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Impacts of Distributed Generation on Power System Protection

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Abstract: Distributed generation (DG) offers huge benefits to the power system network to cater to the rapidly growing demand for electric power. The integration of DG units into existing power networks is beneficial to both utilities and consumers. However, the installation of DG units in distribution networks might impose some operational, technical, and economic impacts. Increased short-circuit level and changes in load flow direction are examples of the technical issues arising from the high penetration of DG. Such issues will affect the existing protection system, mainly overcurrent relays. Thus, to ensure reliable and selective operation of protection relays, the impacts of DG should be considered. This paper discusses the impacts of DG on the protection systems by identifying various protection problems. The paper is complemented by a simulation case study on the impacts of DG on fault levels, protection coordination, and distance relays. The simulated system was modeled using DIgSILENT PowerFactory® software.

Keywords: distributed generation, protection, fault current, relay, protection coordination.

1. INTRODUCTION

Distributed generation (DG), which might be referred to as dispersed generation or embedded generation, is nowadays very common in electric systems. Broadly speaking, DG units are those installed on the customer side of the electric network or generally in the distribution networks (DNs). In fact, the definition of DG is not consistent. Generally, it can be defined based on its capacity and location. However, some entities define DG based on other characteristics, such as being renewable, having cogeneration, and being non-dispatchable. Furthermore, there are different types of DG units, such as photovoltaic systems, thermal solar power systems, wind turbines, biomass-based generation units, and storage systems [1].

The integration of DG into electric power networks is beneficial to both utilities and consumers. Such introduction of DG into DNs will have positive impacts such as reducing technical losses, supporting the voltage profile, improving power reliability, releasing transmission and distribution lines' capacities, and shaving peak demand. Moreover, integration of renewable-based DG leads to reducing both fossil fuel consumption and greenhouse gas emissions [1], [2].

Despite the benefits mentioned above, there are several negative technical impacts that DG units might impose on the electric distribution system. Below are some common technical impacts arising from the high penetration of DG into DNs [3].

A. Power Quality

Even though DG units are used to enhance power quality, these units can also contribute to deteriorating power quality in some cases as discussed below:

1) System frequency: The imbalance between demand and supply can result in frequency deviation from the rated value. Moreover, the connection of DG is likely to affect the system frequency as it consists of independent small power sources [3].
2) Voltage Level: The impact of the grid-connected DG units on the voltage level can be significant. It will not be an issue for a system facing low voltages, but it can result in additional problems in some other cases [3].

B. Change in Power Flow and Short-Circuit Level

In traditional distribution systems, power flows unidirectionally from high voltage to low voltage. Furthermore, it may flow bidirectionally at some medium voltage levels, especially in ring systems. However, with the DG units connected to the grid, the power is expected to flow bidirectionally or even multidirectionally, as DG units can induce reverse power flows from the lower voltage to higher voltage levels. Moreover, DG will generate a current that partially contributes to the short-circuit level of the network. Even though the contribution of a single DG unit may not have a significant effect on the fault current, several DG units connected to the same network will definitely make a considerable contribution to the short-circuit level [3], [4].

C. Reactive Power

Some DG units such as asynchronous generators are not capable of generating reactive power. However, DG units that use power electronic interfaces can supply some amount of reactive power [3].

D. Power Conditioning

Many DG units, such as fuel cells and solar PV systems, produce direct current; thus, these sources use a DC–AC interface with the grid. Such power electronic interfaces contribute to higher harmonics. Furthermore, they have no physical inertia to respond to rapid changes in the power balance. The same issue can appear in variable-speed wind turbines [3].

E. Protection

Identifying the impacts of DG on system protection is essential, as the system's reliability could be jeopardized. As mentioned above, the presence of DG may lead to changes in both the direction of the fault current and its magnitude. These two changes can cause some coordination problems [2], [5]. Another significant impact appears when customers are allowed to operate in islanding [3].

The influence of DG on the protection system depends upon the DG penetration level, as well as the characteristics and interface of the DG units. In general, DG units connected to the grid can reduce the effectiveness of the protection system. Therefore, the protection scheme must be changed accordingly. The main impacts of DG on power system protection include miscoordination between protection elements, reduction in the reach of the relays, unsynchronized reclosing, protection system blinding, unintentional islanding, sympathetic tripping, and nuisance tripping of generating units [2], [4], [5].

This paper aims to conduct a literature survey on the impacts of DG on the protection system and the possible and effective solutions for a reliable operation of DNs.

This remainder of the paper is organized as follows: Section 2 describes the traditional protection system used in DN. Section 3 discusses the impacts of the DG on power system protection. Section 4 presents an overview of the protection system in the presence of the DG, including some proposed protection strategies. To simulate the impacts of DG units integration on distribution networks, section 5 presents a case study using DIgSILENT PowerFactory® software. Finally, Section 6 presents the main conclusions.

2. Traditional Protection System Without DG

The conventional distribution systems mostly have a radial configuration where the supply is only from one side. Thus, protection schemes' design is a simple straightforward task. The protection system of such a conventional network consists mainly of overcurrent relays, auto reclosers, and even fuses. Usually, the protective relays are installed at the sending end of the power source, specifically at the outgoing feeders. With such a design, those relays will protect the downstream parts of the circuit.

Moreover, in many cases, fuses will be added to the DN protection where reclosers or inverse overcurrent relays are usually installed at a distribution substation, while fuses are used at the laterals, as illustrated in Fig. 1. This protection configuration works effectively, since no supply is expected from the downstream, but it is not valid anymore in the presence of DG units [2], [6]. Protection coordination is well maintained between the fuses, AR, and relays assuming a radial system; thus, introducing DG units to the DN will cause miscoordination, as the system is not more radial [6].

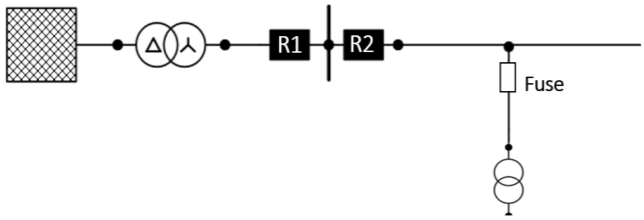

Fig. 1. Conventional Protection System Configuration

3. Impacts of DG on Power System Protection

Integration of DG into the DN causes the following network impacts:

A. DG Effect on Fuse and Auto Recloser Operation

Fuses are high-speed protection devices that need to be replaced once they blow. Nevertheless, 70–80% of faults on DNs are transient; hence, it is reasonable to apply a fuse-saving strategy to save the costly fuses. Fuses are saved during transient faults by de-energizing the line with faster protection devices, mostly auto reclosers (ARs). The AR will then automatically re-energize the line after some time delay. Such AR-fuse coordination is achieved by the time-current characteristics curves. Adding DG to the network will increase the fault level. Thus, the AR–fuse coordination will be affected, leading to operating the fuse first or simultaneously with the AR. The impact of DG on the AR–fuse coordination depends on the DG location, capacity, and type [4], [5].

B. Impact of DG on Automatic Reclosing (AR)

Penetration of DG might cause another problem to the AR operation regardless of the existence of a fuse. AR is used to clear the transient fault in the radial network by operating the protection device in the front of the fault as only one power supply exists. AR is intended to reclose the faulty line from the source end while the other end is unenergized. Conversely, in the case of DG, the system configuration will change to a loop or ring system, as the DG will act as another power source. Therefore, both sides of the faulty line might be energized, hence obstructing AR service. However, once the fault occurs, DG units are expected to be isolated before the reclosing time has elapsed to have a successful reclosing. The DG isolation speed has an impact on the system, as slow disconnection will prevent timely clearance of transient faults. In the case of islanding operation, the DG operation will continue even when AR is operated. This will prevent timely clearance of the fault. Consequently, the fault might develop into a permanent fault. Such an act will further impact the DN reliability, as the outage time will increase. Moreover, network equipment, including DG, will experience high stress due to unsuccessful AR operation [4,5]. The effects of DG connection on AR operation are illustrated in the study case presented in [7].

In addition, according to [4], protection issues related to AR operation in the presence of DG can be extended beyond obstructing AR operation to incorrect tripping of feeders, out-of-phase reclosing, and protection blinding.

To overcome the AR issues, utilities include AR as part of anti-islanding protection. However, mandating anti-islanding protection in the DG might not be enough to overcome these issues. In addition, utilities might need to increase AR deadtime to give more time for DG units to be disconnected. On the other hand, increasing AR deadtime will increase the outage time, affecting network power quality [4].

C. Impact of DG on Protection Coordination

Protection coordination aims to achieve selectivity in the protection system, whereby only the faulty part of the system will be isolated upon the occurrence of a short circuit. The selectivity in the protection system is maintained by relay coordination, as the relay closest to the fault will act first, and upstream relays will operate after a certain time delay if the fault is not cleared yet. DN protection provides separate protection for each feeder. Thus, the faulty feeder will be isolated without affecting the healthy feeders. Such a protection system will work correctly under unidirectional power flow. However, the case is no more valid in the presence of DG units as bidirectional power flow is expected [4]. Thus, DG penetration may lead to miscoordination where some healthy feeders may be disconnected during the fault. The impacts of the DG on the protection relays coordination are discussed below:

1) Mal-trip

Maloperation of the protection device is present when the healthy feeder trips instead of the faulty feeder. This case can occur when DG units in a healthy feeder feed a fault into the upstream network. Such a wrong relay operation happens when a nondirectional protection device is used for feeder protection [4].

In many cases, such false tripping of the feeder can also be referred to as sympathetic tripping, where the feeder protection is operated for a fault on the adjacent feeders, as illustrated in Fig. 2 [8], [9].

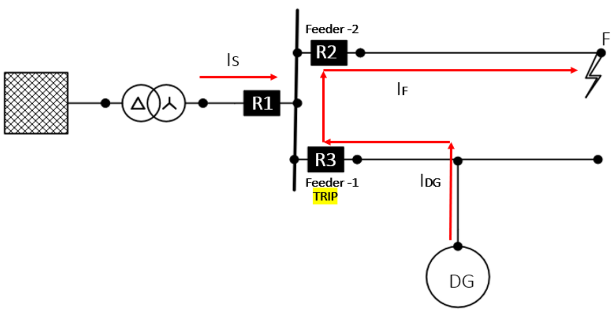

Fig. 2. Sympathetic Tripping

2) Fail to Trip

Protection system failure can be referred to as protection blinding. This failure occurs when the relay does not sense the fault current. Such failure may occur during a downstream fault where the grid's fault current contribution is decreased due to the presence of the DG unit. Thus, the current measured by the feeder protection could be less than the relay threshold; hence, the relay will not operate [4], [8].

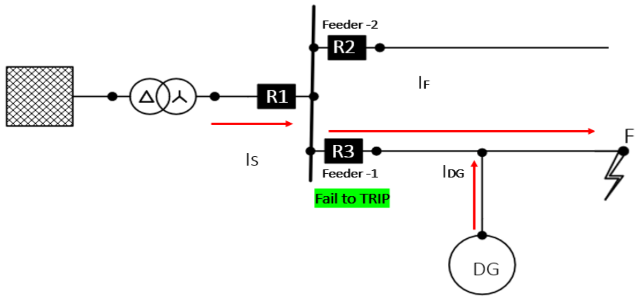

Fig. 3. Protection Blinding

Fig. 3 shows an example of protection blinding, as the main protection R3 did not sense the fault, as the contribution from the source is less than the required threshold.

However, DG's effect on protection coordination might be limited for small-capacity DG units. [10] studies the effect of DG penetration level on the protection coordination, stating that different protection issues will begin at a certain DG penetration level. Moreover, protection coordination issues are further discussed in [6] with multi-DG units connected to the system.

To mitigate the negative impacts of integrating DG into DNs on protection system coordination, several factors are to be considered [4]:

1) The protection system should be able to operate during a failure of parallel operation of DN and DG units.
2) DG units' protection should be provided, as DG units might experience several issues due to network disturbances such as AR.
3) The increased short-circuit level due to the high DG penetration in the system is to be considered.

D. System Undesired Islanding

Usually, standards do not permit islanding operation, as it can lead to reliability and safety issues. However, in some standards, such as the Oman Electricity Standard (OES), islanding mode can be permitted by the local distribution utility in emergency cases. In such cases, islanding protection is usually a part of the prevailing standards to prevent islanded operation [4], [11].

DG units connected to DNs are usually equipped with interface protection against frequency and voltage deviations. Also, DG units are to be disconnected from the grid during abnormal conditions such as short circuits [5].

E. Reduction in Reach of Impedance Relays

Impedance relay or distance protection is mostly used in transmission lines. Such relay operates within defined impedance zones. It measures the line impedance at the relaying point to the fault point and compares it with preset values to detect faulty conditions. Thus, the relay operates only if the measured impedance value is less than preset values on the relay. Moreover, relay response times vary based on the fault location or, in other words, the protection zones in the relay. Furthermore, an important terminology in impedance relay is the "reach of the relay," which is the minimum fault current at which the relay can operate. The reach of the relay can be referred to as the maximum distance at which the relay can operate [4].

Introducing DG units to a line protected by an impedance relay will increase the reach of the relay. For a fault downstream of the busbar where DG units are connected, the relay will measure an impedance bigger than the actual fault impedance. Therefore, this will affect the relay accuracy, as it might sense the fault to be beyond its zone of operation. This phenomenon is referred to as "underreaching." The DG unit size and location will affect the impedance relay underreaching [4].

The relay underreach can be illustrated using Fig. 4, where for a fault at point *F*, the currents *IF*, *IS*, and *IDG* are the fault current, the current through the relay from the grid during the fault, and the DG unit's current contribution to the fault.

For instance, the DG unit's impacts on the impedance relay will depend on the unit's location and size. Hence, for a DG unit installed at the end of the feeder, the impact on the impedance relay will be high, as the fault current coming from the grid *IS* will be less. Thus, the measured impedance will be high, leading to relay underreach. The same impact is expected when the DG capacity is higher: higher DG current contribution to the fault *IDG* and less *IS*. The lower the current from the grid, the higher the impedance measured by the impedance relay and the higher the percentage of the relay underreach. In general, the presence of DG units in the system will lead to a change in the apparent impedance of the line, which will cause the impedance relay to misestimate the actual line impedance [4].

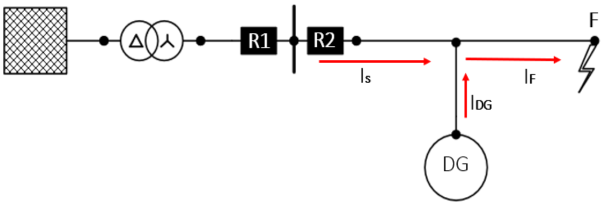

Fig. 4. Impedance Relay Under-reach

The impact of DG on distance protection performance goes to different extents. For instance, DG can affect different power system parameters such as the source to line impedance ratio (SIR), which affects system elements such as capacitive coupled voltage transformers, thus indirectly affecting the distance relay [12].

Revising the impedance relay setting might solve the relay underreach issue, but the setting needs to be revised every time the DG unit is connected or disconnected, which might not be a reliable solution [4].

4. Case Study

A typical DN is simulated in DIgSILENT PowerFactory software, to investigate the impacts of DG on power system protection. The system, shown in Fig. 5, consists of a 33kV grid station modelled by a voltage source, feeding a 20MVA 33/11kV substation through a 30 km OHL. Additionally, two typical 11kV feeders with a length of 7 km each are modelled. A 4.8MVA DG unit is installed on feeder 1 at 500 m from the substation.
ABB REF 615 Overcurrent/Earth Fault (OC/EF) relays are installed at the 11kV transformer income and both 11kV outgoing feeders 1 and 2 with settings as shown in TABLE I.

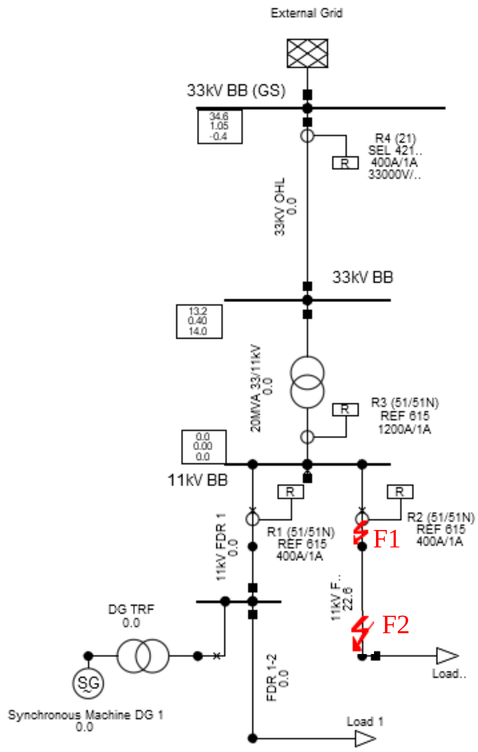

Fig. 5. A typical DN

TABLE I. OC/EF RELAYS SETTING

Setting/ Circuit	OC Setting			EF Setting		
	I pickup	*Curve*	*TMS*	*Ie pickup*	*Curve*	*TMS*
11kV TRF I/C	1200	IEC Normal Inverse	0.1	120	IEC Normal Inverse	0.1
11kV FDR 1 & 2	400	IEC Normal Inverse	0.05	40	IEC Normal Inverse	0.05

The 33kV OHL is equipped with a SEL 421 distance relay with zone 1 covering 85% of the line, zone 2 covering 120% of the line, and zone 3 covering 150% of the line plus 150% of the transformer impedance.

Different fault scenarios are simulated to investigate the DG unit impacts on the fault level, OC/EF protection coordination, and distance relay's reach.

A. DG Impacts on Fault Level

A fault was created at point F1 to observe the impact of DG on the fault current level. As shown in TABLE II, both phase and earth faults current increased by more than 20% once the DG unit is connected to the system.

TABLE II. DG IMPACTS ON FAULT LEVEL

Scenario	*With DG (A)*	*Without DG (A)*	*Change (%)*
3Ph fault at F1	8815	6578	+25%
Ph-E fault at F1	10864	8381	+23%

B. DG Impacts on Protection Coordination

The OC/EF relay coordination is expected to be disturbed in presence of the DG unit. TABLE III shows the OC relay operating time for a fault at point F2.

TABLE III. OC RELAYS OPERATING TIME

Scenario	*With DG (Sec)*	*Without DG (Sec)*
11kV FDR 2	0.178	0.19
11kV FDR 1	0.623	No operation
11kV TRF I/C	1.29	1.05

For a fault at F2, the current contribution from the DG has increased the operating time of the 11kV incomer relay which serves as backup protection for the 11kV feeder relays. The DG impact on relay coordination is more substantial for scenarios in which the fault is closer to the DG unit location. Sympathetic tripping occurred on the 11kV feeder 1 during earth fault on feeder 2 at point F1. Fig. 6 shows the time overcurrent curve where 11kV feeder 1 EF relays operated at the same time as faulty 11kV feeder 2.

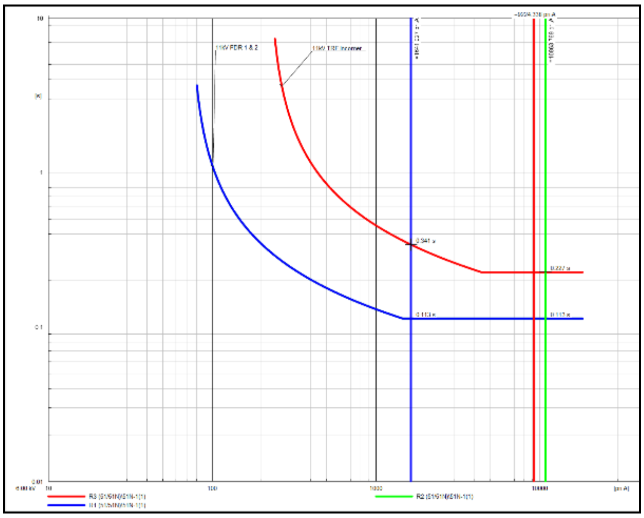

Fig. 6. Time Overcurrent Curve for EF at F1

C. Impact on Distance Relays

The distance relay is the main protection for the 33kV OHL, and it works as a backup protection for downstream relays by means of zones 2 and 3. For instance, distance relay zone 3 will operate for a fault at point F2 as shown in Fig. 7.

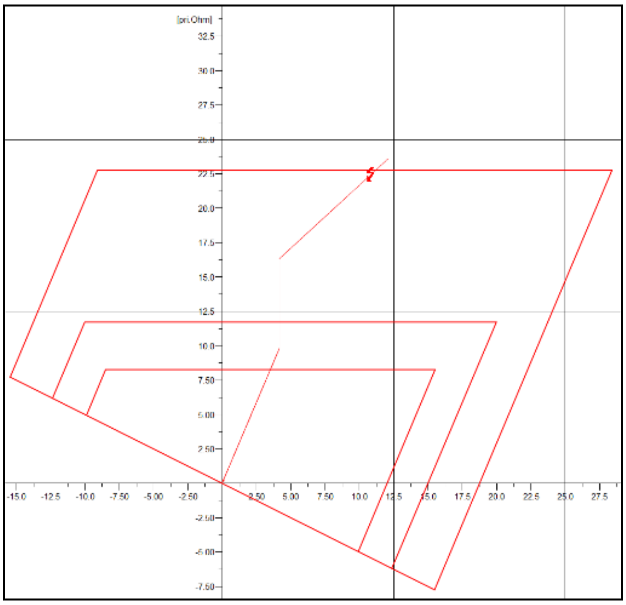

Fig. 7. Distance relay operation for a fault at F2 without DG

However, the presence of the DG will cause the relay to underreach as illustrated in Fig. 8. The fault point is within zone 3 reach, yet the measured impedance by the relay during the fault is more than the zone 3 setting.

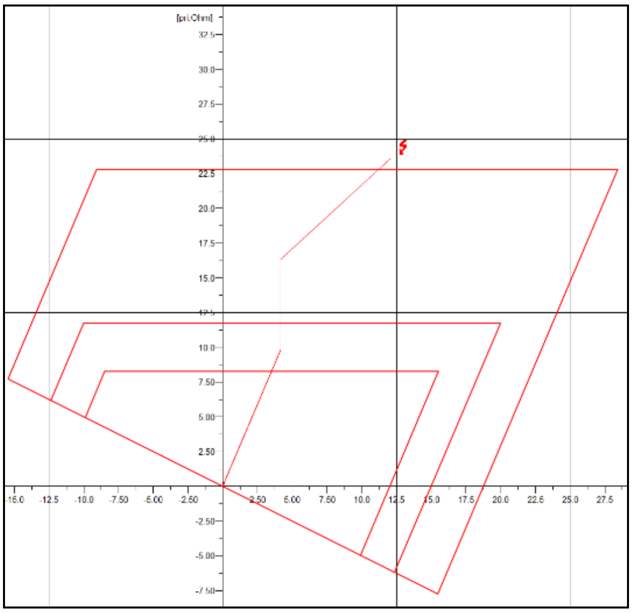

Fig. 8. Distance relay operation for a fault at F2 with DG

5. PROTECTION SYSTEM IN PRESENCE OF DG

Integration of DG into DNs requires a protection system capable of handling the multidirectional power flows and different power system conditions that result from DG penetration. Moreover, the DG must work in islanded mode and stay connected even during short circuits to increase system reliability and provide ancillary services to provide voltage and frequency support at the point of common coupling [9].

Several studies discuss the protection systems in the presence of DG, yet no standard methodology is proposed. However, two strategies are usually discussed: 1) isolating the DG during faults; 2) modifying the existing protection system design.

The first strategy assumes DG units are disconnected during faults, thus permitting a small change in the short-circuit level while relying on the conventional protection system. However, depending on the size of the DG units, this option can cause some stability issues. Moreover, this strategy goes against most regulations that require the DG unit to remain connected during power quality disturbances to provide support to the network.

The second strategy proposes introducing changes to the protection system design to cater to the presence of DG. It depends on different techniques such as modifying the protection system, applying new functions, limiting the fault current, and utilizing communication links. Using this strategy might be costly and unreliable. Other approaches are proposed, such as adaptive protection algorithms and regional protection schemes, which divide the microgrid into smaller grids based on directional protection [13].

[14] studies the effect of DG allocation on the protection system, mainly the short-circuit level, and based on that, it proposes an approach to including the DG impacts on the protection system during the planning stage.

5. Conclusion

Installation of DG in the DN provides several advantages to the system, such as loss reduction, voltage support, power reliability improvement, and peak shaving. Despite these benefits, the wide deployment of DG in DN might impose negative impacts on the system power quality, power flow direction, system conditioning, and system protection. Identifying the impact of the DG on the existing protection system is essential to maintain the system reliability. In general, DG's impacts on the power system depend on the DG size, characteristics, type, location, and interface. Traditional DN protection systems mainly consist of time-current coordination protection devices, including overcurrent earth fault relays, ARs, and fuses. Those protection devices are affected by changes in the power flow and the short-circuit level. DG impacts extend to different protection system elements, such as impacts on fuses, auto reclosers, inverse time relays, and impedance relays.

The case study demonstrated that the presence of DG in the simulated test system resulted in increasing both phase and earth faults current. It was demonstrated that the impact of DG integration on relay coordination is more substantial for scenarios in which the fault is closer to the DG unit location. In addition, it was demonstrated that the integration of DG can cause distance relays to underreach.

Hence, improving the protection system is mandatory, as the traditional protection system might fail when the DG penetration level is high. While there is no single solution for these issues, utilities ought to improve the existing protection systems or provide new reliable protection systems.

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