Elimensi Journal of Electrical Engineering

Volume 03 | Number 01 | 2025
E-ISSN : 2987-2928

Risk-Based Arrester Placement in Substations: A Multi-Objective Probabilistic Approach

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Article Info

Keywords:
Risk-based surge arrester placement; multi-objective optimization; NSGA-II; Latin Hypercube Sampling (LHS); electromagnetic transient (EMT) simulation; insulation coordination (BIL/LIWV); Expected Energy Not Supplied (EENS); SAIDI/SAIFI; grounding grid resistance (Rg); Pareto front.

ABSTRACT

This study proposes a risk-based arrester placement framework in substations using a multi-objective probabilistic approach that combines electromagnetic transient (EMT) modeling, Latin Hypercube Sampling (LHS) for uncertainty propagation, and NSGA-II to generate a set of cost–risk Pareto solutions. The model incorporates lightning and switching surge sources, equipment characteristics (BIL/LIWV, arrester V–I curves, energy duty limits), and technical–economic consequences (EENS, interruption costs). A case study on a double busbar substation with eight candidate points shows three representative solutions: minimum-cost (3 arresters), knee-point (5 arresters), and minimum-risk (7 arresters). The knee-point solution—arresters at incomers L1–L2, the main bus, and HV & MV transformer terminals—reduces Expected Risk by ≈ 58% and SAIDI by ≈ 57% compared to the deterministic baseline (arresters only at incomers), with improved insulation coordination margins (e.g., p95 of the transformer HV terminals drops from ~712 kV to ~635 kV) and energy reserves of ≥30% over manufacturer specifications. Sensitivity analysis identifies ground grid resistance (Rg), lightning peak current, and strike position as the primary risk drivers, indicating that co-optimization of arresters and grounding has the potential to further improve performance. The results confirm that this approach is robust and economical, and ready to be adopted as a basis for protection investment decisions in modern substations.

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INTRODUCTION

Introduction (Background)

Substation reliability is significantly influenced by the isolation and protection systems' capabilities against lightning and switching surges. Inaccurate arrester placement and rating can trigger residual voltages that exceed insulation coordination, accelerate equipment aging (transformers, circuit breakers, and CTs/VTs), and increase the probability of tripping, leading to service disruptions and high restoration costs. Common practice still relies on deterministic guidelines (based on BIL/LIWV and protection distances) and simple one-line diagrams, which often ignore uncertainties such as local lightning density, ground impedance, incident wave characteristics, and correlations between events across multiple bays. Budget constraints, on the other hand, force utilities to optimize the location and number of arresters, rather than simply "maximizing protection" without considering the costs and benefits. This situation demands an explicit, probabilistic, and multi-objective risk-based approach to make protection investment decisions more transparent and accountable.

Terms/Scope

This research focuses on medium-high to extra-high voltage substations, including:

1. probabilistic models of surge sources (lightning and switching) on the transmission and interconnection side,
2. wave and voltage propagation modeling at key equipment terminals (power transformers, CB, disconnectors, CT/VT, cables/overhead),
3. risk evaluation as expected loss (frequency × consequence) combining the probability of insulation failure and the technical-economic impact (EENS, repair costs, reputation/penalty consequences), as well as
4. multi-objective optimization to determine the location and specifications of arresters (energy rating, Uc, protection level) at several candidate points in a single/dual bus scheme.

Problems

Conventional deterministic approaches have difficulty capturing:

- Uncertainty in the intensity and shape of the surge waveform, which impacts the distribution of peak voltages at the equipment terminals.
- Variations in field parameters (soil resistivity, line/cable impedance, connection conditions) that affect the arrester residual voltage and insulation coordination margin.
- Inter-equipment interactions (e.g. voltage sharing when multiple arresters are installed) as well as the effects of physical location and length of conductors to ground.
- Cost constraints require a compromise between protection CAPEX and failure risk reduction—this compromise cannot be represented by a single metric.

As a result, arrester placement decisions are often “heuristic” based and do not show a clear trade-off between costs and reliability benefits.

Problem Statement

How to design a placement strategy and select arrester specifications in a substation that:

1. probabilistically model the uncertainty of surge sources and system parameters,
2. quantify the risk of isolation failure and its economic impact, and
3. optimizing several conflicting objectives—for example, minimizing expected risk (EENS/loss) while minimizing investment costs—so that a set of Pareto solutions is produced that can be the basis for utility decisions?

Research Contribution (Objective)

1. Integrated Risk Framework: Proposes a risk evaluation framework that combines probabilistic surge models, arrester residual voltages, and technical-economic loss functions for each key equipment in a substation.
2. Multi-Objective Optimization Formulation: Formulate arrester placement and specification as a multi-objective optimization problem (e.g. total cost vs expected risk/EENS), resulting in a Pareto curve that makes it easier for policy makers to

choose a solution within budget constraints/reliability targets.

3. Uncertainty Quantification: Integrating uncertainty sampling/propagation techniques (e.g. Monte Carlo/Latin Hypercube) to obtain statistically robust risk metrics with confidence bounds.
4. Practical Implementation Guide: Provides step-by-step procedures for utilities (candidate point selection, arrester parameterization, insulation coordination limits, and solution acceptance criteria) so that they can be easily replicated at substations with different configurations.

Novelty

- Substation-specific risk-based placement with explicit multi-objectives: Not only minimizing peak voltage/overstress, but simultaneously minimizing expected economic loss and CAPEX, resulting in a transparent decision space (Pareto set) for asset management.
- Co-optimization of arrester location and rating under uncertainty: Unifying "where" and "what rating" decisions in one probabilistic formulation, instead of post-tuning after the location is set.
- Rich consequence model: Risk is not only measured by the isolation coordination margin, but also links to service indicators (EENS, local SAIDI/SAIFI) and life cycle costs, making it relevant for regulation and investment planning.
- Configuration portability: The framework can be applied to a variety of bus topologies (single, double busbar, breaker-and-a-half) and equipment mixes (overhead/cable), with field parameters as random inputs—increasing generality over fixed rule-based approaches.

Thus, this study presents a comprehensive multi-objective probabilistic approach for arrester placement in substations, which not only improves the technical resilience to surges, but also optimizes the economic value of protection investment decisions under real-world uncertainty conditions.

METHODS

Problem Formulation & Decision Variables

The research begins by formulating a decision space that combines two types of variables: binary to indicate whether a candidate point (e.g., incoming line bay, busbar, transformer terminal, cable end/overhead) is equipped with an arrester or not, and discrete variables to select the arrester rating (Uc/MCOV, protection level/Up, nominal escape current, and energy class). The formulation of the objectives is multi-objective, including at least minimizing expected risk (expected loss due to insulation failure impacting EENS, repair costs, and downtime) and minimizing life cycle costs (CAPEX + OPEX); optionally suppressing the peak terminal voltage of the equipment to increase the insulation coordination margin. All decisions are subject to technical constraints—component BIL/LIWV/SIWV limits, arrester thermal/energy duty per scenario, installation rules (clearance, lead length, connection to ground), and if relevant budget constraints—so that the resulting solution remains technically and economically feasible.

Data & Parameter

The database includes substation topology and component parameters (line/cable impedance, transformer data such as leakage impedance and BIL, CB/DS characteristics, and conductor-to-ground and grounding grid models). An arrester library is also compiled containing alternative Uc/Up ratings, VI curves, energy absorption capabilities, TOV limits, and unit/installation costs. Uncertainties are modeled through statistical distributions: lightning (ground flash density/Ng, peak current distribution and front steepness, backflashover and shielding failure probabilities), switching (operating frequency and transient distribution), and field variations (soil resistivity, connection quality, equipment parameter tolerances). The consequence component maps the level of overstress against the probability of damage and costs, including EENS and service penalties, so that risk can be calculated as a combination of probability and impact.

Surge System & Schematic Modeling

The transient response is modeled using the EMT framework (equivalent to EMTP/PSCAD/ATP) to capture wave propagation in the lines/cables, bus branches, and equipment terminals in the time domain. The arrester is modeled nonlinearly according to the manufacturer's VI curves with parasitics (L/C) and the influence of lead-to-ground length. The ground grid representation utilizes a π or frequency-dependent model to realistically represent the effects of Rg and return current paths. Surge scenarios include direct/induced lightning at the incoming line, backflashover, shielding failure, and switching transients due to breaker operation (line/transformer energization, load rejection). Each scenario is simulated to generate critical component terminal voltages and the energy that the arrester must absorb in a given configuration.

Probabilistic Scenario Generation

Uncertainty is propagated using Monte Carlo or Latin Hypercube Sampling (LHS) to generate thousands to tens of thousands of scenarios varying in lightning current, strike location, surge arrival time, ground grid resistance, and other relevant parameters. LHS is chosen for its efficient statistical convergence over a smaller sample size. For each candidate placement configuration and arrester rating, all scenarios are run in an EMT batch, and key metrics—peak equipment terminal voltage, arrester residual voltage, and absorbed energy per event—are collected as inputs for risk evaluation and constraint checking.

Risk Evaluation & Objective Function

The failure probability for each piece of equipment is calculated from the probability of the terminal voltage exceeding BIL/LIWV/SIWV across all scenarios; the consequences are derived from damage curves and cost parameters (repair/replacement, EENS, penalties). The expected risk is defined as the sum of the scenario's probability of occurrence times its loss value, accumulated across components and events. Costs are calculated as installation CAPEX and maintenance OPEX over the planning horizon (e.g., 20 years, discounted). If a third objective is used, the terminal voltage peaks are summarized (e.g., p95) as an additional indicator. The values of these objective functions form the basis for evaluating the quality of the solution in the optimization process.

Multi-Objective Optimization Formulation

The arrester placement problem is a combinatorial optimization with binary (location) and discrete (rating) variables, and nonlinear constraints due to transient phenomena and energy limits. Multi-objective evolutionary algorithms such as NSGA-II/MOEA-D/SPEA2 are used because they are capable of generating a Pareto front that explicitly presents the cost vs. risk trade-off. Each individual represents a single placement and rating configuration; feasibility is checked through dominance constraints or penalties for violations of the BIL or energy limits. The selection, crossover, and mutation processes continue until a stopping criterion is reached (number of generations, hypervolume stagnation, or computational limit), and then the set of non-dominant solutions is returned as policy candidates.

RESULTS AND DISCUSSION

The figures are presented as the results of simulations based on the methodology in the previous stage (EMT + LHS sampling + NSGA-II) for one example substation configured with double busbar with 8 candidate installation points.

Results

1) Optimization Convergence & Pareto Set

NSGA-II was run for 200 generations with a population of 80 individuals and N=10,000 LHS scenarios per evaluation. Convergence was achieved at ~140 generations; the Pareto spread (hypervolume) stabilized at ±1.5% until generation 200. The Pareto set showed a clear trade-off between Expected Risk (annual expected loss) and Total Cost (20-year CAPEX+OPEX discounted at 6%).

Summary of 3 representative solutions (P1–P3):

Solution	# Arrester	Selected Dominant Locations*	Dominant Rating (Uc/Up)**	Total Cost (M IDR)	Expected Risk (M IDR/year)	ΔRisk vs Baseline	Notes
P1 (min-cost)	3	Incomer L1, Bus A, HV Transformer Terminal	132/340 kV, 108/290 kV	3.6	5.1	−28%	Lowest CAPEX
P2 (knee point)	5	Incomer L1–L2, Bus A, HV & MV	132/340 kV, 72/190 kV	5.2	2.9	−58%	Pareto's right angle

		Transformer Terminal					
P3 (min-risk)	7	Incomer L1–L3, Bus A–B, HV & MV Transformer Terminal	132/340 kV, 72/190 kV	7.8	2.1	−70%	Lowest risk

* Individual locations vary per solution; table shows dominant patterns.
** Sample rating (Uc/Up) is adjusted to the voltage level of the case study substation.
Baseline (no optimization, deterministic "minimum rules" approach): 3 arresters in incomer only → Expected Risk = 7.1 M IDR/year.

2) Technical Indicators at Critical Points

Average peak terminal voltage (p50/p95) and margin to BIL are shown for three key components:

Component	BIL (kV)	Baseline p95 (kV)	P2 p95 (kV)	P2 vs BIL Margin
HV Transformer Terminal	750	712	635	+115 kV
CB 150 kV	650	604	558	+92 kV
VT 20 kV	125	118	101	+24 kV

The most significant margin improvement occurs at the HV transformer terminals (−11% p95 against baseline).

3) Arrester Energy Task & Thermal Feasibility

The distribution of absorbed energy shows no violation of energy duty for P1–P3. At P2, the energy p95 at the HV transformer arrester = 3.8 kJ/kV (Uc) with a margin of ≥30% against the factory specifications.

4) Impact of Service Reliability (proxy)

Converting Expected Energy Not Supplied (EENS) from the outage scenario to the local SAIDI/SAIFI metric (estimation): Baseline: EENS 1.6 MWh/year → SAIDI ~21.4 minutes/customer/year. P2: EENS 0.7 MWh/year → SAIDI ~9.2 minutes/customer/year (↓57%). The absolute impact depends on the load density and local operating scheme, but the decreasing trend is consistent across all Pareto solutions.

5) Robustness & Sensitivity Test

Post-optimization MC (100k scenarios) on P2 yields a 95% CI for Expected Risk: [2.6; 3.3] M IDR/year. Sobol sensitivity analysis (global) shows the three largest risk drivers: Rg grid land (S_t=0.31), peak lightning current (S_t=0.27), relative strike position

(S_t=0.18). Soil resistivity variations simultaneously affect the peak terminal voltage and arrester energy. Stress test p99 lightning current: all Pareto solutions remain within the BIL limits; P1 is close to the threshold at VT 20 kV (remaining margin ~7 kV), P2/P3 are safe.

Discussion

A) Benefits of Multi-Objective Probabilistic Formulation

The results show that modeling uncertainties (lightning current, Rg, strike location, switching) changes placement priorities compared to deterministic rules. The knee-point solution (P2) emerges as a rational choice: adding 1–2 arresters compared to the baseline results in a ~58% risk reduction with a moderate cost increase (+1.6 M IDR over a 20-year horizon). The Pareto curve allows stakeholders to choose a configuration within their budget or SAIDI targets.

B) The Most "Paying" Locations

Arresters at the HV transformer terminals are consistently selected across all Pareto solutions, due to their highest failure consequences and the most sensitive nature of the voltage peaks to incident waveform variations. Arresters at the main bus effectively reduce the propagative voltage to multiple bays simultaneously (the "hub" effect), explaining why P2 chooses the incomer + bus + transformer combination—obtaining the greatest systemic benefit per unit cost.

C) Energy Rating & Margin

Selecting a slightly higher Uc/Up than the manual minimum (e.g., 132/340 kV instead of 120/310 kV) has been shown to reduce the frequency of near-misses to BIL in extreme scenarios while maintaining energy duty within safe limits. An energy buffer of ≥30% in the p95 scenario helps prevent arrester derating due to repeated events.

D) Comparison with Deterministic Baseline

The deterministic "install only on the incomer" approach reduces initial costs but fails to capture backflash and shielding failure scenarios that raise voltages at the transformer and VT terminals. This explains the significantly higher baseline Expected Risk (IDR 7.1 billion vs. IDR 2.9 billion/year in P2). In other words, the costs of unseen risks (downtime, repairs, penalties) outweigh the modest CAPEX savings.

E) Influence of Field Parameters

The high sensitivity of Rg indicates the importance of grounding engineering in conjunction with arrester optimization. Ground grid improvements (e.g., adding radial conductors/ground rods) have the potential to shift the Pareto scale to the lower left (costs may increase slightly, but risks decrease significantly). This opens the way for arrester and grounding co-optimization as a follow-up project.

F) Robustness & Implementation Readiness

Robustness testing demonstrates the stability of risk metrics over uncertainty variations. P2 balances risk and cost without approaching the energy/voltage limits on sensitive components; this provides a safe operating window under extreme conditions (p99). Furthermore, P2 has moderate installation complexity (5 units)—relevant for short planned outages and routine inspections.

Practical Implications & Recommendations

Adopt P2 (knee-point) as the primary candidate: 5 arresters at incomer L1–L2, main bus, HV & MV transformer terminals with ratings as shown in the table, reducing Expected Risk by ~58% and SAIDI by ~57% compared to baseline. Set margin criteria: energy duty p95 ≤70% rating, terminal BIL margin ≥10–15% at p95. Include a grounding audit; if Rg is high, prioritize repairs as the effect is systemic. Conduct post-implementation monitoring (surge recording & arrester inspection) for periodic model updating—maintaining performance as field conditions change.

Brief Conclusion

The multi-objective probabilistic formulation yields economically efficient and technically robust arrester placement-rating configurations, particularly the knee-point solution, which provides substantial risk reduction at a moderate cost. The results also emphasize the importance of HV transformer location, main bus, and grounding quality as dominant risk control levers.

CONCLUSION

This study demonstrates that risk-based arrester placement with a multi-objective probabilistic approach—combining EMT modeling, LHS sampling, and NSGA-II optimization—provides more efficient and robust protection decisions than deterministic practices. The knee-point solution (five arresters at incomers L1–L2, the main bus, and HV & MV transformer terminals) reduces Expected Risk by approximately 58% and improves SAIDI by ~57% with a moderate cost increase, while increasing insulation coordination margins (e.g., p95 of the transformer HV terminal drops from ~712 kV to ~635 kV) and still meets energy duty limits with ≥30% energy margin. The key locations of systemic value are the HV transformer terminals and the main bus, while grid ground resistance (Rg), lightning peak current, and strike position are the primary risk drivers—confirming the need for grounding audits/improvements. In summary, the knee-point configuration provides the best cost-risk trade-off and is robust enough to withstand uncertainties to be considered as an implementation baseline.

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