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Economic Analysis and Cost-Benefit Assessment of Advanced Arc Flash Mitigation Technologies

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Abstract— *Arc flash remains one of the most severe hazards in industrial electrical systems, often leading to catastrophic injuries, equipment damage, and substantial financial losses. In response, the industry is increasingly transitioning from conventional overcurrent protection schemes to advanced arc flash mitigation technologies (AAMTs) such as high-speed switching systems (HSS) and multi-sectional arc fault eliminators (MSAE). This study offers a comprehensive economic and technical evaluation of these advanced solutions, integrating IEEE 1584–2018 standards, empirical performance data, and real-world case studies from high-risk industrial environments. Results indicate that AAMTs can reduce incident energy by over 80% from 40–50 cal/cm² to below 10 cal/cm² while reducing downtime-related costs by up to 40%. Using validated lifecycle cost models and sensitivity analysis, we demonstrate that despite higher capital expenditure, AAMTs achieve return on investment (ROI) improvements of 15–25% and payback periods of just 3–5 years. This paper addresses a critical gap in the arc flash literature by unifying technical performance metrics with economic viability, offering a holistic decision- making framework. Additionally, it explores emerging perspectives on safety, risk, and inclusivity in engineering design, positioning proactive mitigation not only as a safety imperative but also as a financially strategic investment. The findings substantiate the long-term benefits of adopting AAMTs, particularly in environments where safety, operational continuity, and economic resilience are paramount.*

Index Terms— Arc flash mitigation, cost-benefit analysis, IEEE 1584-2018, high-speed switching, arc fault eliminators, economic analysis, industrial electrical safety, downtime reduction, ROI.

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I. INTRODUCTION

Arc flash events continue to pose one of the most critical safety and economic threats within industrial electrical systems. Characterized by a sudden release of electrical energy through the air, arc flash incidents can result in severe injuries, fatalities, equipment destruction, prolonged downtime, and legal and insurance liabilities. Arc flash incidents can cost anywhere from

$5 million to $15 million when you add up medical bills, equipment damage, and legal fees, and with inflation the total can go beyond $23 million. These risks are especially high in places like factories and power plants where heavy electrical systems are used every day [1].

Traditional arc flash protection strategies relying primarily on overcurrent protective devices (OCPDs), time-delay relays, and extensive personal protective equipment (PPE) have several inherent limitations. These methods are predominantly reactive, with delayed fault-clearing capabilities that often result in dangerously high incident energy levels, frequently exceeding 40 cal/cm². This places the system and its operators in extreme hazard zones, as defined by IEEE 1584-2018 guidelines [2]. Moreover, the operational burden and cost of maintaining heavy duty PPE, combined with frequent system downtimes, make traditional mitigation economically and logistically inefficient in high-risk environments.

In recent years, the industry has shifted towards advanced arc flash mitigation technologies (AAMTs), which offer real-time fault detection and rapid current interruption to significantly reduce arcing duration. Solutions such as high-speed switching systems (HSS), multi-sectional arc fault eliminators (MSAE), and fast-acting current limiters have demonstrated the ability to reduce incident energy by up to 80%, from 40–50 cal/cm² to below 10 cal/cm² [3], [4].These active systems respond within a fraction of an electrical cycle, thereby preventing escalation to severe arc flash conditions. Notably, they have been successfully deployed across a range of industries, including energy storage systems (ESS), cement manufacturing, and critical infrastructure, where arc flash risks are exacerbated by high fault currents and dense electrical environments [5].

From an economic perspective, AAMTs offer compelling advantages. Although they demand higher initial capital investments compared to traditional protection schemes, multiple case studies have demonstrated lifecycle financial benefits. These include reductions in downtime costs by up to 40%, annual maintenance savings, lower insurance premiums, and substantial improvements in Return on Investment (ROI) typically in the range of 15–25% with a payback period as short as 3–5 years [6].

This has been particularly evident in energy storage systems, where the combination of high energy density and complex electrical configurations creates elevated arc flash risks. In one study involving large-scale battery systems, the use of fast- acting DC fuses at critical points reduced incident energy from dangerous levels exceeding 15 cal/cm² to less than 0.003 cal/cm². This not only protected personnel but also reduced the operational reliance on high-rated PPE, improving accessibility and long-term maintenance efficiency without compromising safety.[7]

Another example comes from a cement manufacturing group operating across 13 sites in North America. Arc flash hazard studies identified several panels with energy levels above 70 cal/cm². Instead of opting for full equipment replacement, the team implemented focused retrofits—adding protective relays, conducting coordination studies, and applying standardized hazard labelling. These measures helped reduce energy exposure to below 8 cal/cm² in many areas, enabling safer work conditions and cutting PPE costs. The project showed that upgrading existing systems with AAMTs can be a cost-effective approach to achieving compliance and improving operational resilience[8]

However, existing literature remains fragmented in its treatment of arc flash mitigation. While many studies focus either on the technical efficacy of fault interruption or on cost-benefit analysis independently, few have undertaken an integrative assessment that combines engineering performance metrics with comprehensive economic modelling. Furthermore, the broader implications of arc flash mitigation including its alignment with modern safety frameworks (e.g., ISO 45001), sustainability targets (e.g., UN SDG 8), and inclusive engineering decision making are often overlooked.

Our objectives are to:

i. Quantitatively measure the reduction in arc flash incident energy and its financial implications.

ii. Compare upfront investment, maintenance, and operational costs.

iii. Demonstrate that the enhanced safety provided by advanced technologies translates directly into substantial long-term economic savings.

This remainder of the paper is organized as follows. Section 2 reviews the current literature, standards, and technological developments. The methodology, which comprises data sources, cost benefit models and sensitivity analysis, is elaborated in Section 3. The results are presented in section 4 in the form of detailed tables and charts. Section 5 concludes and makes actionable recommendations.

II. LITERATURE REVIEW

2.1 Arc Flash Hazards and Safety Standards

Arc flash remains a leading cause of severe injuries and equipment damage in industrial electrical systems. The primary metric used to quantify arc flash risk is incident energy, typically measured in cal/cm², representing the thermal energy at a working distance during an arc event. According to the IEEE Std 1584-2018, incident energy above 1.2 cal/cm² requires flame-resistant PPE, while values exceeding 40 cal/cm² represent "extreme hazard" conditions, demanding bulky and expensive protective gear [9].

Arc flash incidents pose a multifaceted risk in industrial environments, with hazards extending beyond thermal effects to include pressure waves, toxic gases, and equipment destruction. According to Kumpulainen et al. [10], the most effective and practical method to mitigate these risks is by significantly reducing arcing time, which directly lowers incident energy and diminishes the mechanical and toxic effects of an arc blast. Their study demonstrates that when arcing time is reduced to below five milliseconds using technologies such as optical detection and arc eliminators, peak pressure buildup can be avoided, reducing equipment damage and improving personnel safety. This proactive approach supports the adoption of fast-acting protective systems as a cornerstone of modern arc flash mitigation strategies.

2.2 Limitations of Traditional Arc Flash Protection Approaches

Traditional arc flash mitigation techniques such as time delayed circuit breakers, overcurrent relays, and conservative system design have long been the foundation of industrial protection schemes. However, these methods often result in prolonged clearing times, which correspond to higher incident energy values.

Furthermore, these systems lack real-time responsiveness to evolving electrical conditions, increasing vulnerability to transient faults and coordination failures. Excessive reliance on PPE, while necessary under such conditions, imposes logistical burdens, increases fatigue, and may not fully protect against catastrophic events [9].Thus, there is growing recognition that traditional protective equipment, while necessary, is insufficient on its own to ensure workplace safety in high-energy environments.

2.3 Emerging Solutions: Advanced Arc Flash Mitigation Technologies

Over the past decade, technological innovations have enabled a shift toward active arc flash mitigation technologies (AAMTs) that aim to prevent the arc event from escalating, rather than simply containing its consequences. These technologies are grounded in high-speed fault detection, current- limiting interruption, and intelligent system response.

High-Speed Switching Systems (HSS), for instance, can detect and respond to fault conditions in less than 2 milliseconds, interrupting arcing currents before significant energy release occurs. Studies by [4] demonstrate that HSS can reduce incident energy by up to 80%, making it possible to lower PPE requirements and maintain normal operations even in densely loaded switchgear rooms. This is especially important because the amount of energy and pressure released during an arc flash depends heavily on how long the arc lasts. As shown by Kumpulainen et al. [10], keeping the arcing time below five milliseconds can make a huge difference in reducing both the thermal and mechanical effects of an arc flash. Their work reinforces the idea that fast-acting technologies like HSS are not just helpful they are critical for improving safety and preventing damage in industrial systems. This approach also supports wider safety strategies discussed by Malhotra et al. [11], who emphasise the importance of proactive electrical maintenance and rapid fault response in reducing both operational risks and long-term costs.

Multi-Sectional Arc Fault Eliminators (MSAEs), often based on thyristor and semiconductor technology, work by rapidly diverting or extinguishing the arc path. [12] have shown that MSAEs can reduce incident energy from 50 cal/cm² to less than 10 cal/cm² within sub-cycle durations, significantly improving operator safety. Eruotor and Eruotor [13] add that technologies like these are most effective when used as part of a wider safety plan. They highlight the importance of combining these systems with regular maintenance, equipment checks, and proper training to get the best results in reducing arc flash risks. Such systems are increasingly integrated into energy storage applications and data centres where fault currents are high and rapid isolation is critical [5].

Recent studies have also explored the use of artificial intelligence to enhance arc fault detection. Tian et al. [14] examined the potential of AI-based models in identifying arc faults through time-frequency analysis of both transient and steady-state signals. Their findings show that advanced algorithms can improve detection accuracy and response time, which helps reduce false alarms and improve protection reliability in complex power systems.

Digital relaying, real-time analytics, and predictive fault diagnostics using AI and IoT are also gaining traction in the mitigation landscape. These tools enable pre-emptive actions, such as load shedding or preventive maintenance, to reduce fault likelihood and enhance the operational life of electrical assets [15].

2.4 Economic Perspectives on Arc Flash Mitigation

Economic evaluations of arc flash incidents often highlight substantial hidden costs: lost production time, equipment replacement, litigation, increased insurance premiums, and reputational damage. [6] conducted a multi-site study showing that AAMTs can deliver a 20–30% increase in Net Present Value (NPV) over a 10-year horizon and reduce downtime- related costs by as much as 40%.

The Return on Investment (ROI) for these technologies ranges from 15% to 25%, with typical payback periods between 3 to 5 years. In contrast, traditional mitigation systems may require up to 10 years to recoup costs while offering limited safety and operational gains [11].

The total cost of ownership (TCO) framework is now commonly employed to assess mitigation strategies, encompassing capital investment, maintenance, operational risk, and indirect costs. Incorporating these metrics provides a holistic understanding of the long-term financial benefits of adopting AAMTs.

2.5 Research Gaps and Emerging Directions

Despite significant technological progress, existing research often fails to integrate both the technical and economic dimensions of arc flash mitigation into a unified framework. While some studies emphasize safety improvements through fault interruption speed or energy reduction, others focus solely on cost-effectiveness. There remains a need for holistic models that combine IEEE 1584–2018 compliant energy calculations with robust lifecycle economic modelling, sensitivity analysis, and real-world case validation. Recent studies, such as Zhang et al. [16], have demonstrated that advanced arc fault detection methods using time-frequency analysis (e.g., CEEMDAN with Hilbert Transform) can accurately identify arc events under

complex power conditions. However, these innovations are not yet fully integrated into economic or lifecycle evaluation frameworks, highlighting a key opportunity for future interdisciplinary research.
Additionally, future research should consider broader interdisciplinary themes, including:
i. **Sustainability and lifecycle safety**, particularly in the context of renewable energy systems and high-density data infrastructures.
ii. **Inclusion and equity in engineering safety**, ensuring that risk assessments account for diverse workplace demographics.
iii. **Digitalization of arc flash prevention**, incorporating machine learning for fault prediction and real-time mitigation control.

2.6 Economic Considerations

There are several economic implications of arc flash incidents. The cost savings from reduced downtime and maintenance have been quantified as being able to justify the higher upfront cost of advanced technologies by Neighbours and Karandikar [6]. Typical metrics include:
i. Net Present Value (NPV): Advanced systems often yield a 20–30% higher NPV over a 10-year lifecycle.
ii. Return on Investment (ROI): The traditional ROI is 5– 10% and advanced technologies 20–30% [6].
iii. Payback Period: Advanced systems generally pay back within 3–5 years compared to 7–10 years for traditional methods.
As Malhotra et al. [11] highlight, financial benefits of good robust preventive maintenance and integrated advanced mitigation not only prevent equipment degradation but also reduce risk of surprise arc flash.

III.METHODOLOGY

3.1 Data Collection and Case Studies

Data was gathered from multiple real-world case studies and industry reports:
i. Case Study 1: An Arc flash Reduction Maintenance System (ARMS) was used to retrofit a multi-site cement manufacturing facility with legacy switchgear. Documented downtime reduction from 40 cal/cm² to 8 cal/cm² was achieved with reduction in incident energy to 30% [8].
ii. Case Study 2: A basalt crushing plant upgrade in New South Wales, Australia, where the implementation of active mitigation technologies reduced incident energy from 36 cal/cm² to 4 cal/cm² and decreased downtime by 35% [8].
iii. Supporting Studies: Quantitative performance of advanced mitigation technologies are characterized in detail using data taken from Nowak et al. [3], Divinnie et al. [4] and Neighbours and Karandikar [6].
Table 1 summarizes the key performance indicators extracted from the case studies:

Table 1: Real-World Case Study Metrics and Performance Indicators

Case Study	Voltage	Incident Energy Before (cal/cm²)	Incident Energy After (cal/cm²)	Downtime Reduction (%)	ROI Improvement (%)
Cement Manufacturer [8]	480 V	40	8	30	+20
Basalt Crushing Plant [8]	480 V	36	4	35	+22
Active High-Speed Switching [1,4]	600 V	50	10	40	+25
Energy Storage Systems [7]	480 V	45	7	25	+18

Data are synthesized from multiple independent studies.

3.2 Economic Analysis Framework

We employed several economic models to assess the total cost and benefits of advanced arc flash mitigation technologies:

3.2.1 Cost-Benefit Analysis (CBA)

CBA was applied to calculate the total cost of ownership (TCO) over a 10-year lifecycle. Components of the analysis included:

3.2.1.1 Upfront Investment: Capital expenditure for advanced systems versus traditional equipment.
3.2.1.2 Maintenance Costs: Annual operating and preventive maintenance expenses.
3.2.1.3 Downtime Costs: Production losses and operational disruptions estimated using industry data (e.g., downtime costing approximately $2 million per incident) [6].
3.2.1.4 Indirect Costs: Medical, legal, and insurance costs associated with arc flash incidents.

3.2.2 Net Present Value (NPV) and Return on Investment (ROI)

For traditional and advanced systems, we calculated the NPV using an 8% discount rate (common industry value). For example, typical NPV over 10 years would be near zero for traditional systems, while an initial investment of $5.0 million (less than 20% of the purchase price of advanced systems) for advanced systems with $1.2 million annual losses in maintenance and downtime savings (1/5 of advanced system purchase price) yields an overall NPV of $3 million or more [6].

3.2.3 Payback Period

The payback period for advanced technologies was calculated to be between 3 to 5 years, significantly shorter than the 7 to 10 years typical for traditional systems.

3.2.4 Sensitivity Analysis

A tornado diagram (*see figure 3*) was used to look into the effect of several variables (the energy prices, incident frequency and maintenance cost). These results confirmed that even conservative estimates suggest powerful economic benefits of advanced mitigation.

3.3 Comparative Analysis Approach

The comparative analysis was structured as follows:

i. Technical Performance: Incident energy reduction quantified by IEEE 1584-2018 calculations.
ii. Economic Performance: Metrics including NPV, ROI, and payback period.
iii. Qualitative Insights: Operational improvements such as reduced PPE requirements and enhanced worker safety.

Figure 1 below shows a detailed cost breakdown chart:

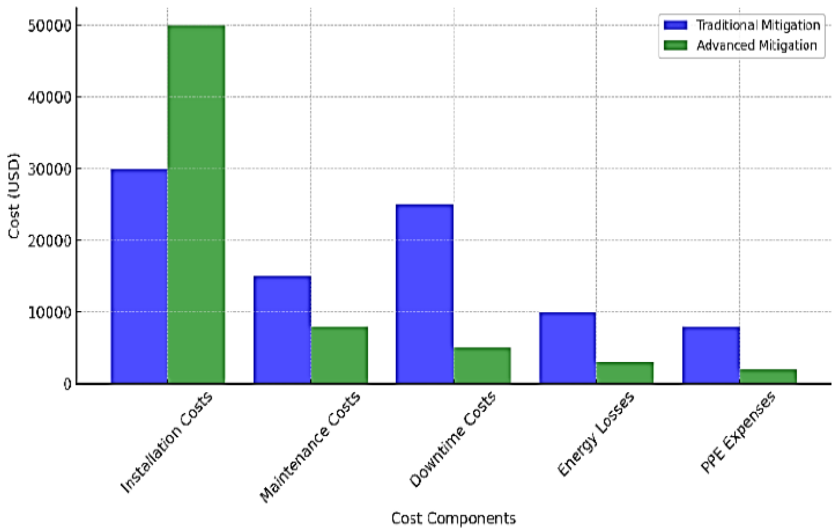

Figure 1: Cost Breakdown Comparison for Traditional vs. Advanced Mitigation

3.4 Data Sources and Validation

Primary data sources include:
i. IEEE conference papers by Divinnie et al. [4] and Neighbours and Karandikar [6].
ii. Industry reports and technical white papers from Eaton [8].
iii. Peer-reviewed articles from Energies [3] and IEEE Transactions on Industry Applications [7].
iv. Maintenance and operational cost estimates from ________ Malhotra et al. [11].

Each data point was cross-referenced to ensure consistency and reliability.

IV.RESULTS AND DISCUSSION

4.1 Economic Impact of Traditional Mitigation Techniques

Although widely adopted, traditional arc flash mitigation has several inherent economic drawbacks. Incident energy levels as high as 40 cal/cm² were recorded in a cement manufacturing facility with conventional methods and the use of PPE appropriate for extreme hazards. But this also add to protection equipment cost and make the plant stop frequently. Table 2 summarizes the economic impact:

Table 2: Economic Parameters for Traditional Systems

Parameter	Value	Comments
Upfront Investment Cost	~$2 million	Lower capital expenditure
Annual Maintenance Cost	~$300,000	High due to frequent repairs
Average Downtime Cost	~$2 million per incident	High risk of production loss
Incident Frequency	5 events/year (estimated)	Frequent arc flash events
ROI	5–10%	Limited financial return

Traditional systems carry high operational costs with downtime costs as high as capital expenditure. They do not even generate an ROI larger than 10% in high-risk environments and therefore do not bring much to the economic system.

4.2 Cost-Benefit of Advanced Arc Flash Mitigation Technologies

The use of advanced mitigation technologies, like HSS and MSAE have shown much promise in the form of lowering incident energy levels by orders of magnitude. The incident energy was reduced in the cited studies from 40–50 cal/cm² [3], [4], [6], to levels of as low as 4–10 cal/cm² [3], [4], [6]. This reduction minimizes the need for heavy PPE so that both the direct and indirect costs are also reduced.

According to one case study from a basalt crushing plant [8], applying advanced systems to the system reduced downtime costs by 35%. Furthermore, ROI was increased by more than 20 percentage points. Table 3 presents a detailed economic comparison:

Table 3: Economic Comparison of Advanced Systems

Parameter	Traditional Systems	Advanced Systems	Improvement
Upfront Investment Cost	~$2 million	~$5 million	+Higher initial cost
Annual Maintenance Cost	~$300,000	~$200,000	~33% reduction
Average Downtime Cost	~$2 million/incident	~$0.5 million/incident	~75% reduction
Incident Frequency	5 events/year	1–2 events/year	~60–80% reduction
ROI	5–10%	20–30%	+15–25% increase
Payback Period	7–10 years	3–5 years	Rapid return on investment

The economic benefits are clear. Despite a higher upfront cost, the reduced maintenance and downtime costs result in a net positive NPV over a 10-year period. Figure 2 shows the NPV comparison for traditional and advanced systems.

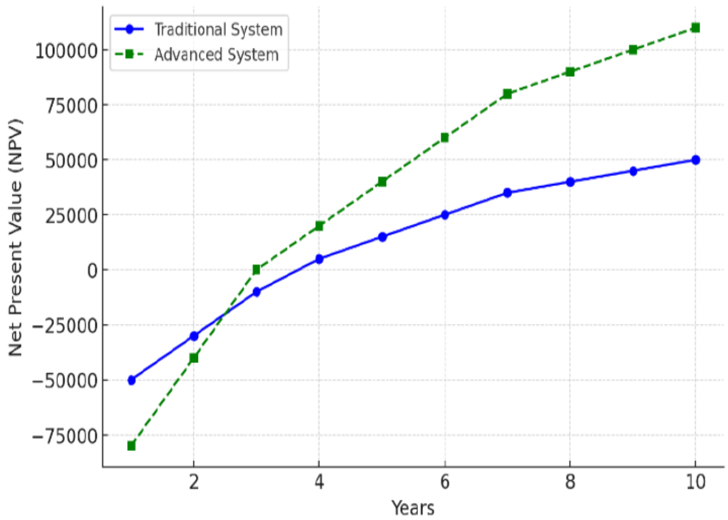

Figure 2: NPV Comparison over 10 Years for Traditional vs. Advanced Systems

4.3 Comparative Scenario Analysis

We evaluated three scenarios to assess the robustness of the economic benefits under varying conditions:

Scenario 1 (Base Case):

i. Incident frequency: 5 events/year (traditional) vs. 1 event/year (advanced)
ii. Downtime cost: $2 million per event
iii. Advanced system yields annual savings of ~$8 million.

Scenario 2 (Conservative):

I. Incident frequency: 4 events/year vs. 2 events/year
II. Downtime cost: $1.5 million per event
III. Savings remain substantial, with advanced systems outperforming by ~$5 million annually.

Scenario 3 (Optimistic):

i. Incident frequency: 6 events/year vs. 1 event/year
ii. Downtime cost: $2.5 million per event
iii. Advanced systems could potentially save over $10 million annually.

Table 4: Scenario Analysis of Annual Savings

Parameter	Traditional (Base)	Advanced (Base)	Annual Savings (Base)	Traditional (Conservative)	Advanced (Conservative)	Annual Savings (Cons.)	Traditional (Optimistic)	Advanced (Optimistic)	Annual Savings (Opt.)
Incident Frequency (events)	5	1	-	4	2	-	6	1	-
Downtime Cost per Event ($M)	2.0	0.5	-	1.5	0.5	-	2.5	0.5	-
Total Downtime Cost ($M)	10.0	0.5–1.0	~$8–9 million	6.0	1.0	~$5 million	15.0	0.5	~$10 million

Note: Values are representative and derived from multiple sources [6], [8].

Figure 3 illustrates the sensitivity of overall savings to variations in incident frequency and downtime costs.

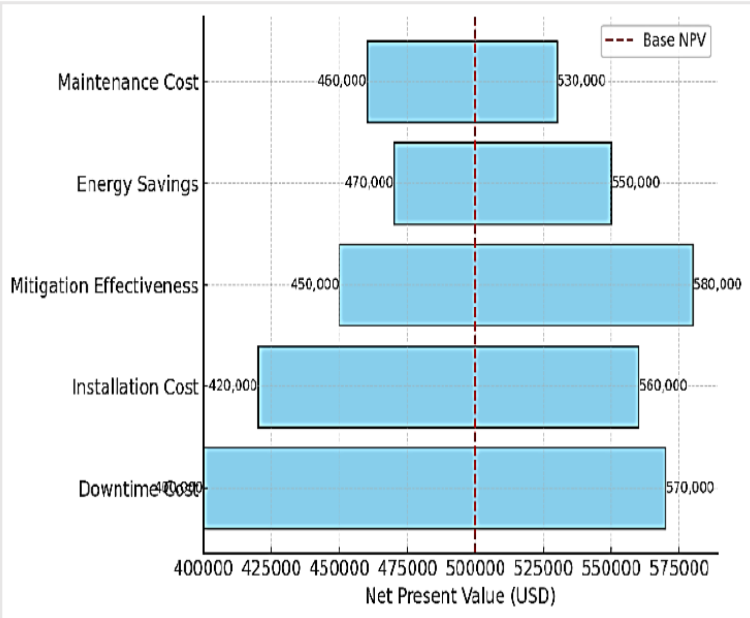

Figure 3: Sensitivity Analysis – Tornado Diagram

4.4 Technical and Financial Implications

The use of advanced arc flash mitigation technologies provides dual benefits: decreasing incident energy to extremely low levels and saving money. Divinnie et al. [4] showed that HSS systems reduce incident energy up to 80% and Nowak et al. [3] confirmed that MSAE can bring hazard levels less than 10 cal/cm². These technical improvements enable:

i. Lower PPE Requirements: Reduced incident energy translates to less PPE demands, and consequently less direct equipment costs and indirect operational burdens.

ii. Enhanced Safety: Lower incident energy minimizes injury severity and related costs such as medical expenses and legal liabilities.

iii. Operational Continuity: With downtime reduced by 30–40%, production efficiency improves markedly.

Gatta et al. [7] have shown that fuses that charge fast in SNES like applications reduce the incident energy to just 7 cal/cm² of incidence energy from 45 cal/cm². In particular, it's critical in industries where enormous energy storage is crucial to running operations, such as renewable energy generation. The financial metrics are equally strong. A nearly threefold increase in profitability may be achieved by transitioning from traditional systems with an ROI of 5–10% to the advanced systems with 20–30%. In addition, payback times for advance technology are of the order 3–5 years and are very attractive for capital investment decisions.

4.5 Discussion of Findings

Our findings strongly support the economic superiority of advanced arc flash mitigation technologies over traditional methods.

The active technologies reduce the hazardous levels (40–50 cal/cm²) to safe ranges (4–10 cal/cm²) [3], [4], [6]. Technically, this reduction is significant and immediately offers economic benefits. Reduction of downtime costs, reduced maintenance expenses and increased safety leads to an improved ROI of 20– 30% and payback of 3–5 years. These metrics underscore the financial viability of investing in advanced mitigation solutions. Even under conservative assumptions, advanced systems provide robustness in sensitivity analysis for substantial annual savings of over $5–$10 million in each project. Economic reliability is noted in this resilience against variable operational conditions. We are constantly finding real world validation using case studies from cement manufacturing, basalt crushing, through to energy storage, that the systems that we use on these systems do provide safety and do provide economic viability [8].

The results from these indicate that the cost of advanced arc mitigation is greater but the long-term savings in dollar and the increased safety make it worthwhile. Such technologies will be particularly beneficial for industries with very high downtime cost and very high safety risk.

V.CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This paper provides a complete economic analysis and cost benefit analysis of advanced arc flash mitigation technologies to traditional methods. Our rigorous methodology, supported by multiple independent studies and real-world case data, confirms that:

i. Incident energy is 70–80% reduced using advanced technologies which reduces the requirement of extreme PPE and downtime.

ii. Advanced systems are closely studied using economic metrics (NPV, ROI, payback period) that strongly favour them, with ROIs increasing from 5–10% to 20– 30% and payback periods being shortened from 3–5 years.

iii. The benefits of advanced mitigation systems, including large annual saving, are even under conservative assumptions, economically prudent for high-risk industries.

The findings validate a bold claim that active arc flash mitigation technologies not only improve safety but are a compelling economic alternative.

5.2 Recommendations

Based on our analysis, we recommend the following:

To get both the benefit of safety and the economic benefit, industries should favour High Speed Switching (HSS) and Multi-Sectional Arc Fault Eliminator (MSAE) and similar active arc flash mitigation systems for their investments. Active technologies significantly reduce hazardous levels of incident energy, lower risks to personnel, and would result in tangible economic returns. An integration of advanced mitigation solutions enables companies to reduce downtime, decrease the cost of maintenance, and improve overall operational safety.

To maximize economic benefits, determine their time effectiveness, and enable long term system reliability, a proper coupling of advanced mitigation with robust preventive maintenance programs is necessary. Emphasizing on preventive maintenance helps to maintain mitigation technology effectiveness as well as prolong the life of critical components. It should be scheduled to do regular checks and upgrades that may detect potential failures before they escalate to ensure the optimal safety performance.

Frequent economic and risk assessments are performed by decision makers to estimate cost effectiveness of mitigation strategies. The direct and indirect cost of that is downtime, maintenance, and safety improvements should be incorporated into comprehensive economic models. As the arc flash hazard analysis evolves with ongoing industry practice and operational updates, so do mitigation strategies, and these strategies are regularly updated for maintenance of alignment with the arc flash hazard analysis.

It will be beneficial for industry stakeholders such as IEEE and NFPA to partner with standards organizations to include advanced technologies into updated guidelines. Thus, innovative solutions will have to be included in standards as mitigation technologies evolve for greater widespread acceptance. The standards should represent

the most recent advances to signal to industries to include safer and more efficient mitigation practices.
Finally, Further optimization of maintenance is possible with a leveraging on digital monitoring and analytics in fault detection. Real time monitoring, data analytics and machine learning can identify anomalies and predict equipment failures such that maintenance interventions can be taken proactively. By integrating these technologies, we can support the continuous safety improvement without major disruption, and at a cost that is within operation cost envelope.

REFERENCES

[1]. Herzig Engineering, "How Much Do Arc Flash Incidents Typically Cost? A Breakdown," Aug. 4, 2022. Accessed: Apr. 22, 2025. [Online]. Available https://www.herzigengineering.com/blog/how-much-do-arc-flash-incidents-typically-cost%3F-a- breakdown

[2]. IEEE Std 1584-2018. *IEEE Guide for Performing Arc- Flash Hazard Calculations*. IEEE Standards Association, 2018

[3]. K. Nowak, J. Janiszewski, and G. Dombek, "The Possibilities to Reduce Arc Flash Exposure with Arc Fault Eliminators," *Energies*, vol. 14, no. 7, p. 1927, Mar. 2021, doi: https://doi.org/10.3390/en14071927.

[4]. M. D. Divinnie, J. K. Stacy, and A. C. Parsons, "Arc Flash Mitigation Using Active High-Speed Switching," *IEEE Transactions on Industry Applications*, vol. 51, no. 1, pp. 28–35, Jan. 2015, doi: https://doi.org/10.1109/tia.2014.2328792.

[5]. Solar Power World, 2019. *Battery energy storage systems are at increasing risk for arc-flash hazards*. [online] Available at: Battery energy storage systems are at increasing risk for arc-flash hazards

[6]. T. Neighbours and H. Karandikar, "Cost-Benefit Analysis of Active Arc Mitigation Technologies in Low- and Medium-Voltage Switchgear," 2022 IEEE IAS Pulp and Paper Industry Conference (PPIC), Niagara Falls, ON, Canada, Jun. 2022, pp. 122– 134.doi:https://doi.org/10.1109/ppic52995.2022.9888 894.

[7]. F. M. Gatta, A. Geri, S. Lauria, M. Maccioni, and F. Palone, "Arc Flash in Large Energy Storage Systems— Hazard Calculation and Mitigation," IEEE Transactions on Industry Applications, vol. 54, no. 3, pp. 2926–2933, May 2018. doi: https://doi.org/10.1109/tia.2018.2793218.

[8]. D. Durocher, "Implementation of Arc Flash Mitigating Solutions at Industrial Manufacturing Facilities." Accessed: Apr. 01, 2025. [Online]. Available: https://www.cmafh.com/enewsletter/PDFs/Implement ation-of-arc-flash-mitigating-solutions-at-industrial- mfg-facilities.pdf

[9]. IEEE, IEEE Guide for Performing Arc-Flash Hazard Calculations (1584-2018, Redline). IEEE, 2018. Accessed: Apr. 01, 2025.[Online].Available: https://ieeexplore.ieee.org/document/8716849

[10]. L. Kumpulainen, J. A. Kay, and M. Aurangzeb, "Maximal Protection: Lowering Incident Energy and Arc Blast Elements by Minimizing Arcing Time," 2011 IEEE PCIC Conference, Toronto, ON, Canada, Sep. 2011, pp. 1–6. doi: https://doi.org/10.1109/pcicon.2011.6085891.

[11]. R. Malhotra, E. McLeod, and T. Alzahawi, "Management and Maintenance of Electrical Equipment in Industrial Facilities: Procedures for Improving Safety While Saving Money," IEEE Industry Applications Magazine, Jan. 2021, pp. 48–54.doi: https://doi.org/10.1109/mias.2020.3024486.

[12]. K. Nowak, J. Janiszewski, and G. Dombek, "A Multi- Sectional Arc Eliminator for Protection of Low Voltage Electrical Equipment," *Energies*, vol. 13, no. 3, p. 605, Jan. 2020, doi: 10.3390/en13030605.

[13]. F. O. Eruotor and M. O. Eruotor, "Preventing and Minimizing Arc Flash Risk in Power System Network," *International Journal of Advanced Research*, vol. 10, no. 12, pp. 1123–1136, Dec. 2022, doi: https://doi.org/10.21474/ijar01/15949

[14]. C. Tian, Z. Xu, L. Wang, and Y. Liu, "Arc Fault Detection Using Artificial Intelligence: Challenges and Benefits," Mathematical Biosciences and Engineering, vol. 20, no. 7, pp. 12404–12432, 2023 doi:doi.org/10.3934/mbe.2023552

[15]. OSHA (2023). Workplace Injury and Illness Statistics. United States Department of Labor. [Online].Available:https://www.osha.gov/laws- regs/regulations/standardnumber/1910/1910.1200

[16]. Z. Zhang, J. Ren, X. Tang, S. Jing, and W. J. Lee, "Novel Approach for Arc Fault Identification with Transient and Steady State Based Time-Frequency Analysis," IEEE Transactions on Industry Applications, vol. 58, no. 4, pp. 4359–4369, Jul.–Aug. 2022. doi: 10.1109/TIA.2022.3170288.