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Original Article

Overcurrent Protection Scheme for Industrial Distribution System with Decentralized Power Generation Resources

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Abstract - *There has been a potential rise in the usage of renewable energy sources in the distribution system over the past few years because of advantages like less power loss, improved voltage regulation, reliability, and environmental friendliness. In spite of these advantages, these sources, known as Decentralized Power Generation Resources (DPGRs), cause alteration of system parameters. Bidirectional power flows, increased and variable fault currents can lead to protection miscoordination, nuisance tripping, and reduced system reliability. An adequate protection should be provided for reliable protection and operation of the distribution system. An Overcurrent Protection (OCP) scheme for Industrial Distribution Network (IDN) with Decentralized Power Generation Resources (DPGR) with a Fuzzy Logic-based controller is proposed in this article. Simulation of the suggested Over Current Protection (OCP) is done through ETAP software, incorporating Decentralized Power Generation Resources (DPGRs) in the Distribution System. Impact of Decentralized Power Generation Resources on protection system and protection coordination is verified in a site study. Results demonstrate that the proposed scheme reduces fault clearing time, minimizing false operations and enhancing system stability, and it offers a better solution for modern grids and a directing way for future development and enhancement in adaptive protection strategies.*

Keywords - *Decentralized Power Generation Resources, Fuzzy Logic, Industrial Distribution System, Overcurrent Protection, Protection Coordination.*

1. Introduction

An increase in power demand requires large power generation units, which are far away from the load end, and requires the installation of a long transmission and distribution line network for power to reach the load end. These power generation units, being non-renewable, cause pollution, and because of the transmission and distribution line network, there is an issue of power loss and voltage drop. This encourages the usage of Decentralized Power Generation Resource (DPGR), also known as Distributed Generation (DG) Sources, which is an electricity generation facility [1] connected at the consumer end or in the distribution network.

Integration of Distribution Power Generation Resources (DPGRs) like Solar PV, Wind Energy Systems into modern electrical distribution networks has revolutionized energy production and consumption paradigms. These sources have many benefits and drawbacks (as shown in Figure 1) when implemented in distribution networks [2-13], but their proliferation introduces challenges to traditional protection coordination schemes, particularly in managing overcurrent protections which can arise from bidirectional power flows, an increase in fault current magnitude, variable generation patterns from DPGRs, and fault conditions. Apart from increasing fault current, these sources will also increase normal system current, which leads to the upgradation of protection and switchgear components. Factors that affect protection coordination in terms of Decentralized Power Generation Resources are their types, size, location, and number of sources connected in the system (as shown in Figure 2).

Protection coordination also depends on the type of distribution network (viz., radial, ring main). When Decentralized Power Generation Resources (DPGRs) are connected in a distribution network for supply to various consumers, it is known as a Microgrid. For distribution network protection, overcurrent protection remains a cornerstone. Conventional overcurrent protection, primarily designed for distribution networks with unidirectional power flow from the utility grid, often fails to adopt the dynamic nature of DPGRs integrated networks, leading to relay miscoordination. This has encouraged research into intelligent protection strategies that can adapt to real-time variation, ensuring sensitivity, speed, and selectivity. This article proposes an overcurrent protection scheme that employs a fuzzy logic controller-based scheme to enhance adaptability and reliability in the DPGR integrated network.

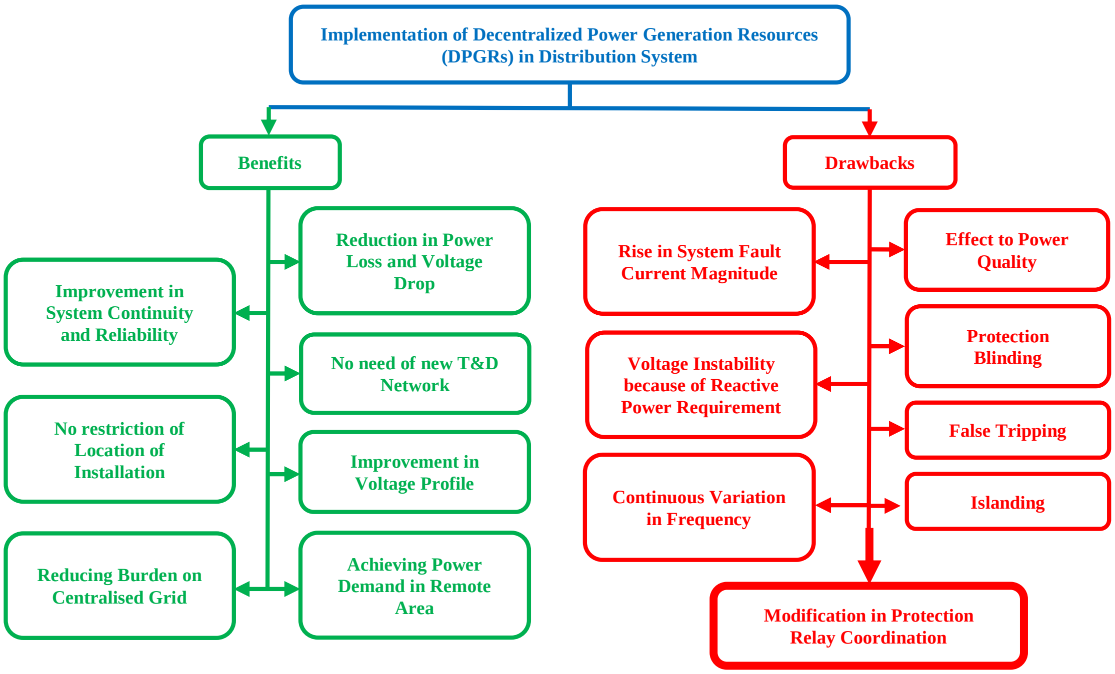


Fig. 1 Benefits and drawbacks of implementing DPGRs in the distribution system

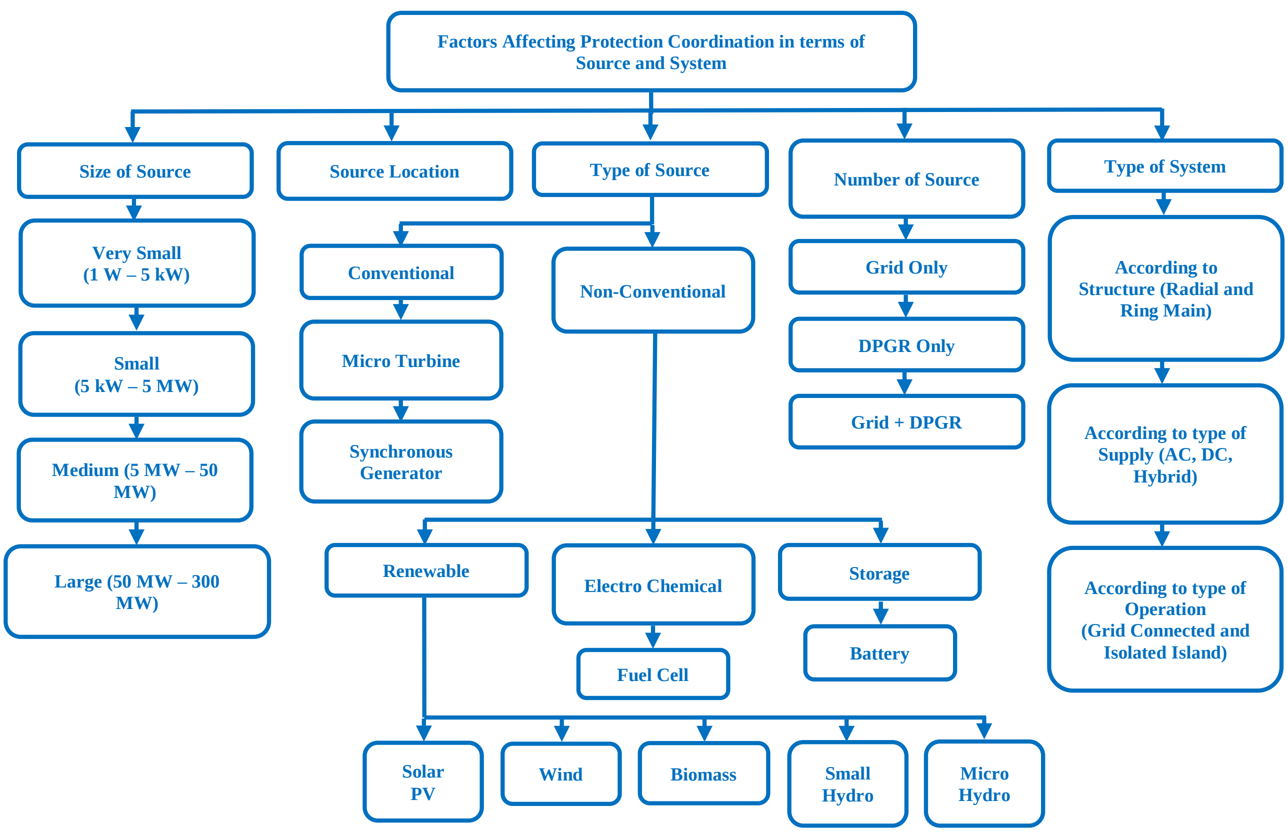


Fig. 2 Factors affecting protection coordination in terms of source and system

The proposed method adjusts relay settings even with the dynamic nature of DPGR. The contribution of this work is to provide a robust, low computational cost alternative to existing methods.

The article is arranged as follows: Section 2 presents details of overcurrent protection used in the distribution system. Section 3 presents a literature review of existing methodologies. Section 4 gives details of the proposed methodology and simulation setup. Section 5 presents the verification and discussion of the proposed methodology. Finally, Section 6 gives concluding remarks of the article.

2. Overcurrent Protection

Overcurrent protection is a critical protection aspect for the distribution network, basically designed to safeguard equipment and ensure system reliability. It involves detecting and mitigating excessive current flows that could damage components or cause system outages. When the current sensed by the relay is more than its pickup or preset value, giving an indication of the presence of a fault in the distribution system, overcurrent relays will operate. As per the requirement of the protection scheme, either a directional or non-directional overcurrent relay is used. According to characteristics, the classification of overcurrent relays is presented in Figure 3.

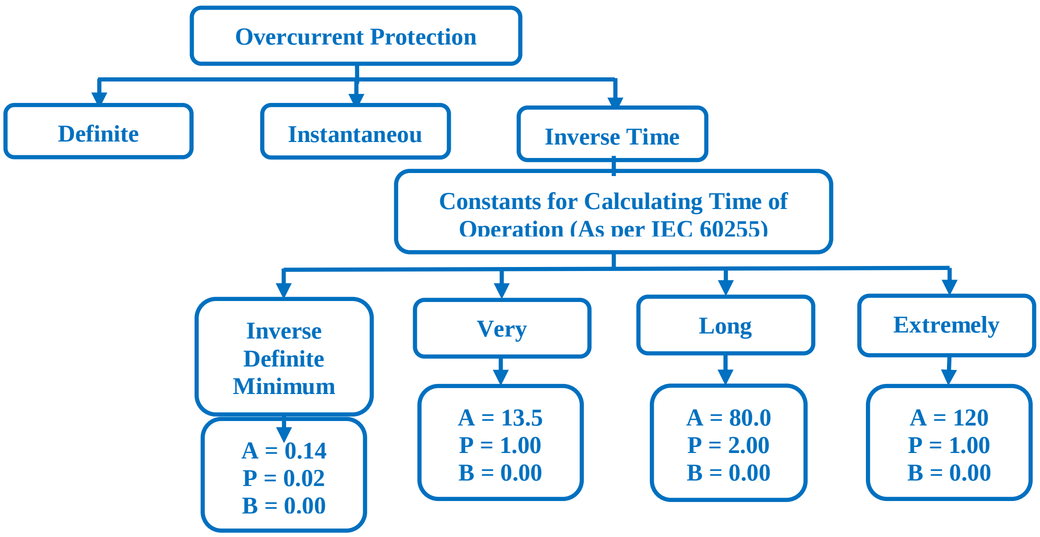


Fig. 3 Classification of Overcurrent (O/C) relay (according to time-current characteristics)

Table 1. Coordination time interval for relay coordination

Relay Types	Coordination Time Interval (CTI) (Sec) *!
Overcurrent Relays (Induction Disc) (With Disc Overtravel Component)	0.3 to 0.4
Overcurrent Relays (Static) (Removing Disc Overtravel Component)	0.2 to 0.3
Overcurrent Relay (Numerical / Digital) (Removing Disc Overtravel Component)	0.2 to 0.3

**CTI is reduced further through Field Calibration by 0.05 s*
!CTI = Relay Over Travel + Relay Tolerance + Circuit Breaker Opening Time + Setting Errors

In a distribution network, an overcurrent relay can be used for primary as well as secondary (or backup) protection. For better coordination between primary and secondary (or backup) relays, Time Gradient Margin (TGM) or Coordination Time Interval (CTI) is an important parameter.

Coordination Time Interval (CTI) for different types of relays according to IEEE Standard 242-2001 is given in Table 1 [14].

Generally, distribution networks are in radial configuration, and for coordinating overcurrent protection, one of the methods used is time-based coordination (as shown in Figure 4) where relays are coordinated such that the relay nearest to the fault will operate first and relay nearest to the source has longer operating time, which is not feasible, as near to the source, fault current is maximum. The second method is current-based coordination, where the setting is done based on pickup current, and the relay nearest to the fault will trip its respective circuit breakers.

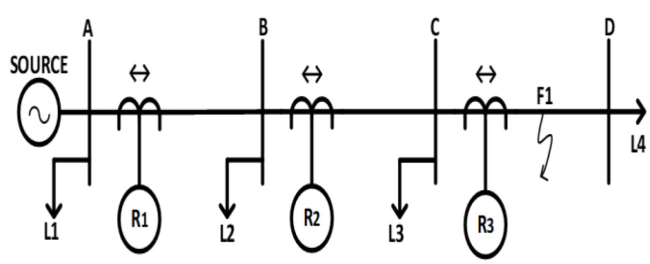


Fig. 4 Radial Distribution Network (RDN)

$$T_{OP} = [\ (A/(M^{P}-1)) * TDS\ ] + B \quad (1)$$

where,

A, B, P = Constants according to IDMT characteristics as per IEC 60255

TDS = Time Dial Setting or Time Multiplier Setting (TMS)

M = Plug Setting Multiplier (PSM)

Overcurrent relays used in the distribution system have inverse time characteristics, so with an increase in fault current, fault-clearing time will decrease. One of the main parameters that needs to be adjusted for an inverse time overcurrent relay is the Plug Setting Multiplier (PSM). Ratio of the current transformer secondary current and the relay operating current is known as Plug Setting Multiplier (PSM). According to the requirements, the pickup current of the relay is adjusted. Another parameter is Time Multiplier Setting (TMS), which adjusts the operating time (Top) of the relay. Equation of operating time (Top) of the relay is given in Equation (1), and constants for calculating the operating time of the relay are given in Figure 3.

3. Existing Methodologies

Researchers have developed overcurrent protection methods with different techniques for distribution networks with distributed generation sources. For ensuring proper operating time (Top) and protective coordination, a protection algorithm for Inverse-Time Overcurrent (ITOC) relays [15] was developed without considering bidirectional flow of fault currents in both radial and ring main distribution networks. Investigation of optimum utilization of Fault Current Limiters (FCLs) [16] for maintaining Directional Overcurrent Relay coordination without changing relay setting and DG status was done, and multi-objective particle swarm optimization was used to identify the location and size of FCLs, but in this scheme, DGs of the same size are used. Directional overcurrent protection [17-19] was also developed, but used only Wind Turbine Generators (WTG) or Synchronous Generators (SG) as distributed generation sources. Artificial Bee Colony (ABC) based optimized coordination of Directional Overcurrent Relay [20] and overcurrent relay having fuzzy inference and neural network learning module [21] were proposed for the Distribution System with Distributed Generation Sources.

Local measurements-based overcurrent protection using the least square algorithm [22] for determining the Thevenin circuit equivalent was developed for a distribution system using only wind power generators. A numerical overcurrent protection with the facility of updating Time Current Characteristic (TCC) online [23] and with Microgrid Communication Medium (MCM) [24] for updating relay operating currents was developed for a distribution network with distributed generation sources. This scheme is working on the communication medium, and if it fails, the protection scheme will not work properly. A new computational method of Plug Setting Multiplier (PSM) for inverse time protection scheme [25] was developed for a distribution network, but has a limitation of working only for a radial system, and the effect of penetration of the DG source is not even considered. Communication-based overcurrent protection [26] was developed for a distribution network with DG sources but has the problem of inaccurate coordination, as there is a possibility that the backup relay gets tripped for a fault in the forward direction. Overcurrent protection based on optimization technique using Genetic Algorithm [27] was also evolved, but again has the limitation of not considering DG source penetration. Numerical Inverse Definite Minimum Time (IDMT) Overcurrent Relay (OCR) [28] for the protection of a microgrid was developed using a Field-Processable Gate Array (FPGA), but has a limitation to its applicability for radial systems only.

A fuse-relay coordination-based Overcurrent Relay (OCR) [29] protection scheme was developed for a microgrid, but considered only diesel generators as DG sources. Researchers have developed a Directional Overcurrent (DOC) protection scheme using a fault steady state component [30] for a distribution system, but not considering high impedance faults. A dual setting directional overcurrent protection scheme [31-33] was proposed for a distribution network, but applicable for a system with only one type of DG. An overcurrent protection that eliminates the impact of DG [34, 35] on branch current, as per the branch contribution factor matrix, was developed, but it works only with one type of DG.

The Dynamic Adaptive Overcurrent Relaying (AOCR) [36] scheme, not dependent on an external controller for estimating relay pickup, was proposed but has a limitation to work for systems with only Solar PV as a DG source. A phase fault protection scheme performing optimal setting of directional overcurrent relay using a meta-heuristic-based optimization algorithm [37] was proposed, but considering only synchronous generators as DG source, and the scenario will be different when inverter-interfaced DG sources are included in the distribution network. An online communication-based protection scheme [38, 39] using numerical directional overcurrent protection relays with a commercial AMPL-based IPOPT solver was proposed, but considering only synchronous generators as a DG source and failure of the communication system makes this scheme inoperative. Other different methods have been developed for distribution system with distributed generator sources based on mixed characteristic curves of relays [40], definite-time grading technique [41], micro genetic algorithm [42], Evaporation Rate Water Cycle Algorithm (ER-WCA) based optimization algorithm [43], Gravitational Search based Algorithm [44], Fault Current Limiter and Cuckoo Linear Optimization Algorithm [45], Non-standard characteristic of overcurrent relay [46] and Ant Lion Optimizer [47].

4. Proposed Adaptive Methodologies and Simulation Setup

Adaptivity is an activity that responds to changes in the system and its requirements with altered protection coordination through necessary control action and externally generated signals [48]. When there is an alteration in fault current level during a change in system condition or topology, the adaptive protection scheme will update the necessary settings of overcurrent protection. In this method, programming can be done for the Overcurrent Relay (OCR) for Automatic Setting Group (ASG) simulation. Switchgears connected in a Microgrid (MG) can be controlled by operation mode auto selection, appropriate protection, and control logic restoration. Different faults (including a major 3-ϕ fault) are simulated at different system locations for calculating fault current, operating time, and identifying relay pairs. Relay will require real-time data from the Distribution System to perform its allocated tasks. It collects locally measured data like 3-Φ line currents from Current Transformers (CTs), details such as Circuit Breaker (CB) status, and fault directions of other relays through the communication network. The proposed protection algorithm is shown in Figure 5. Pre-Installation Analysis like Load Flow Analysis (using NR method) and Short Circuit Analysis will be performed through ETAP Real Time following IEC standards which helps in calculating and/or setting required relay parameters like pickup current (Ipickup considering safety margin) and Time Multiplier Setting (TMS) for primary and secondary protection coordination considering fault location and network operating mode (i.e., grid connected or isolated).

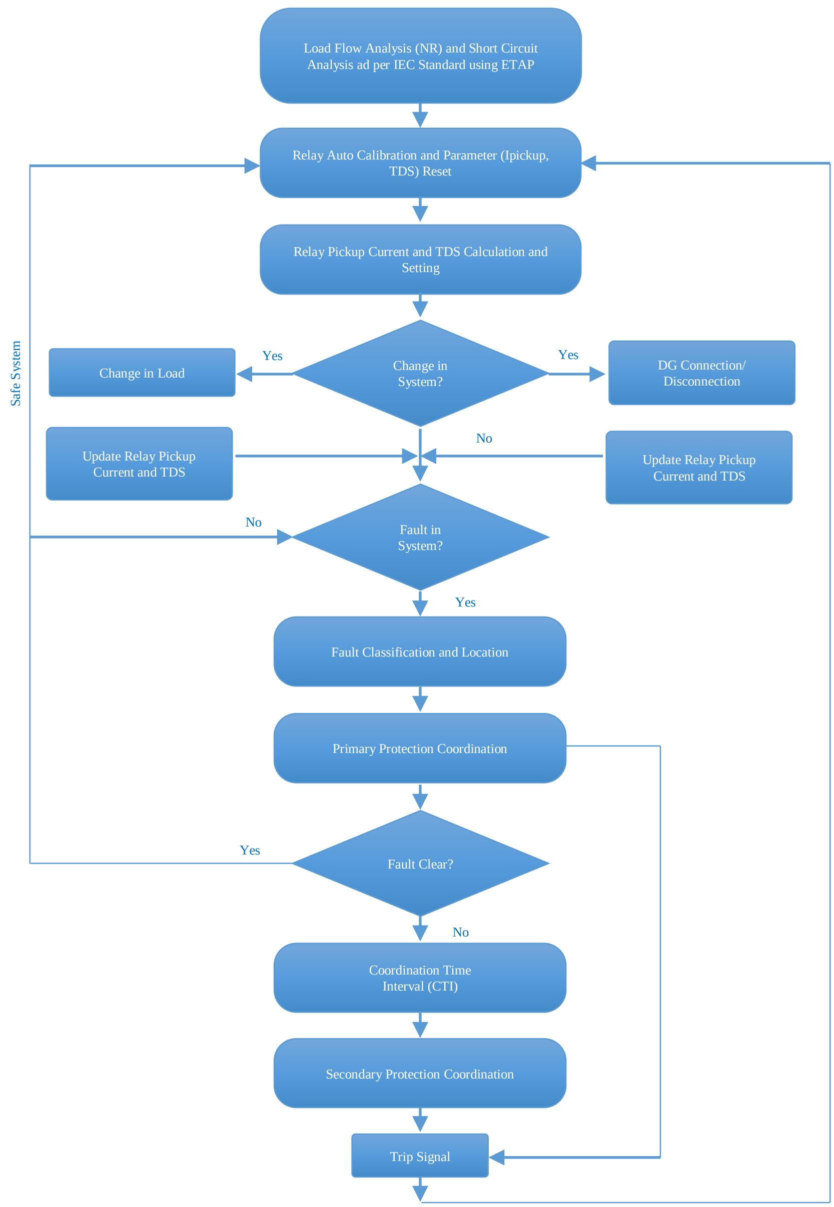


Fig. 5 Proposed overcurrent protection algorithm

The protection relay will do the re-calibration automatically and reset relay parameters like Pickup Current and Time Multiplier Setting (TMS). If there is any change in system configuration or topology, data will be sent to the relay, which will modify its parameters (Ipickup and TMS). Next, it will detect whether a fault is present in the system or not. The algorithm in the overcurrent relay follows Equation (1) with values as per IEC 60255. The primary protection relay will be actuated when fault current on the secondary side of the CT is more than the pickup current, and a trip signal will be sent to the respective circuit breaker to operate and isolate the faulty part of the system. Greater pickup current is an indication of "No Fault" or "Normal Condition".

In case of failure of primary protection or if the fault is still unclear, then secondary protection will be actuated. Primary and Backup protections are coordinated so as to maintain selectivity of the protection scheme with enough delay time for the backup relay to actuate, known as Coordinated Time Interval (CTI). CTI values can be taken from Table 1.

After fault clearance, the relay reset itself back to the initial condition. Coding for the algorithm shown in Figure 5 can be implemented in a Fuzzy Logic Controller (FLC) for use in real time. Protection coordination through Intelligent Electronic Devices (IED) behaves adaptively with real-time calculated settings using Supervisory Control and Data Acquisition (SCADA) and Fuzzy Logic Designer (FLD) application for Microgrid (MG) Central Controller. The application requires a system model for Load Flow (LF) calculation with measurement integration for the collection of online data through a communication medium.

4.1. Simulation Setup

An industrial radial distribution network is considered for this work. Preparation of system SLD, simulation of Load Flow Analysis, Short Circuit Analysis, and Coordinated Time Interval studies are performed through the Electrical Transient Analyzer Program (ETAP) software.

Before doing data entry in ETAP for different components like relays and switchgears, site verification of these components and finalization of the master SLD is done. A 9-bus radial distribution system, a part of an industrial network, is mainly selected as a microgrid for this work. A detailed analysis is performed on this system to get exact values for protection coordination. The ETAP simulation system for the selected 9-bus radial distribution system is represented in Figure 6.

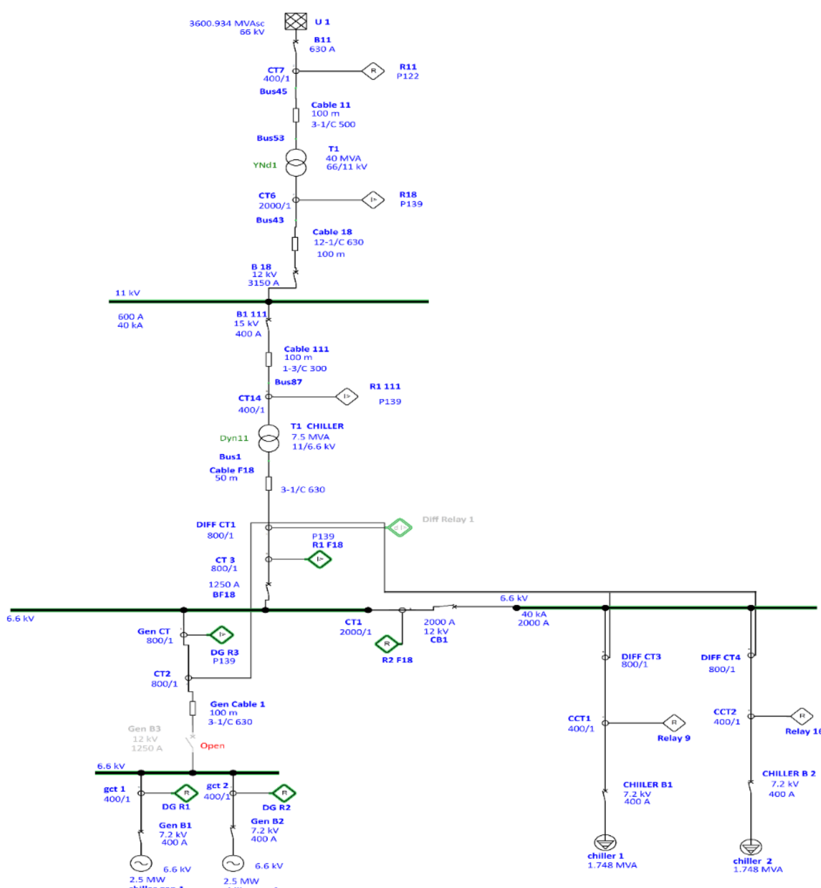


Fig. 6 9-Bus industrial distribution network

4.1.1. Load Flow Analysis (LFA) of 9-Bus Industrial System

Load flow analysis is an important tool for knowing the steady-state behaviour of any industrial distribution network. This study is done on a 9-bus industrial distribution network (as shown in Figure 6) for assessing the impact of decentralized power generation resources on load flow and its implications on overcurrent protection coordination. The Adaptive Newton Raphson (ANR) method is used for Load Flow Analysis (LFA) through ETAP software. Different Setting Group (SG) configurations considered for analysis are presented in Table 2. Summary of Generation, Loading, and Demand from Load Flow Analysis for different Setting Group (SG) configurations is presented in Tables 3, 4, and 5, respectively.

Table 2. Setting group configurations

SG No.	Setting Group (SG) Configurations
1	PG* only
2	PG + 1 DPGR**
3	PG + 2 DPGR
4	Island + 1 DPGR
5	Island + 2 DPGR
* PG = Power Grid ** DPGR = Distributed Power Generation Resources	

Table 3. Load flow analysis generation, loading, and demand summary for SG#1, 2, and 3

Description	MW	MVar	MVA	PF
Source (Swing Bus)	2.952	1.929	3.526	0.83 Lag
Total Demand	2.952	1.929	3.526	0.83 Lag
Total Motor Load	2.377	1.473	2.796	0.85 Lag
Total Static Load	0.564	0.350	0.664	0.85 Lag

Table 4. Load flow analysis generation, loading, and demand summary for SG#4

Description	MW	MVar	MVA	PF
Source (Swing Bus)	1.486	0.876	1.725	0.86 Lag
Total Demand	1.486	0.876	1.725	0.86 Lag
Total Motor Load	1.188	0.737	1.398	0.85 Lag
Total Static Load	0.297	0.184	0.349	0.85 Lag

Table 5. Load flow analysis generation, loading, and demand summary for SG#5

Description	MW	MVar	MVA	PF
Source (Swing Bus)	2.973	1.799	3.475	0.85 Lag
Total Demand	2.973	1.799	3.475	0.85 Lag
Total Motor Load	2.377	1.473	2.796	0.85 Lag
Total Static Load	0.593	0.367	0.697	0.85 Lag

4.1.2. Short Circuit Analysis of 9-Bus Industrial System

An industrial distribution network is incorporating decentralized power generation resources to enhance reliability and sustainability, which complicates short-circuit behaviour. This short circuit analysis is conducted to assess fault levels and optimize overcurrent protection schemes. Short Circuit Analysis (SCA) according to the IEC standard for calculating short-circuit currents in three-phase AC power systems (IEC 60909) for a selected 9-Bus industrial distribution network is carried out, and reading for 3-ϕ faults is taken for setting relay parameters. The effects of Distributed Power Generation Resources (DPGR) on the fault current level are presented in Table 6. Short Circuit Analysis also helps in knowing the effect of different types of faults on the system fault current. Change in fault current demands updation in relay parameters setting and also demands an adaptive protection scheme that can adapt to system changes.

4.2. Simulation for Protection Coordination

For any Industrial Distribution Network, protection coordination is very much critical to ensure reliability and safety of equipment as well as the system.

Protection Coordination involves the design and strategic adjustment of protection device parameters so that they can operate in a coordinated manner, isolate faults, and minimize disruptions to the power supply.

Key elements of any protection coordination are Time Current Characteristics (TCC), Time Grading Margin (TGM), or Coordinated Time Interval (CTI), and Device (Relay, Fuses, Circuit Breaker) settings. In this article, a protection coordination simulation study, Coordination Time Interval (CTI) simulation with fault creation using the Star Coordination module, is used in ETAP software.

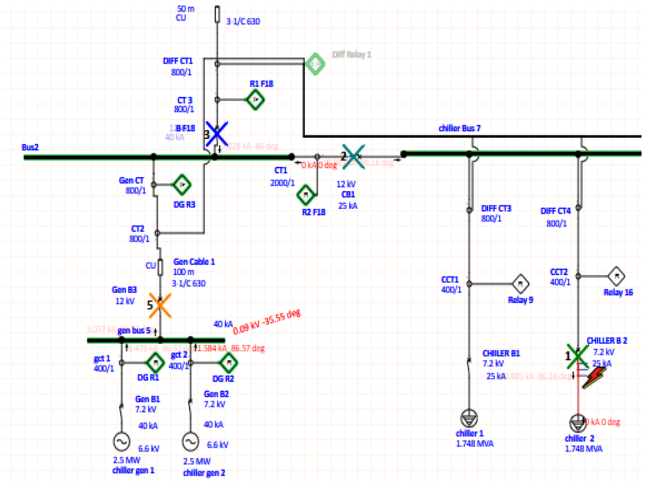
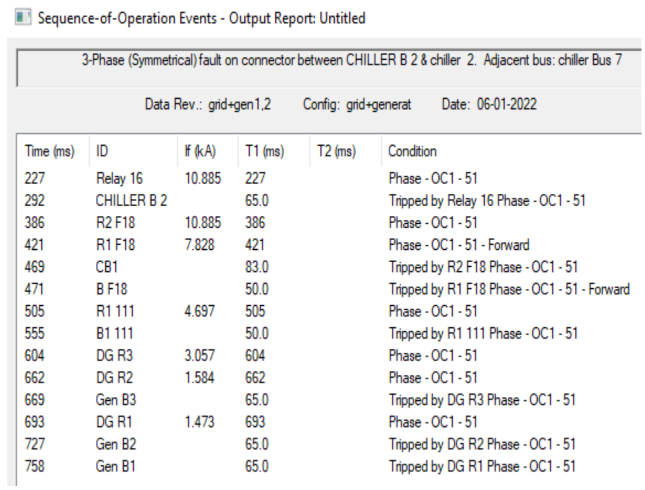


Fig. 7 Relay response sequence of fault simulation for setting group#3



Sequence-of-Operation Events - Output Report: Untitled

3-Phase (Symmetrical) fault on connector between CHILLER B 2 & chiller 2. Adjacent bus: chiller Bus 7

Data Rev.: grid+gen1,2 Config: grid+generat Date: 06-01-2022

Time (ms)	ID	If (kA)	T1 (ms)	T2 (ms)	Condition
227	Relay 16	10.885	227		Phase - OC1 - 51
292	CHILLER B 2		65.0		Tripped by Relay 16 Phase - OC1 - 51
386	R2 F18	10.885	386		Phase - OC1 - 51
421	R1 F18	7.828	421		Phase - OC1 - 51 - Forward
469	CB1		83.0		Tripped by R2 F18 Phase - OC1 - 51
471	B F18		50.0		Tripped by R1 F18 Phase - OC1 - 51 - Forward
505	R1 111	4.697	505		Phase - OC1 - 51
555	B1 111		50.0		Tripped by R1 111 Phase - OC1 - 51
604	DG R3	3.057	604		Phase - OC1 - 51
662	DG R2	1.584	662		Phase - OC1 - 51
669	Gen B3		65.0		Tripped by DG R3 Phase - OC1 - 51
693	DG R1	1.473	693		Phase - OC1 - 51
727	Gen B2		65.0		Tripped by DG R2 Phase - OC1 - 51
758	Gen B1		65.0		Tripped by DG R1 Phase - OC1 - 51

Fig. 8 Fault simulation relays operations report for setting group#3

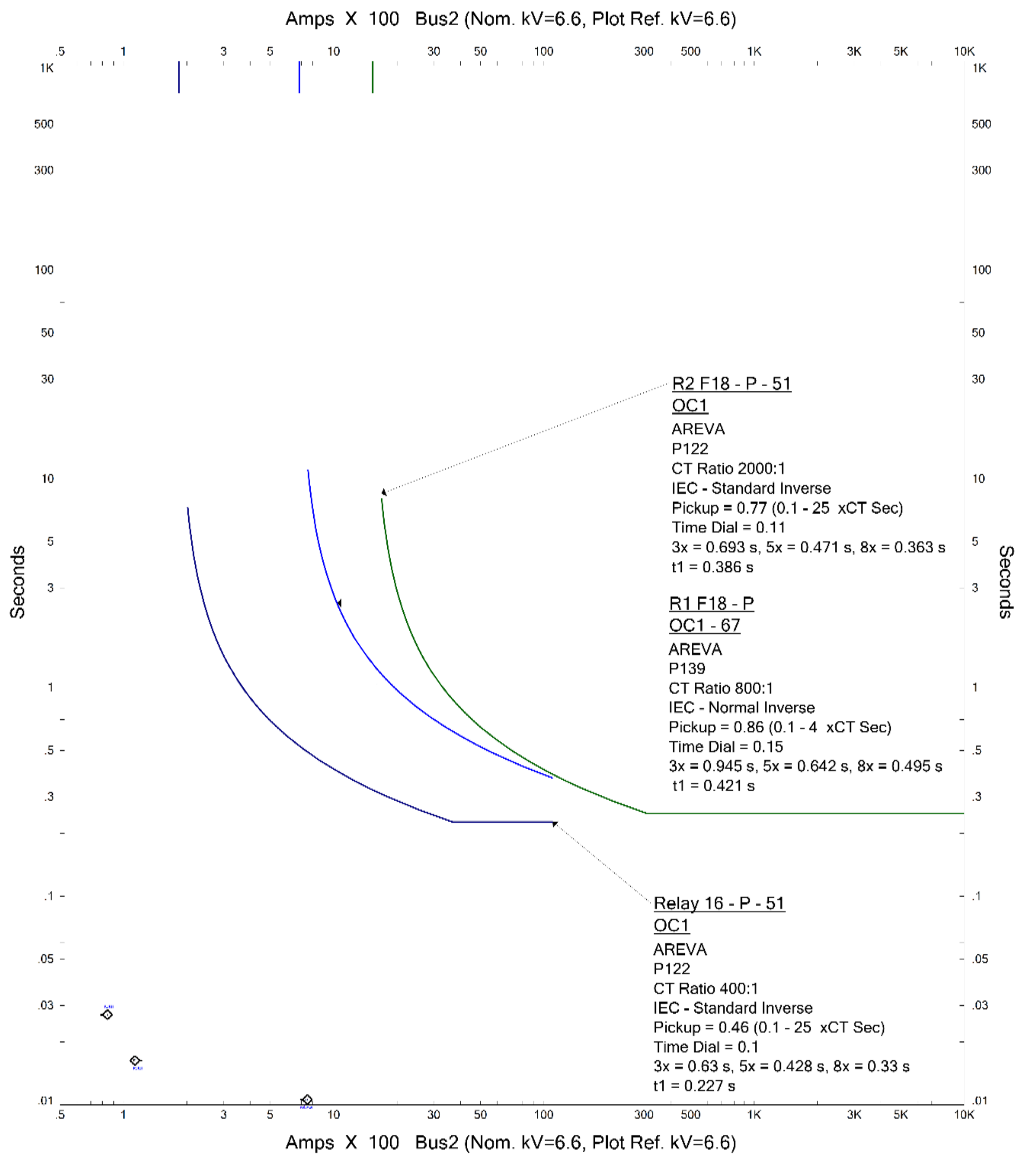


Fig. 9 TCC curve generated in ETAP for setting group#3

Relay response sequence of fault simulation and fault simulation report of relay operations for Setting Group (SG)#3 are presented in Figure 7 and Figure 8, respectively. The IEC Standard Inverse Curve is used for coordinating Overcurrent Relays (OCR) in the 9-Bus Industrial Distribution Network considered for this study. For each Setting Group (SG), relay settings are reviewed for correct operating sequence and the Time of operation (Top). Figure 9 presents the TCC curve of fault simulation with Setting Group SG#3. Table 6 represents the CTI report summary with details like system fault currents seen by relays and protection relay parameters like Pickup Current and Time Dial Setting for different Setting Groups. For analysis, fault location is considered to be on the Feeder of Chiller 2. To ensure reliable operation of the system, analysis is performed with different Setting Groups, Optimum TCC curve, and relay pairs, which also helps in establishing relay programming. From the analysis, relay R2F18 is found to be common and important in all Setting Groups.

Table 6. CTI report and relay operating time (top) summary

SG No.	Setting Group (SG) Arrangement	Relay	System Fault Current seen by Relays (kA)	Ipickup (Amp)	Time Dial Setting (TDS)	T1 (Top) (ms)
1	PG Only	R16	7.828	0.98	0.1	0.227
		R2F16	7.828	0.40	0.12	0.360
		R1F16	7.828	0.98	0.15	0.446
2	PG + 1 DPGR	R16	9.309	1.17	0.1	0.227
		R2F16	9.309	0.55	0.12	0.385
		R1F16	7.828	0.98	0.15	0.446
3	PG + 2 DPGR	R16	10.885	1.37	0.1	0.227
		R2F16	10.885	0.77	0.11	0.386
		R1F16	7.828	0.86	0.15	0.421
4	Island + 1 DPGR	R16	1.48	0.46	0.1	0.329
		R2F16	1.48	0.16	0.12	0.540
		DGR3	1.48	0.39	0.14	0.620
5	Island + 2 DPGR	R16	3.057	0.46	0.1	0.242
		R2F16	3.057	0.31	0.12	0.518
		DGR3	3.057	0.77	0.14	0.604

5. OCR Functional Verification and Discussion

Integration of Distributed Power Generation Resources (DPGRs) into the Industrial Distribution Network has altered the dynamics of the Overcurrent Protection scheme.

This article demonstrates that an Industrial Distribution Network, if it relies on conventional protection, significant disruptions might be encountered because of DPGRs.

The article uses the simulation of a 9-Bus Industrial Distribution Network through ETAP software for analyzing the effect of DPGR on protection coordination with different Setting Groups. Table 6 shows that the relay operating time and system fault currents are different for various SGs. The proposed Overcurrent Protection scheme that employs a Fuzzy Logic Controller offers better performance against the traditional protection approach.

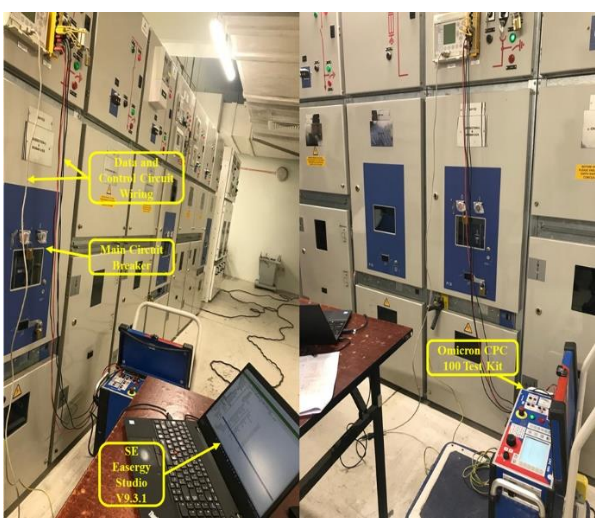


Fig. 10 Hardware In Loop (HIL) test setup

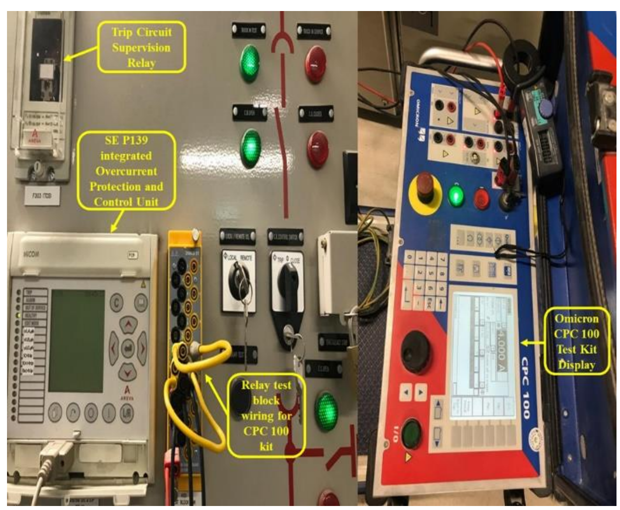


Fig. 11 Relay panel and omicron test kit display from Hardware In Loop (HIL) test setup

For Overcurrent (OC) functional verification, the SE-P139 relay is used, where Setting Groups are programmed with the help of pre-computed values of Pickup Current (Ip) and Time Dial Setting (TDS) identified through fault simulations and CTI settings, done through ETAP software, respectively. Relay programming done through Easergy Studio V9.3.1-SE also determines pairs of relays for Circuit Breaker's control actions. With the help of the Secondary Injection method, existing Distribution Network (DN) panels are set up for Hardware In Loop (HIL) tests (as shown in Figure 10 and Figure 11). The relay test block was wired appropriately, connected with the Omicron CPC 100 testing kit, and relay control was established with the help of Ethernet. Event activity log and summary are also downloaded for analysis. After mitigating protection challenges, the scheme presented in this article enhances network reliability.

6. Conclusion

Integration of Distributed Power Generation Resources (DPGRs) in the Distribution Network (DN) has significantly transferred conventional overcurrent protection strategies. This article gives an overview of challenges imposed by DPGRs, like variable fault current and dynamic network configurations. The proposed overcurrent protection scheme effectively addresses these challenges by enhancing fault detection and system reliability. Protection Single Line Diagram was adopted for the Industrial Distribution Network, and different tests are performed to get the optimum CTI. Relay was tested for different setting groups with various setting parameters, Programmable Logic Controller programming, and responded well. Relay functions' adaptiveness is examined against programmed values. An algorithm is suggested for Overcurrent Relay (OCR) for implementing it in Microgrids (MG) with SCADA and ETAP in real-time. Through comprehensive simulations with various setting groups, it is evident that the risk of miscoordination is mitigated with the proposed scheme, ensuring reliable protection under variable operating conditions.

Overcurrent Relay with technologies like Artificial Intelligence (AI) using real-time data is expected to have widespread use in future microgrids. Future work should focus on integrating real-time data analysis and machine learning techniques for optimizing protection settings with increasing penetration level of Distributed Power Generation Resources (Renewable Energy Sources (RES)). For improving performance further, the Adaptive Neuro Fuzzy Inference System (ANFIS) can be used for designing a Fuzzy Logic Controller (FLC) to utilize its learning capabilities.

Acknowledgments

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