Real-time Protection Scheme for Distribution Networks Connected with Distributed Generation

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Abstract. This research proposes a real-time protection scheme for distribution networks with distributed generation, offering critical insights for benchmarking protection levels against established guidelines. The project aims to (1) propose optimal protection coordination, (2) update settings for network changes in distribution systems, and (3) integrate the protection scheme with an active management system. The first objective involves using a detailed model and optimization algorithms to design a protection coordination scheme that minimizes fault clearance times while ensuring selectivity and preventing unnecessary outages. This model also allows seamless updates to accommodate system changes, ensuring continued effectiveness in a dynamic environment. The third objective emphasizes using the model to bridge the real-time protection scheme with the active management system, enabling proactive interventions and preventive measures. Overall, this research not only introduces a novel real-time protection scheme but also integrates it within a larger framework for proactive risk management and dynamic adaptation, enhancing the reliability and resilience of distribution networks.

Keywords. Distributed Generation; Real-Time Protection; Power Distribution System; Dynamic Adaptation.

1. Introduction

1.1. Background

Electric power systems are recognized as being crucial to modern society, supplying energy to technological devices, residential buildings, and industrial processes. The intricate dependencies among essential infrastructures, such as transportation, telecommunications, water, oil, and natural gas, are illustrated in Figure 1, underscoring the vital role of electricity in maintaining the performance of these infrastructures. The stability and reliability of power transmission and protection systems are thus considered essential for the smooth operation of these interconnected components [1].

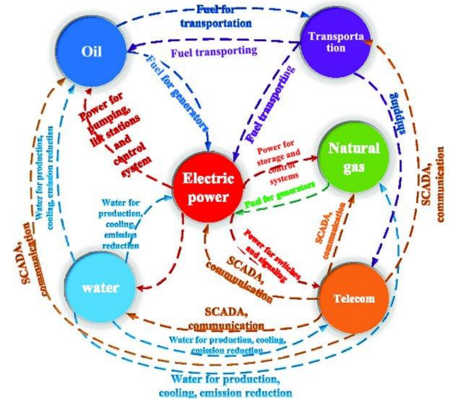

Fig. 1 Interdependence Among Critical Infrastructures [1]

The electric distribution network (DN) is responsible for delivering electricity from substations to end users, including homes, businesses, and industries. Operating at lower voltages than transmission lines, power is stepped down to usable levels. This network, which includes feeders, laterals, and service drops, is managed by sophisticated systems and protective devices to ensure efficient delivery and safeguard against outages. Distributed generation (DG), involving the generation of electricity closer to consumption points using renewable resources like solar and wind, is acknowledged for enhancing grid resilience, reducing emissions, and supporting local economies. However, challenges such as increased fault current sources, bidirectional current flow, and changes in current amplitude are introduced by the integration of DG, which can impact grid stability.

Protection systems are implemented to isolate faults before severe damage is caused. Comprising sensors, relays, circuit breakers, and complex algorithms, these systems are employed to protect infrastructure from natural disasters and equipment failures, ensuring continuous electricity flow and safeguarding individuals, assets, and infrastructure. Attributes like reliability, selectivity, speed, affordability, and simplicity are emphasized for maximizing efficiency. Real-time protection methods, using advanced sensors, communication networks, and algorithms, are employed to monitor electrical characteristics, promptly address issues, and maintain grid stability, thus preventing cascade failures.

1.2. Impact of work to environment and society

Firstly, significant improvements in public safety are achieved. The real-time protection scheme enables faults to be detected and isolated rapidly, leading to a reduction in power outage duration and extent, which ensures the continued operation of critical infrastructure such as hospitals and emergency services. Additionally, the power quality is improved by strengthening the grid's ability to withstand storms, cyber threats, and other disruptions through dynamic adaptation to changing network conditions. This ensures that a reliable and cost-effective service is delivered to customers. Finally, the real-time protection scheme acts as a catalyst for community-based energy solutions, encouraging local energy independence and sustainability by allowing customers to take an active role in the energy environment.

1.3. Literature review

The necessity of adapting current protection strategies to address the challenges posed by Distributed Generation (DG) integration has been discussed by [2]. Two primary strategies are proposed: modifying traditional protection systems with minimal changes to reduce costs and operational disturbances, and completely redesigning the protection system by incorporating additional protective components. This dual approach highlights the need for both cost-effective solutions and innovative strategies capable of handling the complexities introduced by DG.

The importance of maintaining protection coordination in systems with high DG penetration is emphasized by [3]. A method is proposed that adjusts the characteristic curve of the backup relay after determining the lowest and highest fault current values. This adjustment increases the relay's current range, thereby enhancing the protection system's adaptability to varying fault conditions in a DG-integrated Distribution Network (DN).

A multi-agent system-based protection approach that focuses on fault location and autonomous power restoration in DNs containing DG is introduced by [4]. The potential of decentralized and intelligent protection strategies that can operate autonomously to detect and isolate faults, thereby minimizing the impact of DG on protection systems, is underlined.

A real-time adaptive protection scheme that redefines overcurrent relay settings by replacing the conventional time multiplier setting with a new real-time adaptive time multiplier setting is presented by [5]. This approach allows the protection system to dynamically adjust to real-time changes in the network, thereby providing enhanced protection against faults in DG-integrated DNs.

The importance of timely fault detection and classification, particularly in transmission lines, is further reinforced by [6]. Early detection and rapid response are argued to be crucial for preventing disruptions caused by faults. This work aligns with the need for real-time protection schemes that can quickly identify and isolate faults, ensuring the stability and reliability of the power system.

The various complications introduced by DG, including issues related to voltage profile, power quality, security, and protection, are highlighted by [7]. The bidirectional flow of energy from both DG sources and the main utility grid necessitates a reevaluation of existing protection systems. These findings support the development of more sophisticated protection strategies capable of managing the complexities of DG while ensuring network stability.

In summary, the integration of DG into DNs presents significant challenges for traditional protection systems. The literature reviewed emphasizes the need for adaptive, intelligent, and real-time protection schemes that can effectively manage the dynamic nature of modern DNs. These advancements are crucial for maintaining the reliability and safety of power systems in the face of increasing DG penetration.

2. Methodology

2.1. Research method & simulation tools

The research method is divided into two main categories. The first part involves constructing a power flow solution of the test system using the Newton-Raphson method. The second part focuses on generating three-phase bolted faults at different buses to evaluate the functionality of the protection scheme. MATLAB and MATPOWER are the primary software tools used in this study. MATPOWER is a MATLAB library designed for power flow and optimal power flow analysis, offering user-friendly features for simulation and parameter modification.

The IEEE 33-Bus Radial Distribution System, as described by [8], is employed for simulation in this research. This system is a medium-scale radial distribution system designed to deliver 3.72 MW of real power and 2.30 MVar of reactive power. The system comprises 37 transmission lines, including 5 tie lines, and operates with a slack bus at bus 1 on a 100 MVA base. The system maintains bus voltage limits between -9% and +6% relative to a 12.66 kV base voltage. The single-line diagram and detailed statistics for the system are provided in the study.

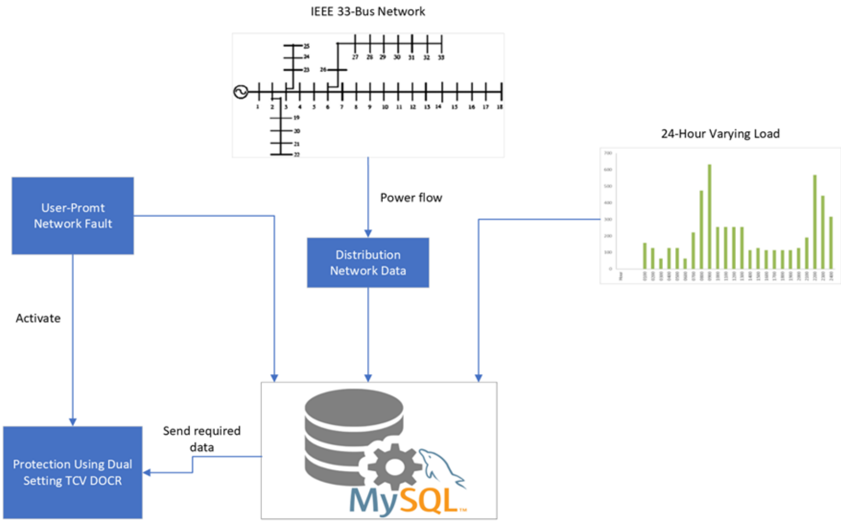

Fig. 2 Algorithm Block Diagram for Real-Time Protection and Fault Analysis in IEEE 33-Bus System Allocation of DG in Test System

Three DGs are allocated in the system at bus 31, 32 and 33. The size of the DGs is set to be 665 kW, 594 kW and 605 kW. The DG location and its size are based on the work in [2], which the DGs are optimized for the same protective devices setting value for IEEE 33-bus system. For comparison, DGs of same size are connected to bus 14,24 and 30. The buses where DGs are changed to PV bus from the original PQ bus.

2.2. Centralized system

A centralized protection coordination scheme is established using a MySQL database system to store and manage all relevant network data. The database includes comprehensive details such as base voltage and current, bus voltage, branch current, power, impedance, and fault current and voltage during faults, along with their occurrence times. This extensive dataset ensures accurate capture of critical parameters influencing the protection scheme.

Real-time data acquisition is facilitated, with continuous updates to the database, crucial for maintaining a responsive protection scheme. An online MySQL database integrated with an HTML-based website is proposed for real-time monitoring and remote observation of network data. However, due to budget and time constraints, the online real-time monitoring system has not been implemented. Despite these limitations, the foundational framework for a centralized protection coordination scheme has been established, providing a solid basis for future enhancements and real-time applications.

2.3. Time-current-voltage directional overcurrent relays (TCV DOCRs)

The integration of DG into the test system introduces bidirectional current flow, necessitating the use of directional overcurrent relays (DOCRs). To address coordination challenges and communication issues with conventional DOCRs, this project proposes the use of dual setting Time-Current-Voltage (TCV) DOCRs specifically designed for radial distribution systems with [9]. These relays, which do not require communication assistance, significantly reduce relay operating times in meshed networks.

The proposed scheme strategically places DOCR-TCV relays at each branch, enabling faster fault detection, isolation, and selective tripping. This ensures only the affected branch is de-energized, improving system reliability and resilience. In the test system, 32 dual setting TCV DOCRs are employed, streamlining protection and reducing complexity. Overcurrent (OC) relays are also placed between each generator and the feeder to mitigate fault current contributions from DGs, safeguarding connection lines and maintaining system stability. The relay settings and parameters, including pickup currents and time dial settings, are calculated to optimize performance based on the system's operational characteristics.

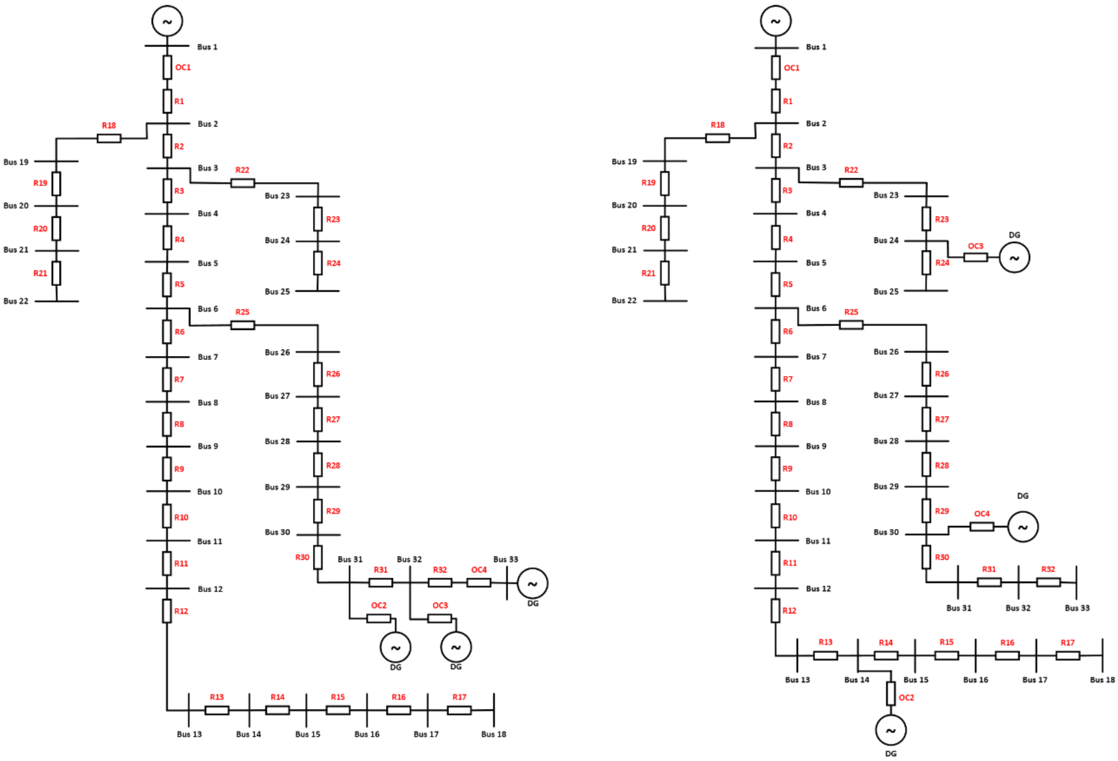

Fig. 3 Proposed Protection Scheme in IEEE 33-Bus Network with DGs

2.4. Simulation of 24-hour time varying load

To integrate the protection scheme with an active management system, relay settings are adjusted based on demand response and a 24-hour time-varying load profile, using data from typical Malaysian household load trend [10]**.** Load values for each hour are multiplied by trend values, with base apparent power values of 120+j80 for DG1, 420+j200 for DG2, and 200+j600 for DG3. These adjusted load, voltage, and current values are then monitored in a database. The pickup current of relays, both forward and reverse, is dynamically adjusted using specific formulas to enhance protection sensitivity, particularly for reverse fault currents.

3. Results & discussion

3.1. Performance of TCV DOCRs for enhanced protection with DG

The proposed solution to address the impact of DG on the protection scheme involves the implementation of TCV DOCRs capable of detecting bidirectional fault currents. The pickup time of the dual setting TCV DOCRs is calculated based on data stored in the database. The results of the pickup time are displayed in the command windows. Fault location detection is conducted based on bus voltage analysis, as shown in Figure 4.

```
From_Bus    To_Bus    FwdPickupTime    RevPickupTime
________    ______    _____________    _____________

    3         23         0.90159             2.5
   23         24         0.82165           1.541
   24         25         0.64212         0.19611


Three phase bolted fault located at bus 25, please check ASAP.
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Fig. 4 Indication of Fault Location and Relay Pickup Time During Fault

For example, in the event of a fault at bus 9, $R8_{fw}$ is designated as the primary downstream relay, with $R7_{fw}$ serving as its backup and R6fw as the second backup. $R9_{rv}$ is assigned as the primary upstream relay, while $R10_{rv}$ functions as its backup and $R11_{rv}$ as the secondary backup. The relay operating times are detailed in Table 1.

Table 1 Relay Pickup Time When Fault Happened at Different Bus (DG at Bus 14,24 &30)

Faulted Bus	**Pickup Time of Relay (second)**					
	Downstream			**Upstream**		
	Primary	**Backup 1**	**Backup 2**	**Primary**	**Backup 1**	**Backup 2**
9	0.28	0.42	0.49	0.11	0.13	0.35
14	0.43	0.67	1.68	0.04	-	-
25	0.64	0.82	0.90	-	-	-
33	0.18	0.34	1.52	-	-	-

From this table, it can be concluded that no communication block is required for the backup relay as the coordination time between each relay is calculated to avoid false tripping.

On the other hand, the OC relays are strategically positioned to isolate the DG or the feeder from faulted parts in the network. For instance, in the event of a fault at bus 30, where the DG is connected, overcurrent relay OC4 and dual setting relays R29 (in forward operation) and R30 (in reverse operation) will serve as the primary relays to isolate the fault. Relay R28, in its forward operation, acts as a backup for R29, while R31, in its reverse operation, serves as a backup for R30.

3.2. Performance of protection scheme with varying load

The pickup current for both forward and reverse operation of relay is calculated according to the load changes. All the data will be stored in a database. Part of the results are shown in Figure 5. From the figure, we can see the pickup current varies at different hours. At 09:00, the forward and reverse pickup currents reach their peak levels due to the load being at its maximum during this time.

Time	FromBus	ToBus	CurrentFW	CurrentRV
0100	1	2	0.018732	0.014718
0200	1	2	0.01808	0.014206
0300	1	2	0.01687	0.013255
0400	1	2	0.01808	0.014206
0500	1	2	0.01808	0.014206
0600	1	2	0.01687	0.013255
0700	1	2	0.020113	0.015803
0800	1	2	0.026387	0.020733
0900	1	2	0.030703	0.024124
1000	1	2	0.020838	0.016372
1100	1	2	0.020838	0.016372
1200	1	2	0.020838	0.016372
1300	1	2	0.020838	0.016372
1400	1	2	0.017828	0.014008
1500	1	2	0.01808	0.014206

Fig. 5 Pickup Current of Varying Load at Different Hour

Ensuring that the pickup current of a relay follows the varying load trend in a system is crucial for maintaining the reliability and safety of the power system. If the pickup current does not adjust accordingly, unnecessary tripping, or false positives, can occur during transient disturbances and periods of high demand, causing unwarranted interruptions in the power supply. Conversely, if the pickup current is set too high as in this project which is shown in Figure 6, the relay might fail to trip during actual fault conditions, resulting in sustained faults that can damage equipment and pose safety hazards. This failure to trip, or false negatives, can also occur during load inrush currents, where temporary spikes are not distinguished from fault conditions.

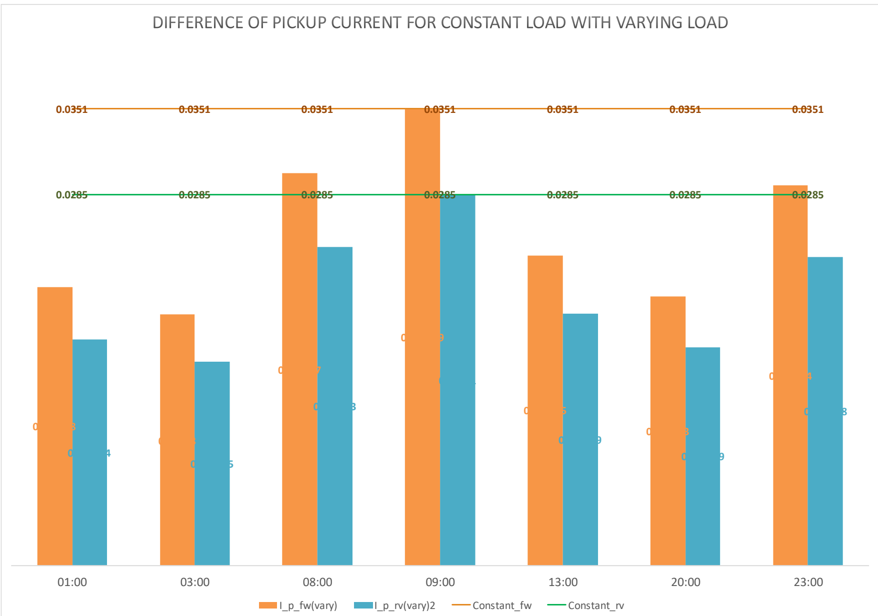

Fig. 6 Visualization of Constant and Varying Pickup Current

3.3. Integration with active management system (AMS)

To integrate the designed protection system with the active management system, a MATLAB-Simulink model of the IEEE 33 Bus System, is sourced from MATLAB Central. This model accepts inputs regarding the circuit breaker status and output voltage and current measurements for each branch. It also monitors changes in relay pickup current. Figure 7 illustrates the raw and smoothed pickup current values for a specific node across various hours, highlighting trends. Figure 8 presents the differences between the forward and reverse pickup currents to emphasize changes over time.

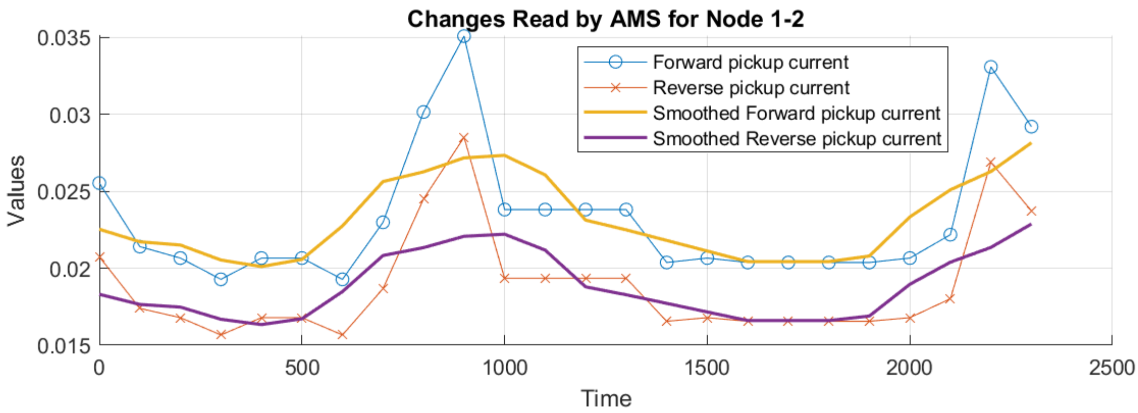

Fig. 7 Time Series of AMS Readings for Node 1-2

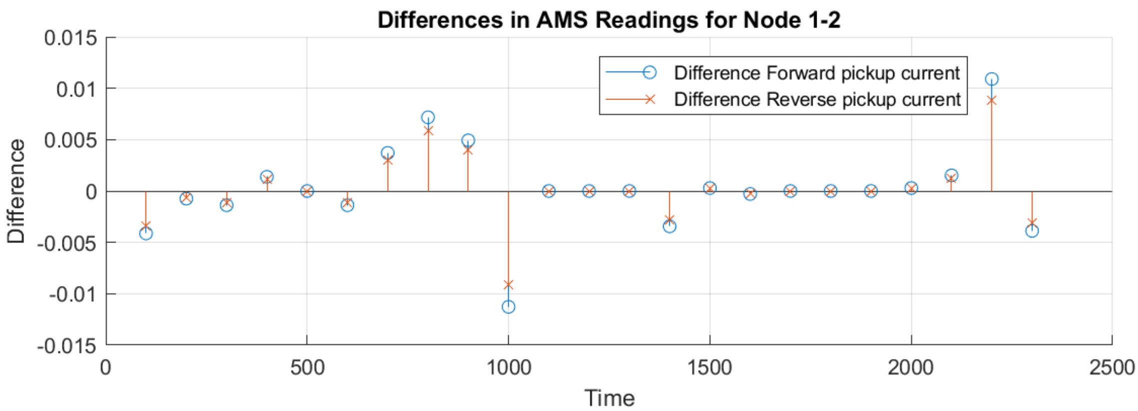

Fig. 8 Difference in Forward and Reverse Pickup Current in AMS for Node 1-2 Over Time

4. Conclusion

In conclusion, substantial benefits in terms of sustainability and energy saving are offered by the integration of DG into DNs. However, new challenges for system protection and reliability are also introduced. Conventional protection schemes, which are designed for unidirectional power flow, often struggle to adapt to the dynamic and decentralized nature of DG-infused grids. Innovative solutions, such as the real-time protection scheme explored in this study, are required.

To achieve Objective 1, a dual-setting TCV DOCR protection scheme is proposed to enhance adaptability and reliability in the presence of distributed generation (DG) by mitigating the effects of loss of coordination in distribution lines. This proposed solution has successfully protected the network from bidirectional faults without the need for communication blocks between primary and backup relays. For

Objective 2, a centralized system using a database has been developed for the efficient management and analysis of protection settings and fault data, allowing for updates in response to network changes. The network's status can always be monitored by users, who can also easily access and retrieve network data, sorting it according to their preferences for more tailored and efficient analysis. Finally, to fulfill Objective 3, a simulation with a 24-hour time-varying load has been conducted to observe and analyze the protection system's performance under diverse load conditions. Integration with an active management system enables the adaptive adjustment of settings within respective zones. This dynamic configuration ensures that protection devices remain reliable during peak load periods while maintaining sensitivity to fault detection during off-peak hours.

The comprehensive approach addresses the challenges of DG integration, ensuring robust and efficient protection while contributing to the overall reliability and sustainability of the distribution network.

Building on this conclusion, future work will be focused on several key advancements to enhance the protection and management of distribution networks with integrated distributed generation (DG). A major initiative will involve the development of a user-friendly website or mobile application for real-time monitoring of the distribution network. This platform will provide network operators and engineers with instant access to critical data and insights, enabling swift responses to faults and optimization of system performance. Features will include live status updates, fault alerts, and performance analytics.

Additionally, machine learning algorithms will be incorporated to dynamically adjust protection settings, continuously fine-tuning the dual-setting TCV DOCR protection parameters based on real-time data. This approach will improve accuracy and responsiveness to changing conditions, helping to anticipate potential issues before they escalate. Extensive research will be required to collect and curate comprehensive datasets for training and validating these machine learning models, involving collaboration with industry partners and utilities to gather diverse data from various operational scenarios.

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