DEVELOPMENT OF AN ADAPTIVE PROTECTION SCHEME USING FUZZY LOGIC FOR DISTRIBUTED GENERATION IN RADIAL DISTRIBUTION SYSTEMS

Zoxidov Iqboljon Zokirjonovich
Fergana State Technical University
E-mail:yoturk1986@gmail.com,
Xaqiqov Anvarjon Umidjon o‘g‘li
Fergana State Technical University
E-mail: haqiqovanvarjon@gmail.com

Abstract: While integrating distributed generation (DG) units—especially those based on renewable energy—into distribution networks has notable advantages, it also introduces coordination issues in protective relays. Traditional overcurrent protection settings are often rendered ineffective due to changes in power flow direction and short-circuit levels. This paper presents a novel fuzzy-logic-based adaptive protection scheme that dynamically adjusts Time Multiplier Settings (TMS) based on DG capacity and system configuration. A 13-bus radial distribution network was modeled using ETAP, and fault analysis was conducted under varying DG scenarios. The proposed system employs a Sugeno-type fuzzy inference controller designed in MATLAB, capable of modifying relay settings in real time. Simulation results demonstrate that the method successfully maintains coordination between primary and backup relays, ensuring system reliability and safety regardless of DG fluctuations.

Keywords: Distributed Generation (DG), adaptive protection, fuzzy logic, relay coordination, fault current, TMS, MATLAB, ETAP.

Аннотация: Хотя интеграция блоков распределенной генерации (DG), особенно тех, которые основаны на возобновляемых источниках энергии, в распределительные сети имеет заметные преимущества, она также создает проблемы с координацией защитных реле. Традиционные настройки защиты от перегрузки по току часто оказываются неэффективными из-за изменения направления потока электроэнергии и уровней короткого замыкания. В данной статье представлена новая адаптивная схема защиты на основе нечеткой логики, которая динамически настраивает параметры умножителя времени (TMS) в зависимости от мощности DG и конфигурации системы. С помощью ETAP была смоделирована радиальная распределительная сеть с 13 шинами, и проведен анализ неисправностей в различных сценариях DG. В предлагаемой системе используется контроллер нечеткого вывода типа Sugeno, разработанный в MATLAB, способный изменять настройки реле в режиме реального времени. Результаты моделирования показывают, что метод успешно поддерживает координацию между основным и резервным

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реле, обеспечивая надежность и безопасность системы независимо от колебаний DG.

Ключевые слова: Распределенная генерация (DG), адаптивная защита, нечеткая логика, координация реле, ток повреждения, TMS, MATLAB, ETAP.

Annotatsiya. tarqatilgan avlod (DG) birliklarini, ayniqsa qayta tiklanadigan energiyaga asoslangan—tarqatish tarmoqlariga integratsiyalashda sezilarli afzalliklarga ega, shuningdek, himoya o'rni bo'yicha muvofiqlashtirish masalalarini ham kiritadi. An'anaviy haddan tashqari oqimdan himoya qilish sozlamalari ko'pincha quvvat oqimi yo'nalishi va qisqa tutashuv darajasining o'zgarishi tufayli samarasiz bo'ladi. Ushbu maqolada DG quvvati va tizim konfiguratsiyasi asosida vaqt multiplikatori sozlamalarini (TMS) dinamik ravishda sozlaydigan yangi loyqa-mantiqqa asoslangan adaptiv himoya sxemasi taqdim etilgan. 13 avtobusli radial tarqatish tarmog'i ETAP yordamida modellashtirildi va xatolarni tahlil qilish turli xil DG stsenariylari ostida o'tkazildi. Taklif etilayotgan tizimda Sugeno tipidagi loyqa xulosa tekshiruvi ishlab chiqilgan MATLAB, Real vaqtda o'rni sozlamalarini o'zgartirishga qodir. Simulyatsiya natijalari shuni ko'rsatadiki, usul DG tebranishlaridan qat'i nazar, tizimning ishonchliligi va xavfsizligini ta'minlab, birlamchi va zaxira o'rni o'rtasida muvofiqlashtirishni muvaffaqiyatli saqlaydi.

Kalit so'zlar: tarqalgan avlod (DG), adaptiv himoya, loyqa mantiq, o'rni muvofiqlashtirish, xato joriy, TMS, MATLAB, ETAP.

Introduction.

In recent years, there has been a steadily growing interest in distributed generation (DG), particularly those technologies based on renewable energy sources like wind turbines and photovoltaic systems. As these technologies become more accessible and cost-effective, the penetration of DG into power distribution networks continues to rise.

The integration of DG into existing power systems brings numerous advantages. These include improved reliability of supply, reduction of line loading, minimization of transmission losses, and lower generation costs. Furthermore, the presence of DG helps postpone major investments in network expansion and reduces overall capital expenditures.

However, despite these benefits, the integration of DG into power distribution networks can also lead to several technical challenges. These include voltage fluctuation, increased fault current levels, and changes in the direction of power flow. Such changes affect the performance of protective relays, which were originally designed for traditional one-way power systems. As a result, coordination between primary and backup relays can be disrupted, especially under fault conditions or during system overload [1-3].

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The main goal of this study is to design an adaptive protection scheme based on fuzzy logic that minimizes the negative impacts of DG integration on protection coordination in radial distribution networks.

One of the key problems that arises when DG is added to distribution systems is the change in network topology. This change may occur whenever a DG unit is connected or disconnected from the grid for any reason. A static protection relay with fixed settings is not capable of responding correctly to these dynamic topological changes. This limitation can reduce the reliability and safety of the entire network.

To prevent maloperation of protection devices, relay settings must be dynamically adjusted each time a new network configuration is detected. This leads us to the concept of adaptive protection.

Adaptive protection can be defined as “an online process where protection settings are changed within a prescribed time in response to changes in system conditions or external signals and control actions” [4]. In modern systems with DG, adaptive protection can be implemented using microprocessor-based relays, which offer the flexibility to easily adjust protection characteristics as needed. With this approach, it becomes possible to improve relay sensitivity and reduce operating times.

The method proposed in this research is based on an online control mechanism that adapts the Time Multiplier Setting (TMS) of protective relays based on the current system state. These digital relays are designed to automatically update their settings according to changes in network topology and DG power level. As a result, overcurrent relays can be optimally selected and coordinated even when operating conditions change due to DG integration.

The proposed scheme allows relays to remain coordinated by ensuring they always respond to faults with correct timing. Even after DG units are added or removed, the system can reconfigure protection parameters without the need for additional hardware or manual recalibration [5].

The adaptive protection method introduced in this paper makes use of digital overcurrent relays capable of performing real-time data processing, communication, and logical decision-making. These relays monitor the network continuously, and update their settings online as fault current levels change due to DG activity.

One of the core ideas behind adaptive protection coordination is that fault current levels in DG-connected systems are no longer constant. They vary depending on the DG’s size, location, and operating state. As a result, the protection system must be able to respond to these changes in real time. To preserve the coordination between relays, especially the operating time of primary and backup

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relays, the Time Multiplier Setting (TMS) of overcurrent relays must be updated accordingly.

A new TMS value can be calculated using the following equation:

$$TMS_{Ri_{new}} = \frac{t_{Ri_{old}} * \left\{ \left(\frac{I_{fault_{new}}}{I_{Pickur}} \right)^{0.02} - 1 \right\}}{0.14} \quad (1)$$

Where:

$TMS_{Ri_{new}}$ −is the updated TMS for relay i.

$t_{Ri_{old}}$ − is the relay's operating time before DG integration.

$I_{fault_{new}-}$ is the new fault current after DG is connected.

I_{Pickup} − is the pickup current of the relay i.

This formula ensures that the relay continues to operate within acceptable coordination intervals, even when fault levels change due to DG connection.

However, real-time calculation of TMS using static equations may not be sufficient in complex or fast-changing scenarios. To make the process smarter and more autonomous, a fuzzy logic controller was developed to determine the optimal TMS value based on the real-time status of the DG.

The fuzzy controller is particularly useful because renewable energy-based DG units—such as wind and solar—are inherently variable. Their power output may fluctuate frequently due to environmental factors like sunlight or wind speed. Whenever the DG output changes, the fault current levels seen by relays may also change. To address this, the fuzzy controller automatically assigns an appropriate TMS value that ensures protection coordination is preserved.

The role of the fuzzy logic controller in this study is to interpret the output level of the DG and adjust the relay settings according to the new network configuration. The controller takes input from key parameters such as:

-DG power output (in MVA),

-Network topology status after DG connection,

-Relay sensitivity requirements.

A rule base is created that correlates different ranges of DG output with appropriate TMS values. This base is then fuzzified and processed through inference logic. The final output is a crisp, actionable TMS value, derived through defuzzification.

By mapping these fuzzy rules into a working controller, the system dynamically tracks the changing nature of the grid and updates protection relay settings accordingly—without human intervention. In effect, the network becomes self-adjusting in response to the presence or absence of distributed generators.

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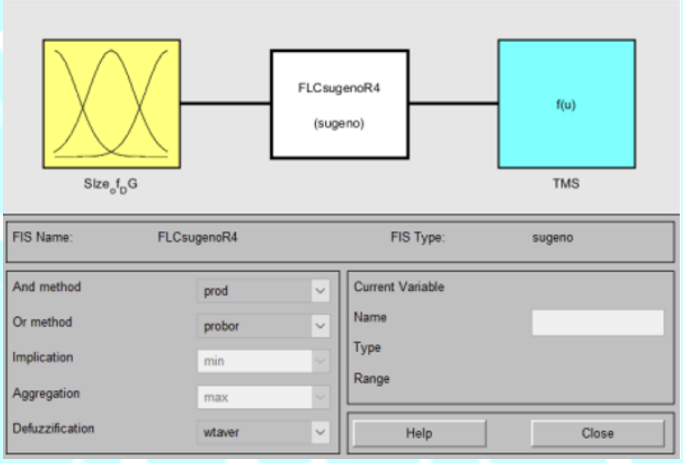


Figure 1: Fuzzy logic structure

The fuzzy logic system used in this study was designed and implemented in MATLAB. Figure 1 (referenced previously) not only illustrates the overall protection scheme, but also highlights the structure of the fuzzy inference system, including its rule sets and defuzzification methods.

In this work, a Sugeno-type fuzzy inference system was selected due to its effectiveness in real-time optimization and its suitability for control applications that require flexibility. In the zero-order Sugeno model used here, each rule's output is a constant value, which simplifies computation and makes it efficient for embedded use in digital relays. The fuzzy system processes uncertain or variable input data—such as DG output power—and converts it into a crisp value for the Time Multiplier Setting (TMS) of a protection relay. Specifically:

-The input variable is the installed capacity of the DG unit, varying from 0 to 8 MVA.

-The output variable is the optimal TMS value corresponding to the current operating condition.

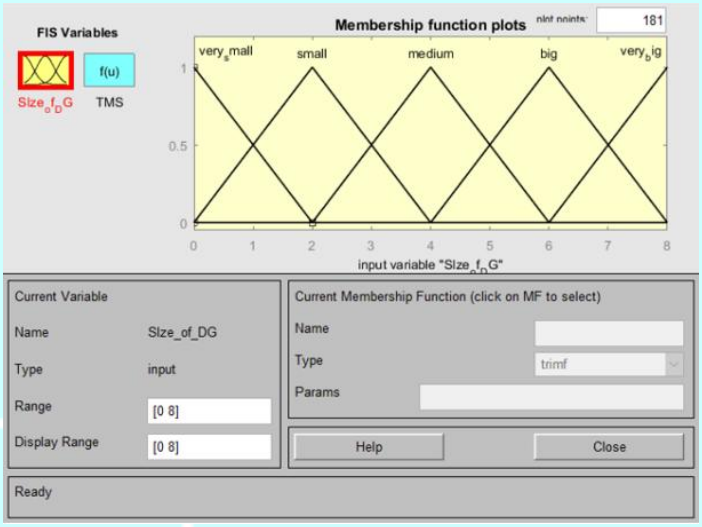


Figure 2: Rules window for the developed controller

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As shown in Figure 2 (not included here), the membership functions were defined for the input variable, allowing the controller to interpret any DG power level within the 0–8 MVA range.

To ensure that the generated TMS values are within practical limits, the fuzzy system was configured with boundary conditions:

-The lower limit of TMS corresponds to the value used when no DG is connected.

-The upper limit is the TMS needed when the DG operates at full capacity (8 MVA).

Once designed, the fuzzy controller was tested across multiple DG capacities. It produced unique TMS values for each case, and these were later used to update the relays' configuration automatically. This allowed the relays to maintain their coordination without the need for manual recalibration.

To assess the effectiveness of the adaptive protection system, fault current levels were compared before and after DG integration. Table 1 summarizes the fault current values at different buses under pre-DG conditions.

These values represent baseline conditions, where fault levels are relatively predictable and protection settings are fixed.

Table 1.

Fault location (Busbar)	1	2	3	4	5	6	7	8	9	10	11	12	13
Fault current (kA) when DG	9.75	7.71	6.24	5.94	5.42	5.19	4.86	4.51	4.24	4.13	4.6	4.33	4.58

Table 2 presents a more dynamic scenario: fault current levels after connecting a DG unit at Bus 2. As expected, the fault levels increased at nearly every bus due to the added contribution of the DG.

These results clearly show that the presence of DG alters the fault current distribution throughout the network. Without proper relay adjustment, these changes would likely lead to miscoordination between protection devices.

Table 2.

Fault current values when connected to DG bus 2

Fault location (Busbar)	Fault current with DG (kA)	Fault current contribution	
		From network	From DG
1	11.75	9.75	2
2	9.73	7.63	2.1

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3	7.55	5.92	1.63
4	7.12	5.58	1.54
5	6.39	5.01	1.38
6	6.07	4.76	1.31
7	5.62	4.41	1.21
8	5.16	4.05	1.11
9	4.81	3.77	1.04
10	4.67	3.66	1.01
11	5.27	4.13	1.14
12	4.93	3.87	1.06
13	5.26	4.13	1.13

The fuzzy controller plays a key role in addressing this issue. By recalculating the TMS for each relay based on DG capacity, the system keeps the relay coordination intervals consistent with their original values—even as the fault current landscape evolves.

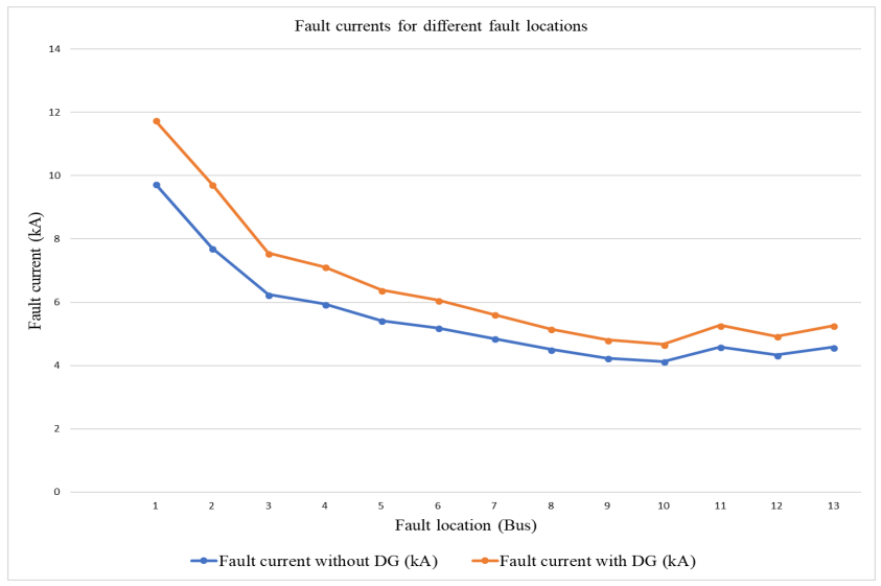


Figure 3: Comparison of fault currents before and after DG is connected to bus 2

To evaluate the effectiveness of the fuzzy logic-based adaptive protection system, multiple test scenarios were simulated (Table 3). In particular, two distributed generators with different power ratings (5 MVA and 3 MVA) were connected to Bus 2 of the network. The fuzzy controller then computed corresponding Time Multiplier Settings (TMS) for each protection relay. These updated TMS values were applied, and the resulting relay operating times and coordination time intervals (CTI) were recorded.

Table 3

The tire that caused the	Coordination pair	Main relay operating time	Backup relay operating time	Coordination time interval

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13	R24 – R12	0.3797	0.6749	0.2952
12	R22 – R20	0.0889	0.3861	0.2972
11	R20 – R12	0.3782	0.6742	0.2960
10	R18 – R14	0.1001	0.3970	0.2969
9	R16 – R14	0.0964	0.3934	0.2970
8	R14 – R12	0.3848	0.6806	0.2958
7	R12 – R8	0.6547	0.9483	0.2936
6	R10 – R8	0.6228	0.9150	0.2922
5	R8 – R6	0.8889	1.1874	0.2985
4	R6 – R4	1.1286	1.4219	0.2933
3	R4 – R2	1.3845	1.6811	0.2966
2	R2 – R1	1.4977	1.7902	0.2925

The coordination results for the 5 MVA DG scenario are summarized in Table 3. For each relay pair (primary and backup), the operating time and CTI were calculated based on the fuzzy-adjusted TMS values. Similarly, Table 4 provides the coordination data when a 3 MVA DG is connected to the same bus.

A comparison was also made with the base case, in which no DG is connected and default TMS settings are used. This allowed for a direct analysis of how closely the adaptive scheme could maintain original protection coordination.

Table 4

The tire that caused the	Coordination pair	Main relay operating time	Backup relay operating time	Coordination time interval
13	R24 – R12	0.3791	0.6742	0.2951
12	R22 – R20	0.0888	0.3850	0.2962
11	R20 – R12	0.3776	0.6742	0.2966
10	R18 – R14	0.0996	0.3962	0.2966
9	R16 – R14	0.0959	0.3924	0.2965
8	R14 – R12	0.3841	0.6802	0.2961
7	R12 – R8	0.6545	0.9454	0.2909
6	R10 – R8	0.6216	0.9131	0.2915
5	R8 – R6	0.8874	1.1844	0.2970
4	R6 – R4	1.1269	1.4192	0.2923
3	R4 – R2	1.3827	1.6784	0.2957
2	R2 – R1	1.4987	1.7919	0.2932

According to simulation results—illustrated in Figure 4 (referenced)—the relay operating times under both 3 MVA and 5 MVA DG integration were nearly identical. More importantly, these operating times were very close to the original values observed when no DG was connected at all.

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This indicates that the fuzzy logic-based adaptive protection scheme successfully preserved coordination between relays, regardless of the DG's size. The ability of the system to maintain consistent CTI values across all test cases demonstrates its robustness and flexibility in adapting to different grid conditions. Such consistency is crucial in distribution systems with intermittent renewable generation. If relay coordination is not maintained, protection systems can fail to operate selectively, leading to unnecessary outages or delayed fault isolation. The results of this study confirm that the proposed approach prevents such issues, enabling safe and reliable DG integration.

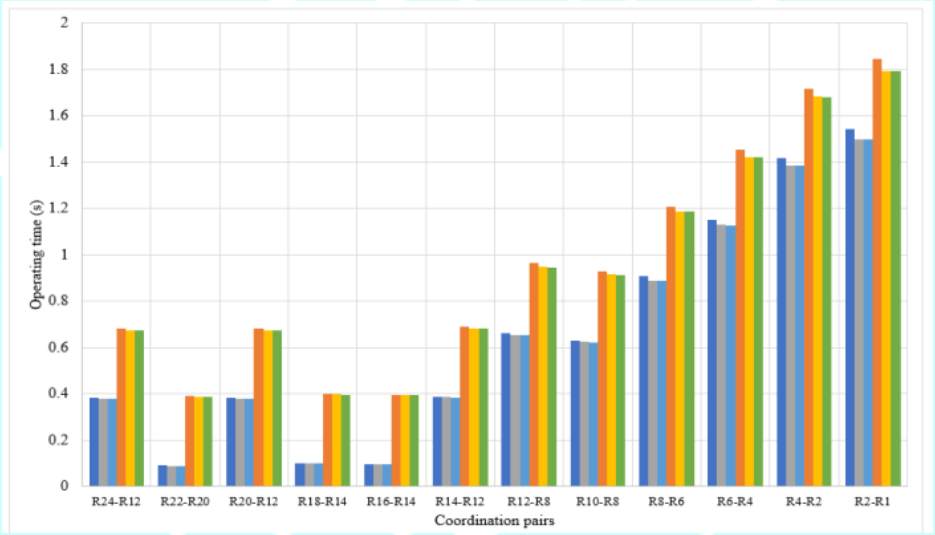


Figure 4: Comparison of tripping times for different coordination pairs after applying a flexible protection scheme based on fuzzy logic.

To further validate the effectiveness of the fuzzy logic-based adaptive protection system, four different scenarios were compared in terms of Coordination Time Interval (CTI) for relay pairs. These scenarios included:

1. Baseline condition: No DG connected; default relay settings used.
2. Non-adaptive condition: 2-bus connected to a DG, but old fixed settings were retained.
3. Adaptive condition, 5 MVA DG: 2-bus connected to a 5 MVA DG, with fuzzy-based adaptive protection applied.
4. Adaptive condition, 3 MVA DG: 2-bus connected to a 3 MVA DG, also using the fuzzy adaptive scheme.

The results of this comparison are illustrated in Figure 5, which displays CTI values for different relay coordination pairs under each condition.

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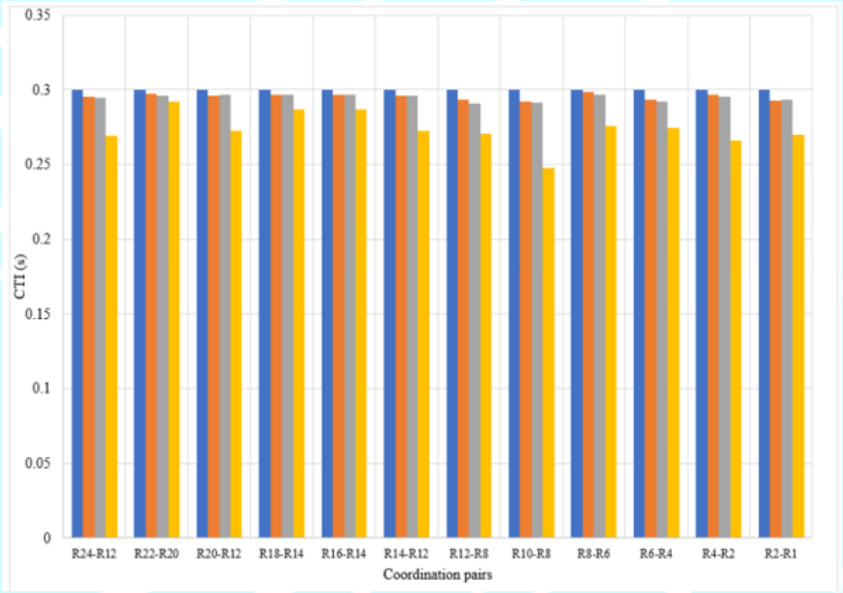


Figure 5: Comparison of coordination time interval (CTI) for different coordination pairs after applying a fuzzy logic-based adaptive protection scheme.

The baseline scenario (Figure 5), without DG, showed a consistent CTI of approximately 0.3 seconds for all relay pairs. However, when DG was added without adapting the relay settings (Scenario 2), CTI values significantly decreased, often falling below the acceptable threshold for reliable coordination. This behavior poses a risk of protection failure or delayed backup relay response.

In contrast, both adaptive scenarios—using fuzzy logic to adjust the Time Multiplier Settings—demonstrated a restoration of CTI values. Whether the DG capacity was 3 MVA or 5 MVA, the fuzzy-controlled TMS allowed the coordination intervals to return to values very close to the original 0.3 seconds.

These results confirm that the proposed adaptive protection scheme effectively preserves the timing relationships between primary and backup relays, even when the network experiences dynamic changes due to DG integration. Maintaining consistent CTI ensures that the system remains selective, reliable, and secure—even under conditions of variable generation.

By comparing all four scenarios, it becomes clear that fuzzy logic provides a practical and scalable solution to protection coordination challenges in modern distribution networks.

Conclusion.

This paper has examined the challenges that arise in overcurrent protection when distributed generation (DG) units are integrated into radial distribution networks. The findings clearly show that connecting DG can significantly alter the fault current levels observed by protective relays, thereby changing their operating times. As a result, the coordination between primary and backup relays may be lost, especially if traditional, fixed protection settings are used.

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The underlying problem stems from the fact that standard relay configurations are typically based on a static, unidirectional power flow model. When DG is introduced—especially from renewable sources with fluctuating output—these assumptions no longer hold true. Fault current magnitudes and directions can change dynamically, and relay systems must adapt accordingly.

In networks with high DG penetration, it becomes increasingly important to implement protection schemes capable of maintaining coordination under varying conditions. One effective solution is the application of adaptive protection systems that automatically adjust relay settings in response to network changes.

This study proposed such an adaptive protection scheme using a fuzzy logic controller. The controller evaluates the size or capacity of the connected DG and determines the most appropriate Time Multiplier Setting (TMS) for each relay. By doing so, it ensures that protection coordination is preserved and the system remains selective and safe.

Simulation results confirmed that the fuzzy logic-based approach can maintain relay operating times and coordination intervals nearly identical to those observed in pre-DG conditions. Thus, the proposed scheme enables the reliable integration of DG without compromising the performance of the protection system. In conclusion, fuzzy logic offers a practical and intelligent method for managing the complexity of modern power distribution networks, ensuring that both protection and coordination are maintained in real time.

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