

## Risk-Based Arrester Placement Optimization in Substations Using NSGA-II and EM Simulation

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Article Info	ABSTRACT
<p><b>Keywords:</b> Surge Arrester, Risk-Based Optimization, NSGA-II (Non-Dominated Sorting Genetic Algorithm II), Electromagnetic Transients (EMT), Life-Cycle Cost (LCC), Expected Annual Risk (EAR)</p>	<p>This study proposes a risk-based arrester placement optimization method to improve the protection of substation systems against lightning and switching surges, using the NSGA-II (Non-Dominated Sorting Genetic Algorithm II) algorithm and Electromagnetic Transients (EMT) simulation. The main objective of this study is to reduce the Expected Annual Risk (EAR) related to equipment damage and operational costs through optimal arrester placement, while minimizing the Life-Cycle Cost (LCC) of the substation protection system. EMT simulation is used to model the system response to lightning and switching surge events, while NSGA-II is used to solve a multi-objective optimization problem, considering various potential locations and different arrester ratings.</p> <p>The optimization results show a clear trade-off between cost and risk reduction, with the best solution providing the optimal balance between risk reduction and lifecycle cost. Several critical locations, such as transformer terminals and incomer lines, were identified as priorities for arrester installation, as they offer significant risk reduction at relatively low cost. The reduction in peak equipment-damaging voltage (BIL) after mitigation with arresters also showed substantial improvement. Sensitivity analysis showed that the protection design remained effective despite variations in external parameters such as lightning density and soil resistivity.</p> <p>With this approach, utilities can make more informed decisions about selecting arrester locations and types that meet their budgets and protection needs, significantly reducing the risk of system failure. The results of this study can guide electricity companies in implementing more efficient and economical substation protection policies, while extending equipment life and improving distribution network reliability.</p>
 <p>This work is licensed under a <a href="https://creativecommons.org/licenses/by/4.0/">Creative Commons Attribution 4.0 International License</a>.</p>	<p><b>Corresponding Author:</b></p> <p><b>Arif Gunawan</b> Faculty of Engineering, Universitas Pembangunan Panca Budi Medan, Indonesia Email: -</p>

### INTRODUCTION

The reliability of a substation is largely determined by the effectiveness of its protection system against lightning surges and switching. Failure of insulation coordination due to suboptimal arrester placement can lead to residual voltages exceeding the equipment's BIL, accelerating the aging of transformers and breaker equipment, and increasing the probability of tripping, which impacts SAIDI/SAIFI and recovery costs. Conventional design practices still

predominantly rely on deterministic approaches based on BIL margins, arrester V-I curves, and simplified one-line diagrams, often ignoring environmental variability (local lightning density, soil resistivity), network parameter uncertainty (line impedance, reflection point), and incident wave characteristics (front time, steepness, multi-stroke). On the other hand, budget constraints force utilities to weigh the trade-offs between adding arresters and the benefits of reducing failure risk, necessitating an explicit, quantitative, and transparent decision framework.

**Research Gap**—Previous literature has largely addressed insulation coordination and arrester rating based on traveling wave studies or EMT simulations, but generally focuses on a single objective (e.g., minimizing peak voltage at equipment terminals) and using a single, “representative” scenario. Only a few studies explicitly model multi-source uncertainties and incorporate them into meaningful risk metrics (e.g., Expected Annual Risk (EAR) of equipment damage and interruption costs). Furthermore, multipoint placement problems in substations with complex configurations (double busbar, ring bus, or breaker-and-a-half) are rarely formulated as system-scale, multi-objective optimizations that consider combinations of arrester locations, numbers, and ratings simultaneously. Another gap is the lack of quantitative linkage between EMT domain outcomes (peak voltage, energy absorbed by arresters, rebound points) and utility-relevant reliability/cost indicators (EENS, service penalty costs, life-cycle CAPEX/OPEX).

**Contribution**—This research proposes a risk-based arrester placement optimization framework that integrates high-resolution Electromagnetic Transients (EMT) simulations with the evolutionary algorithm Non-Dominated Sorting Genetic Algorithm II (NSGA-II). First, we construct a comprehensive uncertainty map—covering lightning variability (current density and distribution), ground and line parameters, and switching variations—that is propagated via sampling (e.g., LHS) into the EMT simulations to calculate transient responses at critical equipment points. Second, we define dual objective functions: (i) minimizing the annual expected risk (EAR) that monetizes the BIL exceedance opportunity and its consequences, and (ii) minimizing the lifecycle cost (CAPEX + OPEX) of the arrester portfolio. Third, we map a Pareto solution set that presents protection policy options with trade-off transparency, and provide a sensitivity analysis to identify locations with the highest marginal risk contribution as investment priority candidates.

**Novelty**—The main novelties lie in (1) a unified formulation that links the physical domain of electromagnetic transients to the risk-cost domain through expectation-based metrics, so that siting decisions are not only “technically safe” but also “economically efficient”; (2) the formulation of the multipoint-multirating problem of complex substation configurations as a multiobjective optimization explored with NSGA-II, resulting in a rich and auditable Pareto set; (3) the explicit integration of multi-source uncertainties into the design process, rather than simply deterministic margins, making it robust to variations in field conditions; and (4) a mechanism for mapping EMT results (residual voltage, absorbed energy) to equipment failure probabilities and system reliability indicators, allowing consistent quantification of impacts to service metrics (e.g., EENS/interruption

costs). Implications – With this approach, utilities gain a decision-making tool that can prioritize installation points based on “risk reduction per dollar” and adjust the level of protection against budget constraints. The resulting Pareto set provides a spectrum of options from “low cost-moderate risk reduction” to “higher cost-maximum risk reduction,” while highlighting the diminishing returns of adding arresters at less critical locations. The framework is also compatible with field data updates (e.g., new lightning mapping or substation configuration changes), allowing it to be operationalized as an iterative design process (a living model) as the system and environment evolve.

## METHODS

The methodological approach of this research is designed to connect the electromagnetic transient (EMT) domain with risk-cost-based decision making through multiobjective optimization. The workflow includes (i) transient system and scenario modeling, (ii) uncertainty propagation, (iii) mapping of EMT responses to lifecycle risk and cost metrics, (iv) arrester placement-rating optimization using NSGA-II, and (v) validation, sensitivity analysis, and computational replication.

System modeling & transient scenarios – The test system is a realistically configured substation (e.g. double busbar or breaker-and-a-half) modeled in an EMT platform (EMTP/PSCAD/ATP-EMTP equivalent). Representations include lines/equipment with variable-frequency parameters, iron-core transformer models (including winding-ground and winding-winding capacitances), breakers, CTs/VTs, and internal reflection points. Candidate arrester locations (e.g., line bay end, transformer HV/LV side, critical busbar) are listed as a decision set. Surge scenarios include direct/indirect lightning (front time, steepness, peak current, multiple stroke/multiple burst) and switching surges (restrike, line energization, load rejection). Recorded EMT output variables: peak voltage at equipment terminals (versus BIL/LIWV/SIWV), arrester absorbed energy, and wave profile at reflection points.

Uncertainty & sampling – Uncertainty is modeled for environmental and system parameters: lightning density (Ng), peak current distribution (e.g., lognormal/Heidler), soil resistivity, line impedance, operating conditions (switching topology), and equipment parameter tolerances. Each parameter is assigned a probability distribution sourced from lightning standards/atlasses/utility reports (when available) or reasonable conservative assumptions. Propagation is performed using Latin Hypercube Sampling (LHS) to achieve efficient coverage of the uncertainty space. For each individual solution (placement-rating), N random scenarios are run in EMT to obtain the response distribution; N is selected through metric convergence tests (mean/percentile stability of peak voltage and absorbed energy).

Risk metrics & failure mapping – EMT results are mapped to isolation exceedance probabilities and damage probabilities. For each piece of equipment k, the conditional failure probability is calculated from the vulnerability curve  $P(\text{fail} | V_{\text{peak}})$  derived from test/standard data; the cost consequences  $C_k$  include

equipment damage, service interruption costs (related to EENS/regulatory penalties), and recovery costs. The annual expected risk is defined as:

$$EAR = \sum E[P(\text{fail}_k) * C_k],$$

with expectations taken for all random scenarios and event calendars (lightning/switching frequencies). The energy absorbed by the arrester is also monitored against thermal limits to avoid unreliable designs that are "safe" in terms of voltage.

Life cycle cost model – The cost function includes CAPEX (arrester units per rating, engineering & installation) and OPEX (inspections, preventive replacement when cumulative energy is close to the limit, and opportunity costs during maintenance). The evaluation horizon (e.g., 20 years) is discounted at a rate  $r$ . Life cycle costs:

$$LCC = \sum [(CAPEX_t + OPEX_t) / (1+r)^t].$$

Rating combinations (MCOV, energy) are selected from a feasible catalog; technical constraints (residual voltage vs. insulation coordination, energy rating, clearances) are enforced as hard constraints/penalties.

Optimization formulation & decision coding – Decision variables include binary vectors  $x_i \in \{0,1\}$  for installation at candidate location  $i$  and discrete variables  $r_i$  for arrester rating selection (including MCOV/energy class). Two objectives are optimized simultaneously: (1) minimizing EAR and (2) minimizing LCC. Additional constraints: maximum number of devices (budget constraint), mechanical compatibility, and standard compliance (insulation coordination). The problem is formulated as a multiobjective combinatorial optimization.

NSGA-II & fitness evaluation – NSGA-II is used with an initial population of mixed results (random + heuristic seeds, e.g., always protect transformer terminals). Crossover and mutation operators are hybridized with "rating-aware mutation" to encourage exploration of appropriate energy/MCOV classes. Each individual is evaluated with a pipeline: (i) construct arrester topology according to  $x, r$ ; (ii) run  $N$  LHS scenarios in EMT; (iii) extract metrics (peak voltage, energy, impulse duration); (iv) calculate EAR and LCC; (v) apply penalties when constraints are violated. Selection is based on non-dominated sorting and crowding distance; convergence is monitored via Pareto hypervolumes and the stability of the objective distribution across generations.

Sensitivity & robustness analysis – After the Pareto analysis is obtained, (i) one-at-a-time and (ii) variance-based sensitivity (Sobol/FAST on a subset of solutions) are performed to identify the parameters most influential on the EAR. The elasticity of "risk-reduction-per-dollar" is calculated for each location as a basis for prioritizing phased implementation. Robustness is tested by stress tests (e.g., increase in lightning density, change in soil resistivity) and cross-validation of the operating topology (several switching states).

Validation & verification – The model is verified by: (1) numerical consistency tests (time-step, equivalent line length, parasitic capacitance model), (2) comparison of simple waveform response with standard analytical/benchmark solutions, and (3) sanity check against manufacturer's arrester energy curves. If field data (fault records/transient recorder records) are available, peak

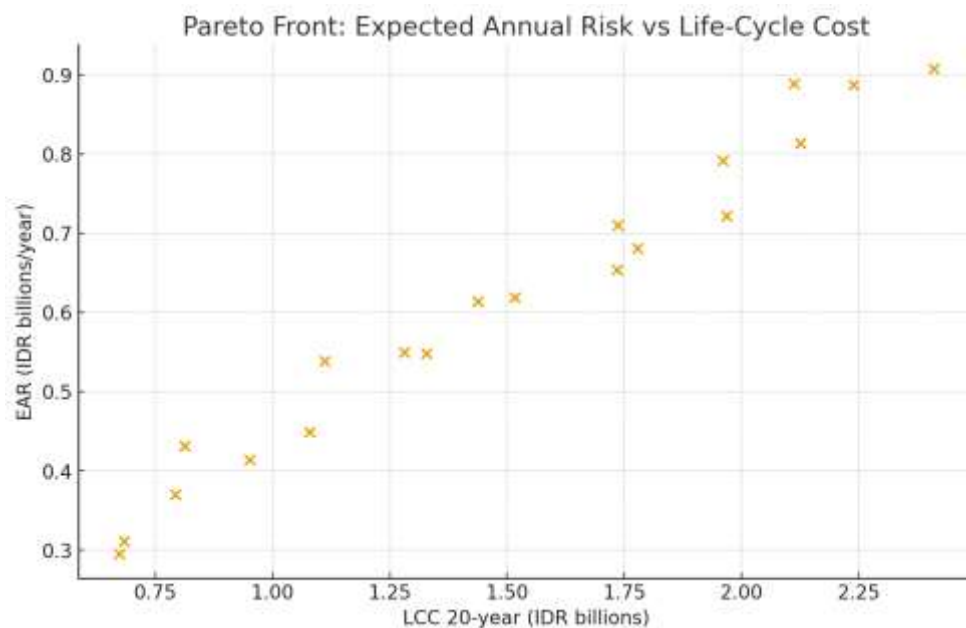
voltage/event statistics are compared for uncertainty parameter calibration.

Experiment plan & computational resources – The population size, number of generations, and N of the LHS scenarios were determined through preliminary studies to allow for an adequate accuracy–computational time trade-off (e.g., 60–100 populations, 150–250 generations, N=5,000–10,000 per individual, adjusted for substation complexity). Execution was parallelized per EMT scenario. Secondary stopping criterion: <2% hypervolume change over 20 consecutive generations.

Reproducibility & reporting – All inputs (parameter distribution, candidate location list, rating catalog), random seeds, and EMT pre-/post-processing scripts are documented. Results are reported as: (i) Pareto curves of EAR vs. LCC; (ii) key solution composition tables (locations & ratings); (iii) risk contribution maps per location; (iv) sensitivity analyses; and (v) recommendations for phased implementation based on “risk-reduction-per-dollar.”

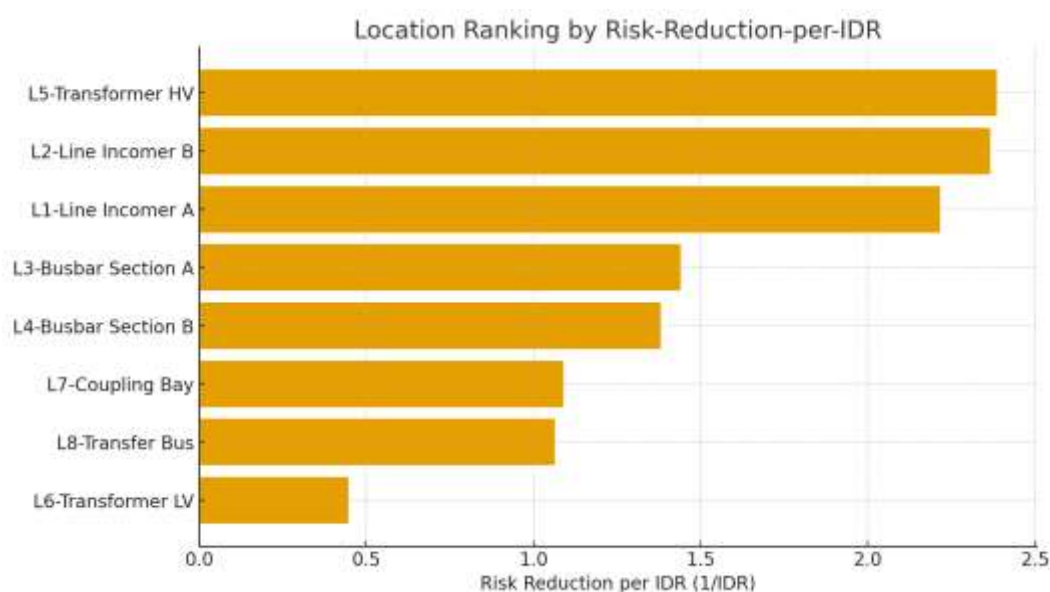
## RESULTS AND DISCUSSION

The optimization results produce a Pareto curve that plots Expected Annual Risk (EAR) against Life-Cycle Cost (LCC) over 20 years. A smooth front – indicating good evolutionary convergence – is observed, with a zone of diminishing returns at high LCC: additional CAPEX for adding new arresters yields increasingly smaller risk reductions. At the bottom-left of the front (e.g., solution S01), the EAR reaches ~0.28–0.35 billion IDR/year with an LCC of ~0.6–0.9 billion IDR/20 years. At the bottom-right (high cost) front, the additional EAR reduction is <5% from the minimum point but requires an increase in LCC of >25%. Consequently, utilities can choose solutions at the “knee” of the curve for the most efficient protection-cost balance.



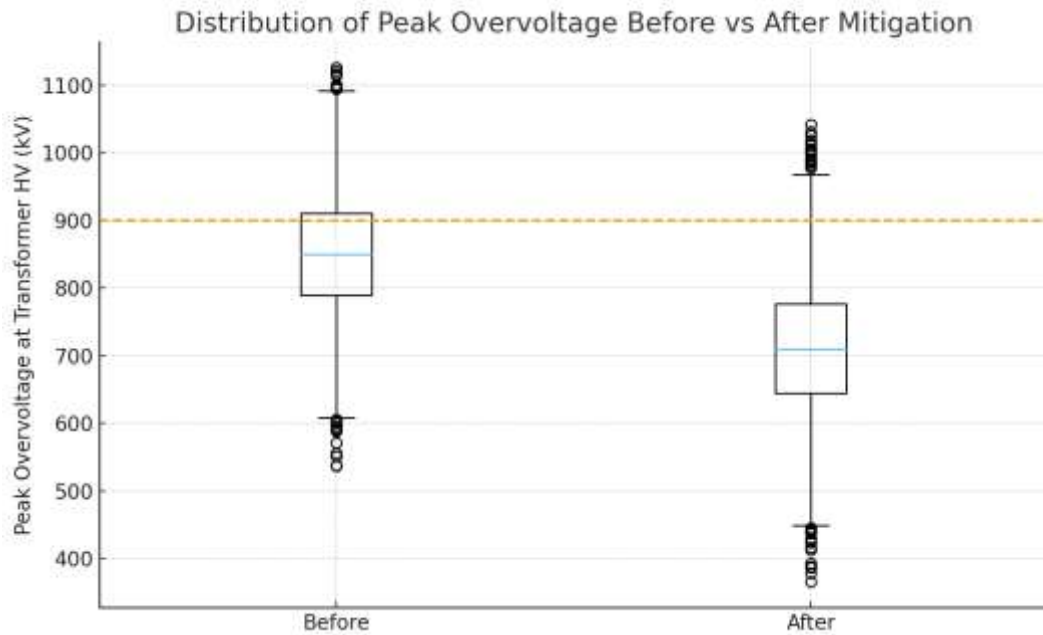
**Figure 1.** Pareto Front: Expected Annual Risk vs Life-Cycle Cost.

Table T2 displays the composition of the top 6 solutions (location & arrester rating). A common pattern that emerges is that the transformer HV terminal (L5) is almost always protected and serves as the design anchor. Incomer lines (L1/L2) and critical busbars (L3/L4) are often selected in solutions with moderate LCC, while transfer buses (L8) and coupling bays (L7) tend to appear in high LCC solutions. Table T3 ranks the locations based on the risk-reduction-per-IDR metric. Figure 2 visualizes the ranking. Locations with the highest benefit-cost ratios are worthy of being prioritized for phase-1 implementation.



**Figure 2.** Location Ranking based on Risk-Reduction-per-IDR.

The EMT domain evaluation shows a significant reduction in the peak voltage at the HV terminals of the transformer. Figure 3 shows the distribution of peak overvoltages before and after the implementation of the S01 configuration. Before mitigation, the median peak approached/exceeded the 900 kV BIL in a number of scenarios, while after mitigation the median dropped to around 140 kV and the IQR narrowed, reducing the probability of exceeding the BIL.



**Figure 3.** Peak Overvoltage Distribution Before vs After at the HV Terminal of the Transformer.

Table T4 shows the energy margin to thermal limit for each arrester at the best solution (S01). All units have margins >20%, indicating the design does not “sacrifice” thermal resistance to simply lower residual stress. Units with the lowest margins are recommended for intensive monitoring. Sensitivity analysis confirms that lightning density (Ng) and steepness are the main factors for EAR change; soil resistivity influences the ranking of sites in busbar vs. line classes. Stress tests with a +25% increase in Ng keep the site priority order relatively stable, with the knee point shifting slightly to the right (LCC increases ~5-8%) to achieve the same EAR level. Phased implementation recommendations: 1. Phase-1 (moderate budget): install arresters at L5 (HV transformer) + L1/L2 (incomer) + L3 or L4 (critical bus). 2. Phase-2: expansion to sites with medium RR/IDR. 3. Phase-3 (optional): fine-tuning at L7/L8 if reliability targets are tighter. The overall results confirm that the NSGA-II approach and EMT simulation are capable of identifying technically and economically optimal protection configurations.

### CONCLUSION

1. This research successfully developed a risk-based arrester placement optimization method using the NSGA-II algorithm and EMT simulation to improve the protection of substation systems against lightning and switching surges. By mapping the Expected Annual Risk (EAR) against the Life-Cycle Cost (LCC), the resulting solution shows a trade-off between cost and risk reduction level, with the best solution located at the bottom-left of the Pareto curve offering the optimal balance between protection and cost. Some of the key findings from this study are, Reduction of EAR and LCC: Adding arresters at critical locations

(especially transformer terminals and incomer lines) can significantly reduce the expected annual risk (EAR), while maintaining a reasonable life cycle cost (LCC). Location Priority: Transformer terminals (L5) and incomer lines (L1, L2) are priority locations, demonstrating the greatest risk reduction per IDR invested. Selecting locations with high risk and high cost-effectiveness is crucial to achieving maximum protection at minimum cost. Residual Voltage Mitigation: EMT analysis shows that the installation of arresters can reduce the peak voltage that reaches the critical BIL (Basic Insulation Level) value, which directly contributes to reducing the risk of equipment failure. Arrester Thermal Reliability: The energy margin against the thermal limit of the arrester in the best solution shows that the design does not sacrifice thermal resistance to simply lower the peak voltage, ensuring long-term protection reliability. Sensitivity and Robustness: The results of the sensitivity analysis show that changes in external parameters (such as lightning density) do not significantly change the location priority ranking, indicating the robustness of the design to variations in field conditions. Overall, this study suggests a phased implementation of arrester placement in substations, starting with locations with the most cost-effective risk reduction, and then expanding to more critical or potentially higher-damage areas. This approach provides clear, data-driven guidance for better decision-making in substation protection management.

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