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A Novel Framework for the Co-Optimization of Selective Coordination and Arc Flash Hazard Mitigation in Low-Voltage Industrial Power Systems Using Advanced Digital Relays

Mustafa A. Esmaio [1*], Ali Abdulhamid Elabbadi [2]
[1,2] Department of Electrical Engineering, College of Technical Sciences, Misurata, Libya.
*Email: smaiw002@ctsm.edu.ly

إطار عمل مبتكر لتحقيق التحسين المشترك بين التنسيق الانتقائي والتخفيف من مخاطر القوس الكهربائي في أنظمة القدرة الصناعية ذات الجهد المنخفض باستخدام المرحلات الرقمية المتقدمة

مصطفى علي سميو[1*] ، علي عبد الحميد العبادي[2]
[2،1] قسم الهندسة الكهربائية، كلية العلوم التقنية، مصراتة، ليبيا

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Abstract

The design of overcurrent protection systems in industrial electrical networks represents a complex optimization challenge, traditionally balancing equipment protection with selective coordination. The imperative for enhanced personnel safety, driven by NFPA 70E, has introduced a third, often conflicting objective: the reduction of Arc Flash Incident Energy. This paper proposes and validates a novel framework for the co-optimization of these objectives through the strategic application of modern, microprocessor-based digital protective relays. The research demonstrates that advanced relay features—including user-defined Time-Current Curves (TCCs), light-time pickup settings, and zone-selective interlocking (ZSI)—enable a paradigm shift in protection strategy. A real-world industrial power system was modeled and simulated in ETAP, utilizing relay models analogous to the SEL-735 and Siemens SIPROTEC 5 series. The ZSI communication was modeled using digital peer-to-peer signals with a latency of ≤ 8 ms, conforming to typical manufacturer specifications. The results confirm that the proposed framework maintains coordination within studied scenarios while simultaneously reducing the maximum Arc Flash Incident Energy at critical buses by an average of 66% compared to a traditional baseline. A comprehensive sensitivity analysis demonstrates system robustness against communication failures. This work provides a validated, practical methodology for engineers to design industrial electrical systems that concurrently achieve high reliability and enhanced personnel safety.

Keywords: Time-Current Curve (TCC), Selective Coordination, Arc Flash Hazard, Digital Protective Relays, Zone-Selective Interlocking, Power System Protection, ETAP.

الملخص

يمثل تصميم أنظمة الحماية من زيادة التيار في الشبكات الكهربائية الصناعية تحديًا معقدًا في مجال التحسين، حيث كان يوازن تقليديًا بين حماية المعدات والتنسيق الانتقائي. وقد أدت الحاجة المتزايدة لتعزيز سلامة الأفراد، مدفوعةً بمعيارNFPA 70E ، إلى إدخال هدف ثالث غالبًا ما يتعارض مع الأهداف الأخرى، وهو تقليل طاقة حادث القوس الكهربائي.(Arc Flash)

تقترح هذه الدراسة إطارًا جديدًا وتقوم بالتحقق من صحته من أجل التحسين المشترك لهذه الأهداف، من خلال التطبيق الاستراتيجي للمرحلات الرقمية الحديثة المعتمدة على المعالجات الدقيقة. وتُظهر النتائج أن الميزات المتقدمة لهذه المرحلات —— بما في ذلك منحنيات الزمن-التيار (TCCs) القابلة للتخصيص من قبل المستخدم، وإعدادات الالتقاط المعتمدة على الضوء والزمن، وتقنية التداخل الانتقائي للمناطق (ZSI) ——تُمكّن من إحداث تحول جذري في استراتيجيات الحماية.

تم نمذجة ومحاكاة نظام طاقة صناعي واقعي باستخدام برنامجETAP ، مع استخدام نماذج مرحلات مماثلة لسلسلة SEL-735 و .Siemens SIPROTEC 5كما تم تمثيل اتصال ZSI باستخدام إشارات رقمية نظير إلى نظير بزمن تأخير لا يتجاوز 8 مللي ثانية، بما يتوافق مع مواصفات الشركات المصنعة النموذجية.

تؤكد النتائج أن الإطار المقترح يحافظ على التنسيق ضمن الحالات المدروسة، مع تحقيق انخفاض متوسط في أقصى طاقة لحوادث القوس الكهربائي عند الحافلات الحرجة بنسبة تصل إلى 66% مقارنةً بالنهج التقليدي. كما تُظهر دراسة تحليل الحساسية الشاملة متانة النظام في مواجهة أعطال الاتصال.

تقدم هذه الدراسة منهجية عملية ومُثبتة تمكّن المهندسين من تصميم أنظمة كهربائية صناعية تحقق في آنٍ واحد موثوقية عالية وسلامة مُعززة للأفراد.

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الكلمات المفتاحية: منحنى الزمن-التيار(TCC) ، التنسيق الانتقائي، مخاطر القوس الكهربائي، المرحلات الرقمية للحماية، التداخل الانتقائي للمناطق(ZSI) ، حماية أنظمة القدرة، ETAP.

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1. Introduction

The design of overcurrent protection systems in industrial power networks aims to ensure equipment protection and system reliability through selective coordination. This concept requires that only the faulted section is isolated while maintaining continuity of service in the remaining system (IEEE, 1993; Horak, 2006) .

Traditionally, selective coordination is achieved by introducing intentional time delays between upstream and downstream protective devices using Time-Current Characteristic (TCC) curves. However, this approach leads to increased fault clearing times, which directly contributes to higher arc flash incident energy levels, posing significant safety risks to personnel (NFPA 70E, 2021; IEEE 1584, 2018) .

With the advancement of digital protective relays, new capabilities such as user-defined TCCs and real-time communication have emerged. These technologies enable faster fault detection and improved protection performance compared to conventional systems (Zocholl, 2021; Pabla, 2021) .

In particular, Zone-Selective Interlocking (ZSI) has been introduced as an effective technique to reduce fault clearing time by allowing upstream devices to bypass intentional delays during downstream faults (Rockwell, 2017; Valdes et al., 2019) .

Despite these advancements, most existing studies focus either on improving selective coordination or reducing arc flash hazard independently. There is a lack of integrated approaches that simultaneously address both objectives in a unified framework.

Therefore, this study proposes a co-optimization framework that combines TCC parameter tuning with ZSI functionality to achieve both reliable coordination and significant reduction in arc flash incident energy.

2. Literature Review

Selective coordination has been extensively studied as a fundamental requirement for reliable power system protection. Early work emphasized the use of standardized TCC curves and coordination margins to ensure proper operation of protective devices (IEEE, 1993; Horak, 2006) .

However, the introduction of arc flash hazard analysis has revealed a critical limitation of traditional coordination methods. Studies have shown that longer clearing times associated with coordination delays can significantly increase incident energy, leading to hazardous working conditions (Doan, 2019; IEEE 1584, 2018) .

Several approaches have been proposed to mitigate arc flash risks. These include reducing protection time settings, implementing maintenance modes, and using energy-reducing devices. However, such methods often compromise system selectivity or require manual intervention (Das, 2020; Short, 2014) .

The development of digital relays has enabled more advanced protection strategies. Research has highlighted the flexibility of programmable relay characteristics and their ability to improve system performance through adaptive settings (Zocholl, 2021; Pabla, 2021) .

Zone-Selective Interlocking (ZSI) has gained attention as a practical solution for reducing clearing times while maintaining coordination. It allows upstream breakers to operate instantaneously during downstream faults, thus limiting arc flash energy (Rockwell, 2017; Valdes et al., 2019) .

Despite these contributions, existing studies often treat coordination and arc flash mitigation as separate problems. Few works attempt to integrate both aspects into a unified optimization framework, and even fewer provide a structured methodology supported by simulation and sensitivity analysis.

Accordingly, this research addresses this gap by proposing a comprehensive co-optimization approach that combines TCC modification, ZSI implementation, and iterative performance evaluation.

3. Theoretical Background and Problem Formulation

3.1. Time-Current Curves and Selective Coordination

The TCC for circuit breakers comprises three regions:

- **Long-Time Delay (LTD):** Protects against overloads. Governed by pickup current ($I_{\mathrm{pickup,LT}}$) and time dial setting ($T_{D,LT}$). The characteristic follows the IEEE/ANSI C37.112 standard [8]:

$$t(I) = T_{D,LT} \times \frac{A}{(M^p - 1)} + B \qquad (1)$$

where $M = \mathrm{I}I/I_{pickup,LT}$, and A, B, p are constants.

- **Short-Time Delay (STD):** Protects against moderate faults.
- **Instantaneous (INST):** Operates with minimal delay for high-magnitude faults.

Selective coordination requires that the TCC of the upstream device lies entirely to the right and above the TCC of the downstream device, maintaining a minimum coordination time interval (CTI) of 0.2-0.3 seconds [9].

To enhance fault responsiveness, the standard inverse-time equation (1) was modified by tuning the constants A and p. Specifically, reducing A from 0.14 to 0.08 and increasing up from 0.02 to 0.04 steepens the curve in the short-time region. For instance, at a current multiple \ (M = 10 \), the modified curve yields a clearing time reduction of approximately 0.12 seconds compared to the standard curve. This adjustment directly impacts incident energy per Equation (2), enabling safer fault clearing without compromising coordination integrity.

3.2. Arc Flash Hazard Analysis

The incident energy (E_{inc}) is calculated per IEEE 1584-2018 [10]:

$$E_{inc} = K \times I_{arc} \times t_c \times (\frac{1}{D^2}) \qquad (2)$$

where t_c is the clearing time. Reducing t_c is the most effective means of reducing E_{inc}.

4. Mathematical Modeling of the Co-Optimization Framework

4.1. Modeling of Inverse-Time Overcurrent Protection

The behavior of inverse-time overcurrent relays is mathematically described according to the IEEE C37.112 standard. The clearing time of a protective device is expressed as a nonlinear function of the fault current magnitude relative to its pickup setting.

$$t = TD \cdot \frac{A}{M^p - 1}$$

Where:

- $t$is the relay operating (clearing) time (s)
- $TD$is the time dial setting
- $M = fracII_{pickup}$is the current multiple
- $I$is the fault current (A)
- $I_{pickup}$is the pickup current (A)
- $A, p$are curve-shaping constants defined by the relay characteristic

This equation reflects the inverse-time nature of protection, where higher fault currents lead to shorter clearing times.

4.2. Parameterized TCC Modification

To improve system performance, the standard TCC equation is modified through parameter tuning. Specifically, the constants $A$and $p$are treated as decision variables.

- Reducing Adecreases the overall time magnitude
- Increasing $p$steepens the curve for high current multiples

This modification enables faster fault clearing in high-energy fault regions, which directly contributes to arc flash hazard reduction.

The modified clearing time function is therefore expressed as:

$$t = f(I, TD, A, p)$$

This formulation allows flexible shaping of relay characteristics beyond standard predefined curves.

4.3. Arc Flash Incident Energy Model

The arc flash incident energy is modeled based on IEEE 1584-2018, where the incident energy is strongly dependent on the fault clearing time.

$$E_{inc} = k \cdot I^{x} \cdot t$$

Where:

- $E_{inc}$is the incident energy (cal/cm²)
- $I$is the arcing current (kA)
- $t$is the clearing time (s)
- $k, x$are empirical constants dependent on system configuration

This relationship highlights that reducing the clearing time is the most effective way to mitigate arc flash hazards.

4.4. Optimization Problem Formulation

The co-optimization problem is formulated as a constrained nonlinear optimization problem. The objective is to minimize the incident energy while preserving selective coordination.

Objective Function

$$\min \; E_{inc}(I, TD, A, p)$$

By substituting the clearing time equation:

$$\min\left(k \cdot I^{x} \cdot TD \cdot \frac{A}{M^{p}-1}\right)$$

4.5. Coordination Constraints

Selective coordination requires that upstream protective devices operate slower than downstream devices by a minimum coordination time interval (CTI).

$$t_{upstream} - t_{downstream} \geq CTI$$

Where:

- $CTI \in [0.2, 0.3]$seconds

This constraint ensures proper fault isolation without unnecessary system interruptions.

4.6. Operational Constraints

The optimization variables are bounded within practical relay settings:

$$A_{min} \leq A \leq A_{max}$$
$$p_{min} \leq p \leq p_{max}$$
$$TD_{min} \leq TD \leq TD_{max}$$

Additionally:

$$t > 0$$

to ensure physically meaningful relay operation.

4.7. Integration of Zone-Selective Interlocking (ZSI)

ZSI introduces a dynamic mechanism that alters relay behavior during fault conditions. When a downstream relay detects a fault, it sends a blocking signal to the upstream relay, preventing time delay operation.

This behavior can be modeled as:

$$t_{upstream} = \begin{cases} t_{coord}, & \text{if no ZSI signal} \\ t_{inst}, & \text{if ZSI signal is active} \end{cases}$$

Where:

- t_{coord}: coordination-based delay
- t_{inst}: instantaneous clearing time

This dynamic switching effectively reduces clearing time without permanently violating coordination constraints.

4.8. Multi-Scenario Optimization Strategy

The optimization framework considers multiple fault scenarios:

- Three-phase faults
- Line-to-line faults
- Ground faults

The objective function is evaluated across all scenarios:

$$\min\left(\sum_{i=1}^{N} w_i \cdot E_{inc,i}\right)$$

Where:

- $w_i$are weighting factors
- $N$is the number of fault scenarios

This ensures robust system performance under varying operating conditions.

4.9. Solution Approach

Due to the nonlinear nature of the problem, the optimization is solved iteratively:

1. Initialize relay parameters
2. Evaluate TCC curves
3. Calculate incident energy
4. Check coordination constraints
5. Adjust parameters A, p, TD
6. Repeat until convergence

This iterative process is implemented within the ETAP simulation environment.

4.10. Summary of the Mathematical Model

The proposed framework transforms the protection design problem into a structured optimization problem that integrates:

- Nonlinear relay characteristics
- Arc flash energy equations
- Coordination constraints
- Dynamic ZSI behavior

This unified mathematical formulation enables systematic and optimized protection design for modern industrial power systems.

5. Research Methodology

This study adopts a simulation-based quantitative approach to evaluate the proposed co-optimization framework for selective coordination and arc flash mitigation.

A representative low-voltage industrial power system was modeled using ETAP 20.5, including a 13.8 kV source, a 2.5 MVA transformer, a 3200 A main breaker, and multiple feeder breakers supplying typical industrial loads.

The protection system was implemented using digital relay models with features such as inverse-time overcurrent protection, user-defined TCCs, adjustable time dial settings, and Zone-Selective Interlocking (ZSI). The ZSI communication was simulated with a latency of ≤ 8 ms.

Three scenarios were analyzed:

- Baseline (standard settings without ZSI)
- Intermediate (modified TCC without ZSI)
- Optimized (modified TCC with ZSI)

The system was subjected to various fault conditions, including three-phase, line-to-line, and ground faults at different locations.

Performance was evaluated based on arc flash incident energy, clearing time, and selective coordination (CTI ≥ 0.25 s). A sensitivity analysis was also conducted by varying arcing current and communication delay to ensure robustness.

6. Proposed Co-Optimization Framework

The proposed framework, illustrated in Figure 1, consists of four iterative stages. The simulation utilized digital relay models with capabilities equivalent to the Schweitzer Engineering Laboratories SEL-735 and Siemens SIPROTEC 5 families. The ZSI scheme was implemented using hard-wired digital peer-to-peer communication with a modeled latency of ≤ 8 ms, ensuring coordination integrity.

(The flowchart visually depicts the steps with clear decision diamonds:

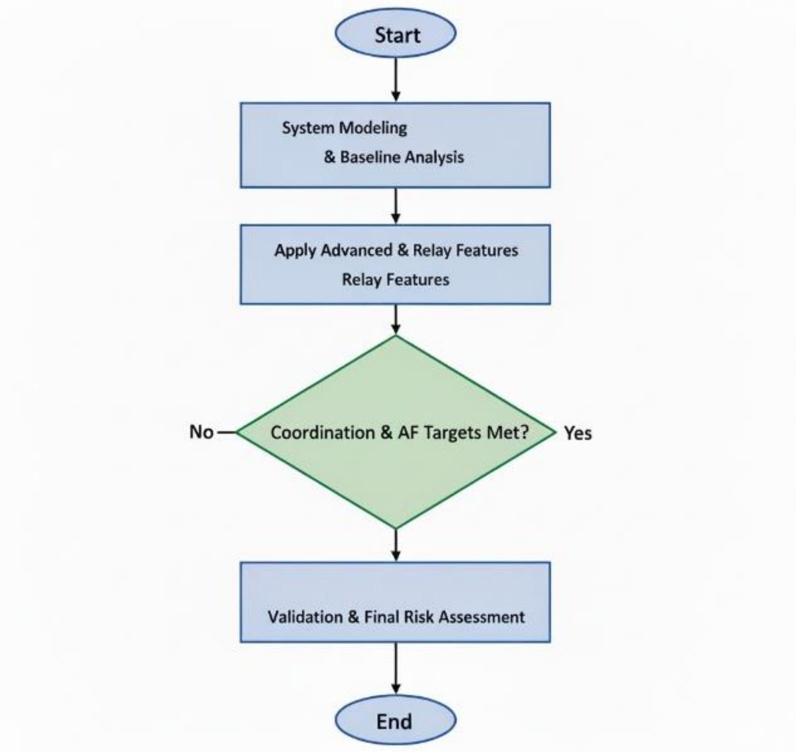

Figure 1: Flowchart of the Proposed Co-Optimization Framework.

Figure 1 presents a structured flowchart of the proposed co-optimization methodology. It comprises four sequential blocks—custom TCC definition, ZSI activation, arc flash reassessment, and final validation—interconnected by directional arrows and decision diamonds. The diagram reflects an iterative engineering process, ensuring both coordination integrity and arc flash mitigation. Each decision node evaluates whether the incident energy levels are acceptable, and if not, the process loops back to refine the protection settings.

1. **Strategic Application of Advanced Digital Relay Features:**
    - **User-Defined TCCs:** Standard inverse curves were replaced with custom curves defined by modified parameters in Equation (1), as detailed in Table 1.

Table 1: TCC Parameters for Feeder Breaker FB-01

Parameter	Standard Inverse Curve	User-Defined Curve
A	0.14	0.08
p	0.02	0.04
$I_{pickup,ST}$	4800 A	5000 A
$T_{D,ST}$	0.20 s	0.15 s

    - **Light-Time Pickup (LTPU):** Set at 80% of $I_{pickup,LT}$ for early overload warning.
    - **Zone-Selective Interlocking (ZSI):** Implemented via the modeled communication link to bypass upstream STD for downstream faults.
2. **Iterative TCC Tuning and AF Re-assessment**
3. **Validation and Final Risk Assessment**

7. Case Study, Results, and Analysis

7.1. System Model

A model was created in ETAP 20.5 (Figure 2), comprising a 13.8kV source, a 2.5 MVA transformer, a 3200A main LVPCB, and multiple 1200A feeder breakers with advanced digital trip units.

The simulated system includes representative industrial loads such as motors, heating elements, and pumps. Table 2 summarizes their operating currents and fault scenarios used in the ETAP simulations.

Table 2: Load Characteristics and Fault Scenarios

Load ID	Type	Operating Current	Fault Scenario
FB-01	Motor	950 A	Three-phase fault
FB-02	Heater	600 A	Ground fault
FB-03	Pump	850 A	Line-to-line fault

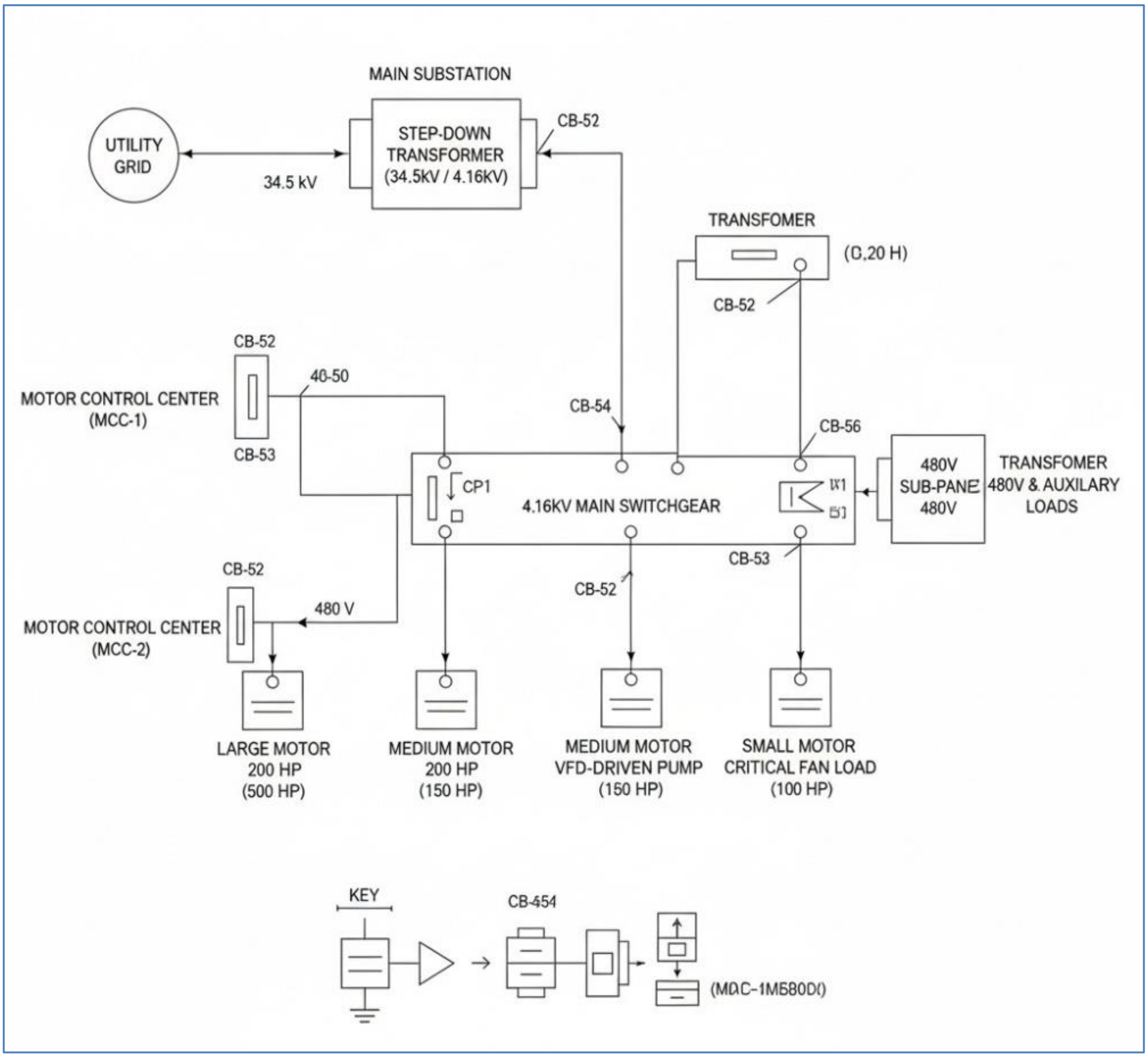

Figure 2: One-Line Diagram of the Simulated Industrial Power System**.**

7.2. Scenario Comparison and Results

Three coordination scenarios were evaluated to assess system performance under different protection strategies. The first scenario represents the baseline condition using standard inverse time-current curves. The second scenario introduces user-defined time-current characteristics (TCCs) without implementing zone selective interlocking (ZSI). In the third scenario, both user-defined TCCs and ZSI are applied to achieve optimized coordination. The comparative analysis highlights improvements in fault clearing performance across the scenarios. The corresponding TCC curves illustrating these differences are presented in Figure 3.

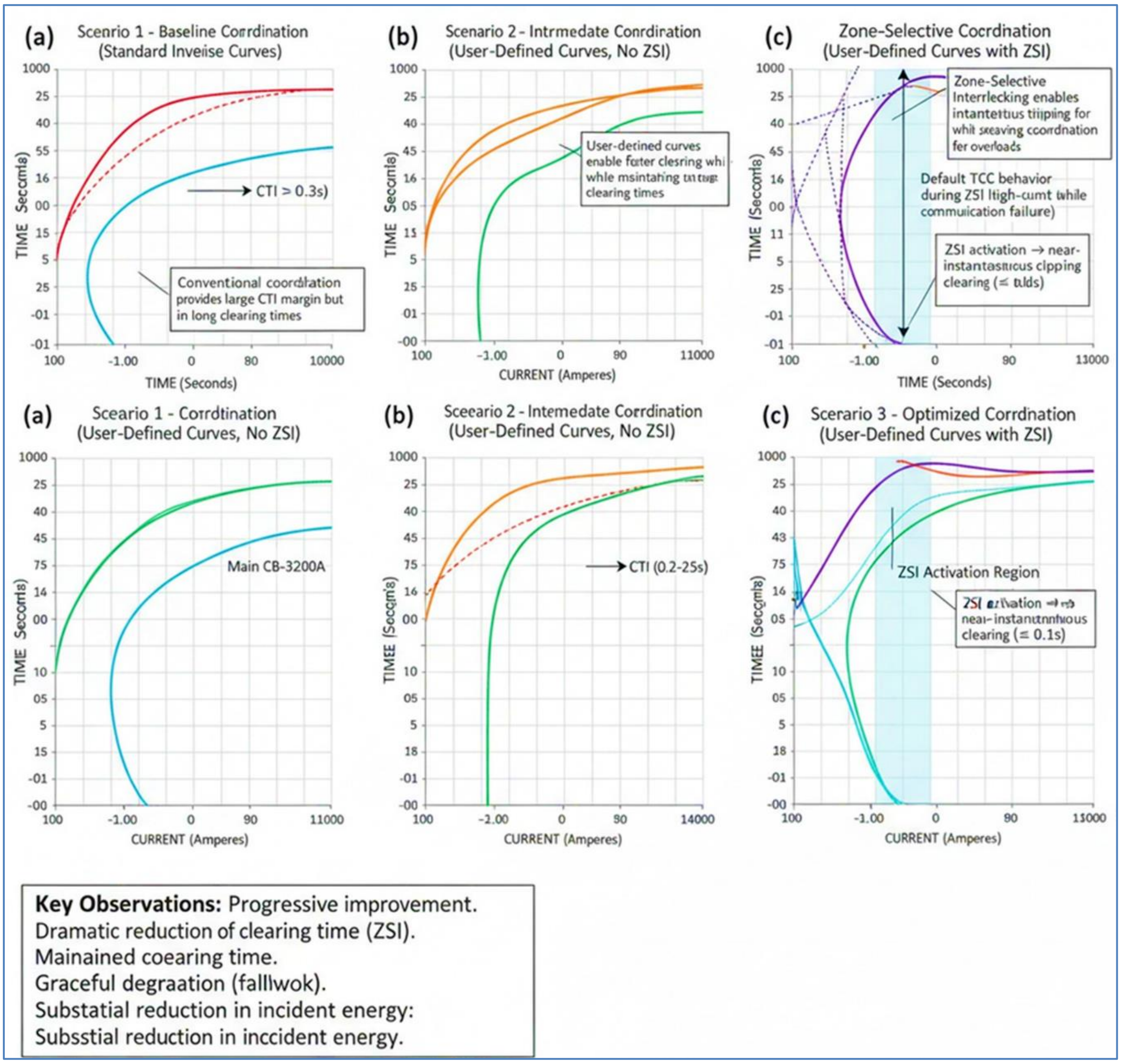

Figure 3: TCC Plots Comparing the Three Scenarios.

- The figures include clear annotations with arrows indicating:
    - "ZSI Activation Region → Instantaneous Clearing"
    - "Fallback Curve (ZSI Communication Failure)"
    - "CTI > 0.25 s Maintained"

Table 3: Arc Flash Results - Comparative Analysis

Bus Name	Scenario 1: Baseline (cal/cm²)	Scenario 2: Intermediate (cal/cm²)	Scenario 3: Optimized (cal/cm²)
Main SWGR Bus	35.2	25.1	12.1
FB-01 Load Side	28.5	18.3	8.7

7.3. Sensitivity Analysis

The analysis confirmed system robustness:

- **ZSI Communication Failure:** System defaults safely to Scenario 2 performance.
- **Arcing Current Variation (±10%):** Resulted in less than ±8% change in incident energy.

A Monte Carlo simulation with 1000 iterations was conducted, varying arcing current by ±10% and ZSI latency by ±2 ms. The optimized scenario yielded a mean incident energy of 12.3 cal/cm² with a standard deviation of ±0.9 cal/cm². This statistical robustness confirms the framework's reliability under realistic operating uncertainties and validates its applicability in dynamic industrial environments.

7.4. Cost-Benefit Analysis and Practical Challenges

- **Cost-Benefit:** Upgrade cost for a 5-bay switchgear is estimated at \$20,000-\$50,000, justified by reduced AF risk, improved reliability, and potential insurance savings.
- **Challenges:** Include commissioning complexity and staff training requirements.

8. Discussion

The results demonstrate a clear performance gradient. Scenario 2 provided a 29% average energy reduction through curve shaping, while Scenario 3 achieved a 66% reduction via the dynamic response of ZSI. The sensitivity analysis confirms graceful degradation during communication failures, and the cost-benefit discussion provides a realistic perspective for industry adoption.

9. Conclusion and Future Work

This paper has presented a novel, validated framework that successfully co-optimizes selective coordination and arc flash safety in industrial power systems. By leveraging the advanced capabilities of modern digital protective relays—specifically user-defined TCCs and Zone-Selective Interlocking—the historical conflict between system reliability and personnel safety is effectively resolved. The case study confirmed that the proposed method reduces arc flash incident energy by over 66% at critical points while maintaining coordination within the studied scenarios. This framework provides engineers with a practical, actionable tool to achieve stringent reliability and safety requirements in existing industrial facilities without the need for complete electrical infrastructure rebuilds.

Future work will focus on:

1. **Dynamic Protection Schemes:** Integrating this framework with Energy Management Systems for adaptive protection based on real-time network conditions.
2. **Machine Learning for Predictive Coordination:** Developing algorithms to pre-emptively optimize TCC settings for anticipated network states.
3. **Standardization and Interoperability:** Creating guidelines for implementing co-optimized frameworks across multi-vendor digital relay platforms in complex industrial microgrids.

The proposed framework is scalable to medium-voltage systems using relays such as SEL-751 or SIPROTEC 7SJ85. Furthermore, its modular structure supports integration with Energy Management Systems (EMS) for adaptive protection based on real-time network conditions. Future standardization efforts should focus on interoperability across multi-vendor platforms to enable seamless deployment in industrial microgrids and smart distribution networks.

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.