Application of Arc Light Protection System in Medium and Low Voltage Switch System

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Abstract: With the acceleration of industrial modernization and the expansion of power distribution networks, the safety and reliability of medium- and low-voltage switchgear have become increasingly critical, particularly due to the rising incidence of arc flash faults caused by insulation degradation and harsh environments. This study aims to address the inadequacies of traditional protection methods by exploring the application of dedicated arc flash protection systems. Using a combination of theoretical modeling and empirical analysis, the research evaluates the performance of arc flash protection in terms of fault detection speed, fault localization, and system adaptability. The findings show that these systems can detect arc faults and issue trip signals within 10 milliseconds, achieving fault clearance in less than 100 milliseconds - significantly faster than conventional protection schemes. Moreover, the integration of tailored protection criteria based on system grounding types enhances overall protection precision. In conclusion, arc flash protection systems provide a high-value and technically feasible solution for improving operational safety and responsiveness in medium- and low-voltage distribution systems.

Keywords: Medium and Low-Voltage Systems; Arc Flash Protection; Switchgear; Power System Safety; Fast Trip Mechanism

1. Introduction

With the continuous advancement of modern industrialization and the expansion of power systems, medium- and low-voltage distribution systems play a critical role in industrial, commercial, and public facilities. As core equipment for power distribution and control, medium- and low-voltage switchgear face numerous challenges: frequent operations accelerate mechanical wear, high-temperature and humid environments hasten insulation material degradation, and dust accumulation or corrosive gas erosion significantly reduce equipment safety. These issues share a common characteristic—arc flashes are prone to occur during initial fault stages, gradually escalating into severe arc faults.

In particular, arc flash faults—once considered rare—are now recognized as high-risk events due to their explosive energy release and unpredictable onset. According to industry data, arc-related incidents account for a significant proportion of medium-voltage switchgear failures, often leading to severe equipment damage, operational downtime, and in worst cases, personnel injuries.

Traditional protective measures such as fuses and standard relays are no longer sufficient to meet the response time and fault isolation accuracy required in modern systems. Therefore, the need for a fast, intelligent, and adaptive arc flash protection strategy has become increasingly urgent.

This study aims to analyze the root causes and physical characteristics of arc flash faults, examine the limitations of existing protection strategies, and evaluate the technical and practical value of applying dedicated arc flash protection systems in medium- and low-voltage environments.

2. Physical Characteristics and Hazards of Arc Flash Faults

An arc flash is a continuous discharge phenomenon formed by electric current in insulating media. In medium- and low-voltage switchgear, it typically originates from instantaneous short circuits between phases or phase-to-ground. The primary hazards of arc flash faults manifest in three aspects:

(1) High-temperature ionization effect

When an arc is generated inside switchgear, the short-circuit power can instantaneously reach 8–60 MW, with the root temperature of the arc exceeding 18,000°C. Such extreme heat causes rapid vaporization of conductor materials near the fault point, forming high-temperature metallic plasma. Simultaneously, it ignites surrounding insulating materials, accelerating fault propagation [1].

(2) Dynamic pressure impact

The pressure wave generated by arc-induced gas expansion can peak at 0.3 MPa, far exceeding the structural tolerance limit of switchgear enclosures (≤0.02 MPa). This may lead to severe deformation or even explosion of the enclosure, posing lethal risks to personnel [2].

(3) Energy accumulation index

As shown in Figure 1, the arc energy (I^2t) increases exponentially with arc duration. Currently, domestic medium- and low-voltage switchgear in China typically adopts IEC 298 as the manufacturing standard. Under this framework, the allowable arc withstand time should not exceed 100 ms [3]. When the arc duration surpasses 100 ms, the energy release rate escalates to over 300 times its initial value, significantly amplifying the risk of catastrophic equipment damage [4].

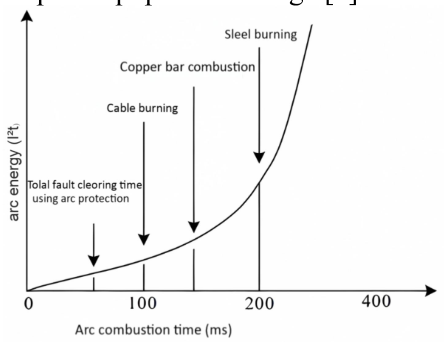

Figure 1. Relationship Curve between Internal Energy Release and Arc Duration in Switchgear

3. Limitations of Conventional Busbar Protection Schemes

Traditional protection approaches used in medium- and low-voltage systems exhibit inherent limitations that compromise their effectiveness in preventing arc flash incidents. Two commonly applied schemes—busbar differential protection and transformer backup overcurrent protection—face both technical and practical challenges that restrict their protective scope and responsiveness.

(1) Busbar differential protection

Currently deployed busbar differential protection schemes in China are primarily designed for high-voltage systems (110 kV and above), with limited application in medium- and low-voltage switchgear. This is largely due to their high implementation cost, complexity in configuration, and reliance on extensive current transformer (CT) infrastructure. As a result, most medium- and low-voltage systems remain unprotected by dedicated busbar differential schemes.

Moreover, busbar differential protection lacks the capability for precise fault localization, leading to prolonged recovery times after a fault occurs [2]. This limitation becomes particularly critical in densely packed distribution systems where rapid isolation of the fault point is essential to prevent cascading failures. Additionally, operational limitations stemming from CT saturation and mismatch further compromise the reliability of differential protection in accurately detecting low-impedance faults.

Furthermore, this protection method is ineffective for cable joint faults at incoming and outgoing lines—areas that are statistically more prone to arc flash events due to insulation wear, joint heating, or poor installation quality. These vulnerable points lie outside the coverage of differential zones, rendering the method incapable of preventing damage or injury resulting from such localized failures [5].

(2) Backup overcurrent protection for transformers

Transformer backup overcurrent protection typically operates under a time-delay setting of 1.2–2.0 seconds to ensure coordination within hierarchical protection frameworks. Even when feeder instantaneous trip blocking is employed, the response time remains between 300–500 milliseconds.

Such latency is significantly higher than the maximum allowable arc flash clearing time (≤100 ms), as prescribed by standards like GB/T 14598.302-2016. This delay allows arc energy to escalate exponentially, increasing the likelihood of severe equipment damage, fire, or personnel injury.

Additionally, this protection scheme is passive in nature—it only responds after fault current reaches a preset threshold, without sensitivity to optical arc signals. As such, it fails to detect early-stage arc development, missing critical opportunities for preemptive isolation. In systems with high short-circuit capacity, this can result in catastrophic energy release within milliseconds.

In summary, conventional busbar protection schemes are not only slow and imprecise but also insufficient in scope, especially in the context of modern arc fault characteristics. These shortcomings highlight the pressing need for faster, more accurate, and spatially flexible protection strategies—such as arc flash protection systems specifically designed to address these gaps.

4. Application Value of Arc Flash Protection

As an advanced protection technology specifically designed for arc flash faults, arc flash protection systems can detect and interrupt arc faults within milliseconds, effectively preventing accident escalation and personnel injuries. According to GB/T 14598.302-2016 Technical Requirements for Arc Flash Protection Devices, the instantaneous trip protection response time of arc flash protection devices should not exceed 10 ms, with fault clearance time controlled within 100 ms through overcurrent protection [6].

Compared to conventional protection schemes, arc flash protection systems exhibit the following advantages:

(1) Ultra-fast response: Detection of arc initiation typically occurs within milliseconds, significantly outpacing traditional relay-based protection systems.

(2) High accuracy: Photoelectric composite criteria minimize false trips and failures to operate.

(3) Flexible installation: Sensors can be strategically deployed based on switchgear structural features to achieve comprehensive monitoring.

(4) Precise fault localization: Rapid identification of fault locations drastically reduces post-fault recovery time.

(5) Compatibility: Seamless integration with existing protection systems, functioning either as primary or supplementary busbar protection.

5. Composition of Arc Flash Protection Systems

(1) Master control unit

The master control unit monitors busbar operation by detecting short-circuit currents and receiving signals from arc flash sensors. In distributed systems, it processes arc signals from incoming line cabinets and circuit breakers, while relying on extension units to monitor current and arc signals in other cabinets. For centralized systems, a single master control unit integrates arc sensors and multiple incoming line currents. However, this configuration demands higher terminal capacity when arc sensors are installed in cable compartments of feeder cabinets, making it suitable only for busbars with limited sections.

To enhance adaptability and processing speed, newer-generation master units adopt modular hardware design combined with high-speed digital signal processors (DSPs), enabling them to respond to arc faults within milliseconds. These units often support multiple communication protocols—such as Modbus, IEC 61850, and CAN bus—facilitating seamless integration with supervisory control and data acquisition (SCADA) systems or intelligent substation platforms [7].

Additionally, some advanced models incorporate LCD or LED display panels for local status indication and diagnostics, improving on-site operability and fault tracking. With built-in self-test and fault recording capabilities, the master unit can also generate historical logs and waveforms for event analysis, greatly aiding post-incident evaluation.

In high-reliability applications, dual-redundant power supplies and communication links can be integrated to ensure uninterrupted operation even under single-point failure scenarios, further reinforcing system stability.

(2) Extension unit

Auxiliary units installed in feeder cabinets collect signals from individual compartments and transmit them to the master control unit. During faults, the master unit displays alarm addresses for rapid fault localization.

These extension units are typically outfitted with current sensing modules and arc flash detectors, allowing them to track both electrical and optical signals in real time. By distributing the monitoring functions, these units help reduce transmission delays and alleviate the computational burden on the main controller.

In practical installations, extension units may be arranged using a daisy-chain topology or configured with dedicated signal loops, depending on the complexity of the system and cabinet layout. The daisy-chain approach is often favored in compact substations due to simplified wiring, while independent signal loops provide superior fault isolation in larger and more segmented networks.

(3) Arc flash sensors

Spectral analysis of arcing light reveals that its energy is predominantly concentrated in two bands: the ultraviolet (UV) spectrum at 300-400 nm and the visible spectrum at 400-700 nm. These spectral components pose potential hazards to human eyes. Meanwhile, considering interference from ambient light, detection systems must integrate robust capabilities of high interference resistance, low noise, and large photosensitive area to ensure reliable operation [8].Mounted in switchgear compartments (busbar chambers, circuit breaker chambers, and cable chambers), these sensors convert optical arc signals into electrical signals via photosensitive components and relay them to upper-level monitoring units. Their strategic placement aligns with the modular design principles emphasized in modern arc-resistant equipment.

6. Arc Flash Protection Operating Criteria and Application Scenarios

(1) Arc flash and current dual criteria

As illustrated in Figure 2, the typical operating criterion for arc flash protection combines arc light detection and current thresholds. The system issues a trip command only when both an arc flash signal and a current exceeding the activation threshold are detected. If only an arc flash or abnormal current is detected, an alarm is triggered without tripping.

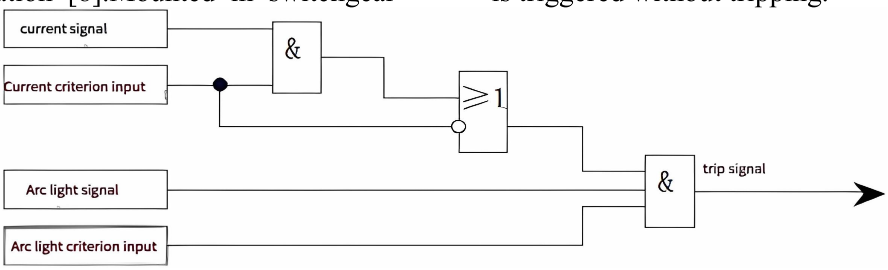

Figure 2. Protection Logic for Arc Flash and Current Dual Criteria

For solidly grounded systems, single-phase ground faults cause a sharp rise in fault-phase current, making the "arc flash + overcurrent" dual criteria sufficient. In such systems, the overcurrent threshold is typically set at 1.1–1.3 times the rated current to ensure rapid fault detection and isolation [9].

This combined criterion not only enhances protection sensitivity but also effectively reduces the risk of false tripping caused by ambient light fluctuations or transient current spikes. By requiring both optical and electrical signals to be present simultaneously, the system achieves a more selective and reliable response to genuine arc faults.

In engineering practice, the coordination of trip logic can also be refined by setting time delays or sensitivity zones. For instance, in areas close to cable terminals or circuit breaker contacts—where arc risks are higher—the response threshold can be lowered to enable earlier intervention. Meanwhile, less critical zones may use slightly elevated thresholds to avoid unnecessary interruptions.

Furthermore, dual-criteria schemes can be adapted for specific industrial scenarios. In metal processing plants or wind farms—where transient light or harmonic currents are common—filter algorithms and signal validation rules can be embedded in the controller to improve discrimination between true faults and benign anomalies.

In impedance-grounded systems (e.g., resistance-grounded systems), single-phase ground fault currents are limited, rendering pure overcurrent criteria unreliable. For these scenarios, a hybrid approach combining "arc flash + overcurrent" (for phase-to-phase faults) and "arc flash + zero-sequence current" (for single-phase ground faults) is recommended [10].

(2) Arc flash, current, and zero-sequence voltage criteria

For ungrounded or resonant-grounded systems, single-phase ground faults exhibit minimal current variation but increased capacitive current to ground. Here, zero-sequence voltage is introduced as an auxiliary criterion, forming dual criteria of "arc flash + overcurrent" and "arc flash + zero-sequence voltage" to address single-phase arc flash faults. The protection logic is shown in Figure 3.

Additionally, the magnitude and duration threshold of zero-sequence voltage can be configured according to system capacitance and expected transient behavior. In medium-voltage networks with high cable capacitance, threshold settings must account for natural background voltages to avoid misjudgment.

To further enhance reliability, advanced systems incorporate logic that cross-validates zero-sequence signals from multiple locations. This multi-point correlation ensures that localized disturbances do not mistakenly trigger system-wide responses, especially in distributed control architectures.

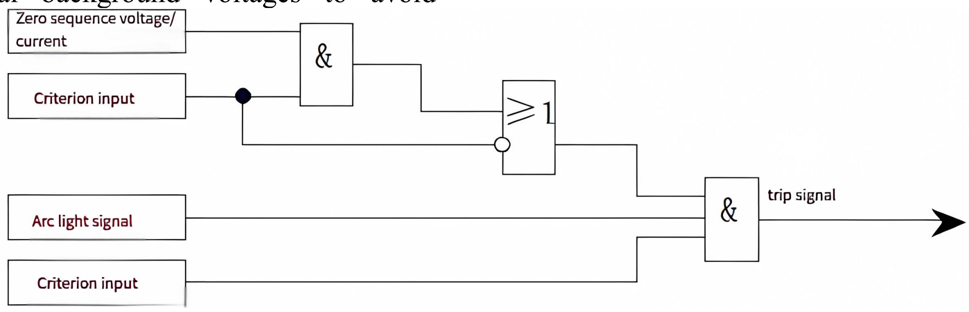

Figure 3. Protection Logic for Arc Flash, Overcurrent, and Zero-Sequence Voltage Criteria

7. Conclusion and Future Prospects

This study focuses on arc flash faults frequently occurring in medium- and low-voltage switchgear. Starting from the causes, physical hazards, and the limitations of traditional protection methods, it proposes and analyzes the practical application value of arc flash protection systems. The findings demonstrate that such systems offer millisecond-level response speed, accurate fault localization, flexible deployment, and strong compatibility with existing equipment. These features effectively compensate for the shortcomings of conventional protection schemes and significantly enhance the safety and reliability of power distribution systems.

Looking ahead, the development of arc flash protection systems can be advanced in two major directions. First, by integrating intelligent recognition technologies—such as AI-based algorithms and multi-source signal fusion—the system's ability to identify arc events under complex interference conditions can be greatly improved. Second, broader field application tests in various power distribution environments should be conducted to accumulate real-world operational data, thereby facilitating continuous performance optimization and engineering implementation.

In summary, arc flash protection systems provide a feasible and efficient solution for enhancing the safety of medium- and low-voltage networks, with promising application potential and deployment value.

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