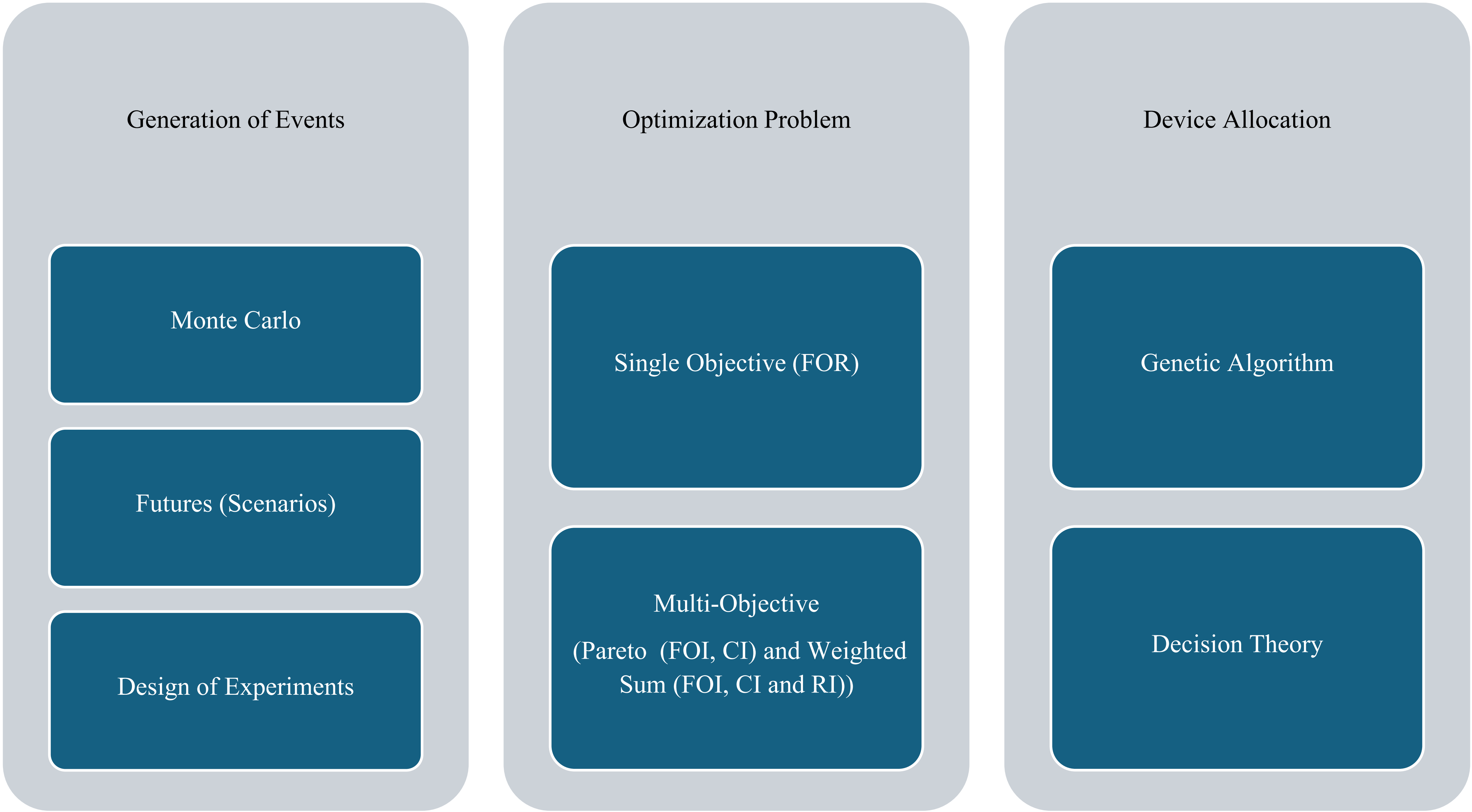




| Description | Proposed Method | Monte-Carlo |
|---|---|---|
| Number of Arrester | 136 | 136 |
| Lightning Samples | 90 | 100000 |
| Computation Time | 1.2 hrs | 42.5 hrs |
| FOR | 0.08 | 1.01 |

# CONCLUDING REMARKS

| | |
|---|---|
| Protective Device Evaluation | Separate evaluation for lightning mitigation devices<br>Use of effective lightning attraction models |
| Analysis of Critical Towers | Assessment of lightning occurrences along distribution lines |
| Heuristic Approaches | Time-consuming nature of traditional heuristic methods<br>Fixed protection alternatives based on “degree of elimination” |
| Consideration of Key Constraints | Critical Towers; Transfer Voltages; Cross Section; Surge Travel; Consecutive Arrangements |
| Design of Experiments (DoE) - Reduction of lightning sample requirements for analysis | Implementation of Full Factorial and Taguchi arrays |
| Decision theory approach for choice of protection alternative | Taguchi multi-area and Decision Theory criteria |

Grazie


Generation of Events
Monte Carlo
Futures (Scenarios)
Design of Experiments
Optimization Problem
Single Objective (FOR)
Multi-Objective
(Pareto (FOI, CI) and Weighted Sum (FOI, CI and RI))
Device Allocation
Genetic Algorithm
Decision Theory