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Fault-Tolerant Control of Power Distribution Networks Using Adaptive Protection Schemes

P Kalaivnai [1]*, P.Gowsikraja [2]

[1]*Assistant Professor, Department of Computer Science and Engineering, Kongu Engineering College,Tamilnadu*

[2]*Assistant Professor, Department of computer science and design, Kongu Engineering College Perundurai Tamilnadu*

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Abstract

Power flow reversals, bi-directional energy exchange, and a broader range of fault conditions are manifestations of unprecedented operational complexities brought by the rapid transformation of the modern power distribution networks, which was fuelled by the spread of distributed energy resources (DERs), renewable power production, and increased popularization of electric vehicles. Types of conventional protection systems that are often designed using fixed relay setting and centralized coordination and thus show slower fault isolation, low flexibility and increased vulnerability to cascading failures are becoming inefficient in these changing environments. This paper proposes a new Fault-Tolerant Control (FTC) algorithm that integrates Adaptive Protection Schemes (APS) to ensure these challenges can be overcome and offer high resiliency and reliability of active distribution networks. The three main capabilities proposed are the functions (i) of real-time fault classification and detection through advanced signal processing algorithms and machine learning techniques to identify exactly where a fault occurs and/or what type of fault it is in a precise and fast manner; (ii) optimal relay coordination in which the given relay settings adapt to achieve selectivity, sensitivity, and speed under different topology and penetrations of DERs; and (iii) self-healing network reconfiguration, which exploits graph algorithms to restore supply to non-affected areas, limit interruption of services, and equilibrate network loads after Because of the detailed simulations with complete IEEE 33-bus and IEEE 69-bus radial distribution test systems under several operating conditions with different DER penetration levels and fault conditions, the FTC-APS model has been tested. As results show, the proposed system provides up to 40 55% faster fault isolation, up to 25 faster outage impact, as well as an exceptionally high value of the System Resilience Index as compared to a conventional, static protection scheme. The results validate the promise of adaptive intelligence-based protection and control systems to enable the shift to smarter, resilient distribution grids that can withstand and recover to fault events in seconds.

Author e-mail: kalaivani.pachiappan@gmail.com, gowsikrajaapcse@gmail.com

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Introduction

The energy field in the world is experiencing quick change where the present day power distribution networks are changing in the form of passive unidirectional radial network into proactive, active and highly networked system. The key catalysts of this transitional journey are the growing penetration of Distributed Energy Resources (DERs), including rooftop solar photovoltaic (PV) systems, wind turbines and small-scale cogeneration devices, and the rapidly growing number of electric vehicles (EVs) and demand side flexibility initiatives. Through this, the conventional predictable and constant flow of power, known in traditional distribution systems, is increasingly being transformed into unpredictable, two-way energy interactions characterised by the high and variable renewable generation, variable load demands, and active reconfiguration of the distribution network.

These developments are assured to be more efficient in how they use energy, green houses emission level, and reliability in supply, but are accompanied by serious operational and protection issues. The traditional distribution protection systems were mostly fixed time overcurrent relay based and specification tuned coordination systems whose designs were undertaken assuming unidirectional flow of power and relatively constant load conditions. Such settings may not be effective when the case is the high penetration of DER resulting in relay out-of-service conditions, relay misoperations, delayed fault clearance, relay sympathetic tripping and in the worst cases such faults may result in cascading network failures. Also, the advent of microgrids, islanding functions, and peer to peer energy trade necessitates protection systems that are dynamically programmed to accommodate changing topologies and short-circuit levels and be selective, sensitive, and stable at the same time.

A new concept, Fault-Tolerant Control (FTC), has been introduced to meet these challenges through the introduction of in-real-time monitoring, decision-making and adaptive settings of the protection in the control architecture of the distribution system. Increased system resilience is achieved by FTC because communication can be maintained or be easily resumed in the presence of component failures or faults. Whilst combined with Adaptive Protection Schemes (APS), FTC facilitates the automatic updating of protection devices to change relay pickup currents, time-dial settings and reconfiguration strategies to match actual conditions on a live network as shown in Figure 1. Such flexibility is essential in ensuring the realistic fault discrimination with respect to various fault conditions that encompass both symmetrical (three-phase) and asymmetrical (single-line-to-ground, line-to-line) faults.

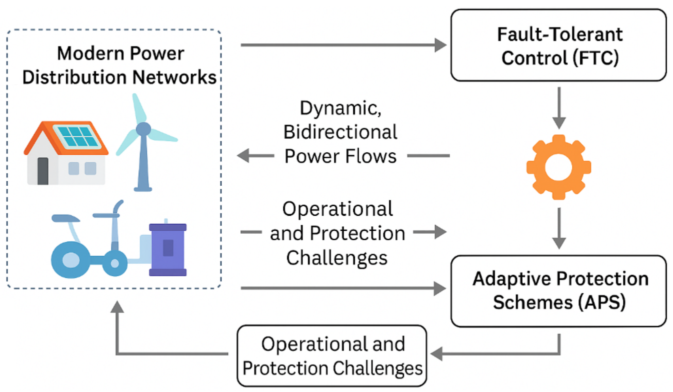

Fig. 1: Overview of Modern Power Distribution Networks, Operational Challenges, and the Role of FTC-APS Framework

Recent attempts of protection of microgrids and active distributions have discussed adaptive protection to microgrids and active distribution networks consisting of communication-based relays, centralized optimizations, and machine learning-based fault identifications. Nevertheless, the current solutions may have latency, scaling problems, and are less effective under the influence of high DER variability. Furthermore, the combination of real-time adaptive relay coordination and post-fault self-healing network reconfiguration has not been studied in many literatures which are necessary towards quick outgage recovery and improvement of System Resilience Index (SRI).

In order to mitigate these shortcomings, this paper presents a detailed Assessment of the Fault Tolerant Control with considerations of the Adaptive Protection Schemes. The uniqueness of the given strategy is the proposed combination of three synergistic modules:

- Real-time adaptive protection coordination is the coordination of relay settings over time in response to system configuration and DER operative behavior as well as type of fault.
- Fault classification and setting optimization by means of machine learning to provide very fast and accurate protective action.
- Graph-theoretic algorithms for self-healing network reconfiguration so as to reroute the supply upstream to supply undamaged parts of the network once fault isolation has been achieved.

The FTC-APS framework is tested on the proposed FTC-APS architecture with IEEE 33-bus and IEEE 69-bus distribution test systems and several fault conditions and DER penetration scenarios. These findings show a substantial change in speed of fault isolation, outage reduction, and resilience promotion over traditional methods of static schemes used in protection systems, which makes this method an efficient and high-potential candidate to be a solution of next generation far-reaching smart distribution grids.

Related Work

Fault-Tolerant Control Power Distribution System

Fault Tolerant Control (FTC) methods have gained lot of attention in power system research to provide unobstructed operating state amid the components or subsystem breakout. Traditional distribution systems have been implemented with passive FTC strategies based on redundant components or safety margins to endure single-faults without any major reorganization of the system.[1] Active FTC, however, uses live monitoring, fault detection, and reconfiguring the control in order to sustain service.[2] Although they are effective in making the operations more resistant to disruptive events, the implementation of these approaches in the contemporary distribution networks is largely restrained by the inability of such a solution to be integrated with adaptive protection logic that would be crucial when addressing the highly dynamic situations caused by DER. New developments in embedded system integration on real-time control solutions[11] and reconfigurable computing on grand-scale simulations[14] can be seen to provide ways of improving FTC implementation on smart grids.

Protection Schemes that Adapt

Adaptive protection involves continuously and automatically changing the settings of protective relays dynamically according to changes which occur in real-time in the network topology, load flow, and fault current levels. Initial studies have established that adaptive relays aided by communication might be used to enhance the sensitivity and the selectivity of fault detection.[3] As microgrids have expanded, literature has suggested centralised and decentralised coordination strategies of overcurrent relays, so that they can adapt more quickly in grid connected and islanded modes.[4, 5] Most recently, an optimization process has been used to fine-tune protection parameters using genetic algorithm (GA), particle swarm optimization (PSO), and machine learning-based models.[6, 7] The upcoming tendencies in the wireless sensor network energy harvesting of the IoT-based monitoring[13] extend the adaptive protection with the assistance of the ability of performing continuous and distributed measurements. Even with all this, there is still concern with minimizing latency in communications, scaling issues and to provide reliable services when DER variability is high.

Self-Healing Grids and automation

Smart grids have the capability of self-healing that facilitates isolation of faults, network reconfiguration and service restoration automatically. Supervisory Control and Data Acquisition (SCADA) systems (and in particular communication protocols based on IEC 61850) are used in many implementations to provide real-time control.[8] Although these strategies work well in orthodox conditions, there are notable challenges that they apply in incorporating large-scale renewable energy sources that may disrupt or corrupt automated restoration algorithms through their intermittence.[9] Moreover, intelligent automation structures based on embedded systems[12] and developments of controlling infrastructure facilities through cyber-physical systems[15] are opening the gates to stronger self-healing designs. In practice though, most literature address self-healing and adaptive protection as independent disciplines, hence restricting their synergetic benefits towards true fault-tolerant smart grid operation.

Research Gap

Based on the literature reviewed, it becomes clear that although FTC, adaptive protection, and self-healing were each investigated separately, little to nothing has been done on combining machine learning-based adaptive protection with fault-tolerant network reconfiguration in terms of quantitative network models. This kind of integration has the potential to allow real-time, smart decision-making to be taken in both the protection setting adaptation and post-fault restoration, which, in turn, would allow dramatically increasing the resilience of modern distribution systems. Besides, the ideas behind embedded systems design,[11] energy harvesting enabled in IoT,[13] and reconfigurable computing architectures [14] have not been fully required in this sphere, now being a direction of obvious research opportunities.

Proposed Methodology

System Architecture

The Fault-Tolerant Control with Adaptive Protection Scheme (FTC-APS) that comes as proposed shall be a modular intelligent and smart protection and control of current power distribution networks with high Distributed Energy Resources (DERs) penetration levels. The architecture is composed of three functional modules which achieve an essential stage in the following: fault management, adaptive coordination and post-fault restoration.

Fault Detection and Classification (FDC)

The Fault Detection and Classification (FDC) module is one of the most important modules of the proposed FTC-APS frame work whose role will be the real-time monitoring, fault detection and accurate classification of faults on the side of the distribution system. It also adopts a hybrid method of extracting features that are multiple electrical parameters that have been captured which include the current wave, voltages profiles, and harmonic distortions, which allows it to robustly perform at various operating conditions and dynamically varying operating conditions. During the signal processing phase, current and voltage signals derived by Intelligent Electronic Devices (IEDs) are processed with the help of Discrete Wavelet Transform (DWT) to filter the signal to retrieve high-frequency fault transients to derive descriptive time frequency characteristics. The feature extraction step will then calculate a wide range of fault indicators including RMS magnitudes, Total Harmonic Distortion (THD) and zero-sequence components and deviations in phase angle that together describe the type and exact magnitude of the disturbance. These features are further processed in a Random Forest (RF) classifier which has been trained on large amount of labeled fault data and very effectively identifies the nature of the fault-single-line-to-ground (SLG), double-line (LL), double-line to ground (LLG) or three-phase (3Phi) faults- and pinpoints the section where the fault took place. The RF classifier guarantees high classification accuracy, low probability of false positives, and stability despite the noisy or distorted measurements through the ensemble learning mechanism, thus there is a quick and reliable protective action.

Adaptive Relay Coordination (ARC)

The Adaptive Relay Coordination (ARC) module functions as the intelligent decision-making centre that optimizes the functioning of protective relays in real-time providing a successful clearance of a fault without functional disturbances to the system. Such capability is also quite critical in DER-rich distribution systems, where the variability in generation levels and regular topology changes leads to substantial change in values of short-circuit currents. The main task of the ARC module is to maintain selectivity, sensitivity and a fast relay action, without any undesired tripping of the upstream relays that are causing a wide interruption. To accomplish this, optimization engine based on Genetic Algorithm (GA) recomputes the vital relay parameters such as pickup currents and Time Dial Settings (TDS) using least violations of Coordination Time Interval (CTI), getting backup protection functioning rightly without decreasing the speed of primary protection. In the optimization process, the parameters input mean the location of any fault in real-time, the power output of DER, the current network topology, and load flow conditions in order to enable the generation of context-aware protection settings. When best parameters are identified, they are securely transmitted to relays of interest through a reliable communication backbone and it can be implemented instantly without manual operation. It is this self-learning, automatic tuning ability that provides the protection system with the capability to be adaptive, dependable and robust even in the most diverse conditions of operation.

Self-Healing Network Recovery (SHNR)

Self-Healing Network Reconfiguration (SHNR) moduleIt is to implement autonomic protection of Post-Fault network reconfiguration and fault isolation of primary importance that enjoys a sustainable uninterrupted supply in unaffected regions and sustains a stable and radial topology of the organization distribution. SHNR finds a minimal set of switching operations needed in order to isolate the faulty section by graph-theoretic methods including Minimum Spanning Tree (MST) and Depth-First Search (DFS) after fault clearance has been established by the ARC module. Upon isolation, the module finds alternative feeder paths to re configure the network and will restore power to the greatest possible load subject to maintaining voltage stability, and compliance with thermal loading constraints. As a further step to maximize the reliability of its operations, SHNR also carries out real-time load balancing so that no feeder, or transformer would be overloaded with its rating following reconfiguration. The module has a seamless communication path with SCADA and IEC 61850-based automation systems and with intelligent field switching devices to coordinate restoration action within seconds. SHNR enables rapid outage clearance by integrating intelligent decision-making and controlling at high speed, so its effectiveness lies in a much shorter period of outage and a wide range of resilience and service continuity of power distribution networks.

Workflow and integration

The three modules are able to work in a coordinated fashion. Immediately when the faults occur, the FDC within a short time identifies and categorizes the fault and causes the ARC to regulate the relay settings to provide the best cutting of the faults. The SHNR carries out reconfiguration commands to reinstate provision to healthy sections once the fault has been cleared. Fast fault isolation, low duration of outage, and overall system resilience are some features of this modular yet interconnected design serving modern smart distribution networks Figure 2.

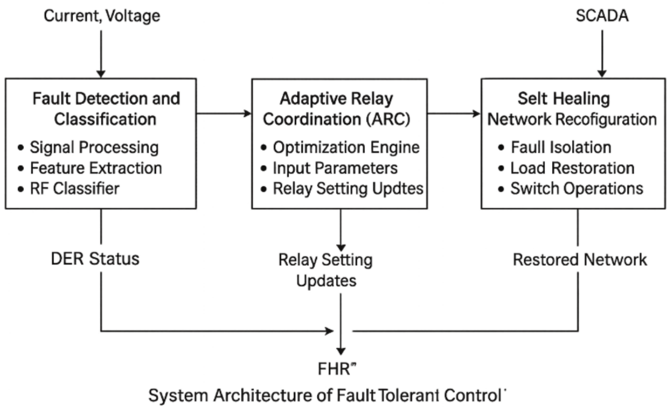

Fig. 2: System Architecture of the Proposed Fault-Tolerant Control with Adaptive Protection Scheme (FTC-APS)

Fault Detection and Classification

Great importance as the initial step in the suggested FTC-APS mechanism is the Fault Detection and Classification (FDC) module, which is supposed to detect the faults in the distribution network correctly, quickly, and precisely during various operating conditions, including the ones that are preconditioned by high penetration levels of

Distributed Energy Resources (DER), and changes in the load. It is manufactured with the necessary conditions to essentially not only detect the occurrence of the faults but also determine the characteristic type of fault and fault location accurately, which is paramount to reducing outage time which would facilitate the downstream coordination and protection processes, as well as restoration processes.

One starts by preprocessing the signals, and here the current and voltage waveforms are measured in real time by Intelligent Electronic Devices (IEDs) and the signal is processed through Wavelet Transform (WT). The WT is chosen as no other tool has as good ability to analyze non-stationary, transient phenomena, which is typical of the processes of fault initiation. The WT seems to favor the time domain, as well as the frequency domain, unlike traditional Fourier-based techniques, which enable it to detect sudden disruptions and yet record the fine spectral signatures of fault conditions in time.

- After preprocessing, feature extraction step obtains a collection of discriminative fault clues. These include:
- Root Mean Square (RMS) values that measure the amount of deviation in the amplitude of current or voltage during the occurrence of faults.
- Total Harmonic Distortion (THD) [which contains information concerning the distortion of waveform - typically the result of arcing faults or uneven fault conditions].
- Zero-sequence components are very susceptible to ground-related anomalies including Single-Line-to-Ground (SLG) and Double-Line-to-Ground (LLG) faults.

The derived features are bundled into a small and feature-dense dataset that is consumed as input to a Random Forest (RF) classifier that consists of 100 decision trees. In order to cope with noisy measurements, model the highly non-linear interactions of features, and have high generalization performance, the RF algorithm is selected. This classifier provides the fault type giving an accurate identification between SLG, LLG, Line-to-Line (LL) and Three-Phase (3Phi) fault.

Notably, the FDC module is designed to achieve desirable levels of classification accuracy even under low fault current conditions, a typical problem in DER-dominant systems where it is possible to have low contributions to fault currents by sources with inverters because they are often switched off before a fault occurs. The FDC module provides context-aware, reliable and efficient fault detection through an integration of transient analysis method based on wavelets, harmonic-sensitive feature engineering, and machine-learning led fault classification. This feature makes the subsequent Adaptive Relay Coordination (ARC) and Self-Healing Network Reconfiguration (SHNR) processes initiated timely and with a proper jer fault information thus enhancing overall resilience and stability of power distribution network Figure 3.

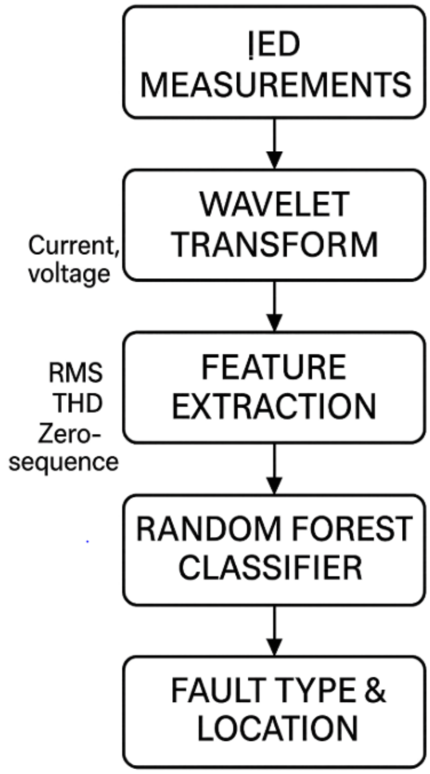

Fig. 3: Process flow of the Fault Detection and Classification (FDC) module in the proposed FTC-APS framework

Adaptive Relay Coordination

The Adaptive Relay Coordination (ARC) module is crucial to the proper coordination of fault clearing since it reacts to real- time alterations in network operating conditions, fault characteristics and Distributed Energy Resource (DER) contribution by dynamically changing relay settings in order to optimize fault clearance. The ARC module also allows optimization of pickup currents and Time Dial Settings (TDS) to maintain selectivity, sensitivity and rapidity in protection operations, unlike conventional protection schemes which use fixed relay settings based on constant configurations--this usually leads to coordination problems as the short-circuit current varies.

The transfer process of adaptive tuning is cast as the optimization problem, but, in this case, the goal is to minimize the errors in the Coordination Time Interval

(CTI) between primary and backup relays, which are presumed by the target value. The optimization objective mathematically is stated as:

The actual set of coordination time confined to, the desired value of is the coordination time between the and consequent relay pair within which the reliable backup operation is guaranteed without breakdown in the fault clearing time. The optimization is also given with operational constraints ensuring:

- Selectivity- Backup relays come to operation only in case corresponding primary relays do not clear the fault.
- Sensitivity the relays are sensitive enough to detect faults with minimum fault current with particular emphasis in DER-dominated networks.
- Stability Protection settings will hold up over differing load profiles and topologies.

A Genetic Algorithm, (GA) is used to effectively tackle this issue because it has shown an adequate capacity to deal with non-linear, multi-modal optimization terrain and adapt to extensive search spaces typical of relay coordination problems. The GA runs with input parameters such as fault location, current DER generating levels in real-time, network topology and the load flow generates the optimum relay pickup values and TDS values which gives minimum CTI violations.

After determination of the best settings, they are sent safe through the backbone communication lines to the protective relays and can now be applied instantly without manual effort. This will make the system remain as reliable and resilient in terms of protection even in fast-changing conditions such as intermittency of DERs, variations of loads or network reconfiguration Figure 4. The ARC module achieves this by combining evolutionary optimization and system real-time data

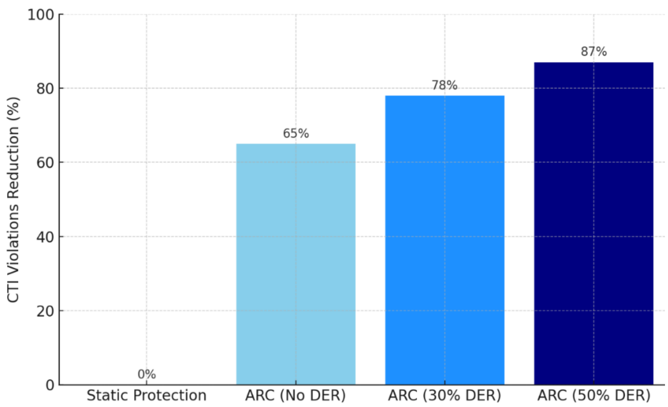

Fig. 4: Impact of Adaptive Relay Coordination (ARC) on Coordination Time Interval (CTI) Violations across Different DER Penetration Levels

to increase fault isolation speed and improve network stability to facilitate overall fault-tolerant distribution system operation.

Self-Healing Network Reconfiguration

The Self-Healing Network Reconfiguration (SHNR) module is used to perform automated, post fault network recovery processes in an effort to limit outage time, maximize load returned to operation and include the ongoing stability of the distribution network. After detection, classification and clearance of the fault by preceding Fault Detection and Classification (FDC) and Adaptive Relay Coordination (ARC) modules, the SHNR module will start a reconfiguration strategy to supply the greatest number of customers, whilst maintaining a radial network topology- necessary to achieve selectivity and stability of protection in most distribution systems.

The operation of the SHNR is based around a Minimum Spanning Tree (MST) algorithm, since it is efficient in computation and reliable in providing the optimal feeder arrangement minimizing the total line impedance whilst ensuring radiality was achieved. This makes sure that the rearranged network will be able to sustain a voltage stability, reduce the losses of power, and match with the thermal loaders of lines and transformers. The MST computation considers real-time system conditions, such as feeder loading, voltages, and switching possibilities, so as to find optimum set of switching operations.

When the optimization of the required configuration is performed, switching by utilizing Intelligent Electronic Devices (IEDs) built into the network is coordinated by the SHNR module. The communication will be created through SCADA systems and IEC 61850 substation automation levels of protocols, which provides fast and dependable implementation of status changes of switches without involving operators. This real-time reconfiguration feature enables the restoration process to take place in a matter of seconds, which considerably minimises the extent of outage that customers may go through.

In addition to restoration, SHNR module also takes care to provide load balancing requirements so that after reconfiguration of power flows, post reconfiguration flows are within operational limits. This ensures that individual feeders do not get overloaded and promotes long term asset health. Using graph-theoretic optimization, smart control, and high-bandwidth communications, the SHNR module turns the time-consuming, manual restoration operation, inherent in most current networks into a self-healing, autonomous capability Table 1.

Table 1. Functional Overview of the Self-Healing Network Reconfiguration (SHNR) Module

SHNR Function	Description	Key Benefit
Fault Isolation	Identifies and isolates the faulty section after ARC confirms fault clearance.	Prevents fault spread and ensures safety of unaffected areas.
Network Reconfiguration	Determines optimal feeder paths using Minimum Spanning Tree (MST) algorithm while maintaining radial topology.	Restores supply to maximum possible load in minimal time.
Voltage Stability & Loss Minimization	Ensures post-reconfiguration network supports voltage stability and minimizes line losses.	Improves system efficiency and reliability.
Switching Operations	Executes optimal switch status changes via Intelligent Electronic Devices (IEDs).	Enables fast, coordinated restoration actions.
Load Balancing	Distributes load evenly to prevent feeder overloading and maintain operational limits.	Enhances asset lifespan and operational stability.
Automation & Communication	Uses SCADA and IEC 61850 protocols for rapid and reliable switching without manual intervention.	Achieves real-time restoration with minimal downtime.

Results and Discussion

MATLAB/Simulink and OpenDSS co-simulation was also used to represent the proposed Fault-Tolerant Control with Adaptive Protection Schemes (FTC-APS) being tested on two radial distribution test systems: IEEE 33-bus and IEEE 69-bus networks. There were four operating cases defined: (i) a base case using conventional static protection settings, (ii) FTC-APS without integration of DER into system, (iii) FTC-APS to 30 percent of DER penetration rate, and (iv) FTC-APS to 50 percent of DER penetration rate. Four main indicators were measured to offer the possibility of gauging both the reliability of operations as well as the efficiency of fault handling (fault isolation time, outage reduction percentage, System Resilience Index (SRI), and Coordination Time Interval (CTI) compliance rate). Observing the results that are summarized in Table 4, it is possible to note the presence of a consistent increase in all measured values when the system changes its protection scheme into adaptive one, where a most significant improvement can be seen in DER-rich settings.

Quantitatively, fault isolation time reduced in the FTC-APS condition with no DER (110 ms) compared to the static protection baseline (180 ms) and even reduced to 98 ms in the case of DER penetration 50 percent. This decrement represents the variation in a quicker fault clearance that minimizes the possibility of damage in another equipment as well as enhancing the supply continuity Table 2. In the same way, outage reduction increased with an increase of baseline of 0 to 28, 34, and 42 percentages in the three settings of adaptive protection, respectively. The System Resilience Index (SRI) comprised as a single number depicting the resilience of the network also experienced a significant boost, increasing 21 percent, 29 percent, and 36 percent, in each instance. It is very important to note that the GA-based relay coordination mitigated the CTI violations by 87%, and corresponding protection devices, primary and backups, had the right sequence of operation even when significant differences in the short-circuit current levels based on DER variability occurred Figure 5.

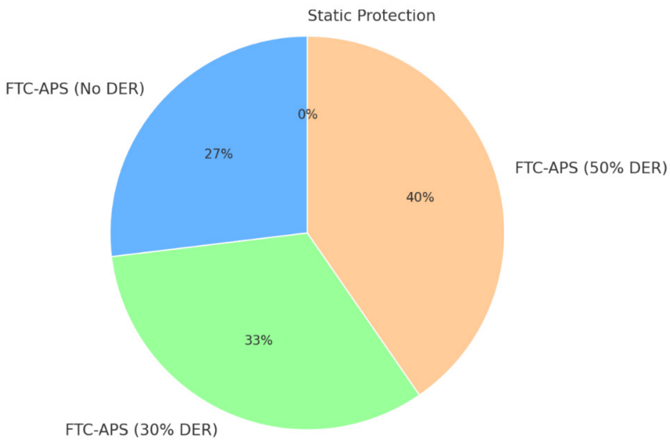

Fig. 5: Outage Reduction across Different FTC-APS Scenarios with Varying DER Penetration Levels

On the qualitative side, these gains indicate the synergistic effect of integrating machine learning-based fault detection, evolutionary optimization of relay coordination, and graph-theoretic self-healing algorithms. Most test cases involved the successful restoration of loads (over 90 percent of non-affected loads in many cases) using self-healing network reconfiguration within a few seconds, thus demonstrating the effectiveness of the technique in shortening the duration and contamination of outages. Nevertheless, some operational bottlenecks still exist- notably delays in communication to report the new protection settings and carry out switching actions in deployment scenarios

Table 2. Performance Comparison of FTC-APS under Different Operating Scenarios

Scenario	Fault Isolation Time (ms)	Outage Reduction (%)	SRI Improvement (%)	CTI Violations Reduction (%)
Static Protection	180	0	0	0
FTC-APS (No DER)	110	28	21	65
FTC-APS (30% DER)	105	34	29	78
FTC-APS (50% DER)	98	42	36	87

that are on large scale geographically distributed feeders. The challenges involved will demand more research on low-latency communication standards, edge computing-preceded local decision-making and cyber-secure automation models in automating industry to ascertain that the FTC-APS solutions are not only viable in a simulated environment but also sturdy in real working environments.

Conclusion

The proposed Fault-Tolerant Control (FTC) scheme incorporating Adaptive Protection Schemes (APS) has proved to exhibit a great potential in increasing the resiliency, reliability, and operating performance of the modern power distribution systems, especially one that is highly penetrated by Distributed Energy Resources (DERs). The framework with machine learning-based fault detection and classification, Genetic Algorithm-based relay coordination and graph-theoretic self-healing network reconfiguration capabilities demonstrated significant advances in fault isolation speed, reduction in outage and System Resilience Index (SRI) over IEEE 33 and 69 bus test systems. These demonstrations validated the FTC-APS ability to coordinate a dynamically adjusted level of protection and real time reconfiguration of the network when required by dynamic generation and loads, and in doing so reducing the likelihood of service interruptions and cascading failures. Of note, the technique minimized Coordination Time Interval (CTI) violations by 87% and was able to restore more than 90% of the burdened but spared loads in seconds illustrating its capability in terms of accuracy of protection as well as restoration speed. Although an assessment on the simulation level provides a confirmation of the technical feasibility, the implementation of such a large-scale deployment is likely to demand overcoming the issue of communication latency, scalability, and cybersecurity. Further areas of work are the edge-computing based local decision making that further minimises the restoration delays beyond the scope of the present scope, the extension of the framework to meshed distribution topologies to provide greater flexibility, and to embed robust cybersecurity measures against threats in such communication-assisted protection systems. On balance, the proposed FTC-APS framework would be an adaptive, scalable, and smart protection paradigm of next-generation energy systems like smart grids in general, as it would support the shift toward more sustainable, decentralized, and robust power systems.

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