Bulletin of Electrical Engineering and Informatics
Vol. 15, No. 2, April 2026, pp. 986~998
ISSN: 2302-9285, DOI: 10.11591/eei.v15i2.10045

Parameters affecting protection coordination of high voltage distribution network with distributed energy resources

Ishan Desai[1,2], Nilesh Chothani[3], Paul Jacob[4]
[1]Department of Electrical Engineering, Gujarat Technological University, Ahmedabad, India
[2]Department of Electrical Engineering, Faculty of Engineering and Technology, Parul University, Vadodara, India
[3]Department of Electrical Engineering, School of Energy Technology, Pandit Deendayal Energy University, Gandhinagar, India
[4]Engineering, Hamad Medical Corporation, Doha, Qatar

Article Info

Article history:

Received Feb 9, 2025
Revised Dec 9, 2025
Accepted Feb 22, 2026

Keywords:

Distributed energy resources
Distribution network
Fault
Protection coordination
Renewable sources

ABSTRACT

Distributed energy resources (DERs) have become favorable sources of power against conventional power sources at distribution level because of their advantages like reduction in power loss and voltage drop, and environment friendliness. Integrating of DERs into high voltage distribution networks (HVDNs) introduces significant challenges to protection relay coordination because of their dynamic operational characteristics. This comprehensive study investigates key parameters influencing effective protection relay coordination in distribution networks (DNs), including fault current variability, DER penetration level, network topology, and relay settings. Through comprehensive simulation conducted on modified IEEE 4-bus HVDN with variable DER configurations through PSCAD/EMTDC 4.5 software, the research analysis evaluates the impact of these parameters on protection reliability and speed. Results indicate that high DER penetration leads to fault current increment by 10-20%, grid current contribution reduction by 10-15% as well as relay current setting alterations approximately by 30-40% which necessitates adaptive protection schemes. Network topology and relay coordination strategy significantly affect fault detection and isolation process. The finding provides understanding of parameters affecting protection coordination which helps in its optimization and having reliable and secure operation of DN.

Corresponding Author:

Nilesh Chothani
Department Electrical Engineering, Pandit Deendayal Energy University
Gandhinagar, Gujarat, India
Email: chothani_nilesh@rediffmail.com

1. INTRODUCTION

Integrating distributed energy resources (DERs) in high voltage distribution networks (HVDNs) has transformed modern power systems, offering advantages like environment friendliness, and improved energy efficiency. Because of dynamic nature of DERs which majorly includes renewable energy sources (RES) [1] like solar PV, wind turbine, and energy storage units, significant challenges to protection relay coordination of DNs are introduced. Relay coordination, which ensures selective and timely operation of protection devices for isolating faults, is very much important for maintaining system stability and security. For India, this analysis is important as in past few years, there is huge rise in integration of DERs in HVDN. As per record of central electricity authority (CEA) [2], as on March-2002, power generation from RES was 1628 MW which as on October-2025 has been increased to 200295 MW (including generation from large hydro power plants connected at transmission level, it is 250643 MW) as shown in Figure 1 showing nearly 94%

rise in usage of RES. Currently, sharing of generation from RES is 45% of total generation which in future will be more than 50%. Out of total generation from RES, ~85-90% generation is from solar PV and wind energy system only. This increase in integration of RES in power system has big impact on protection relay coordination of system because of dynamic power generation.

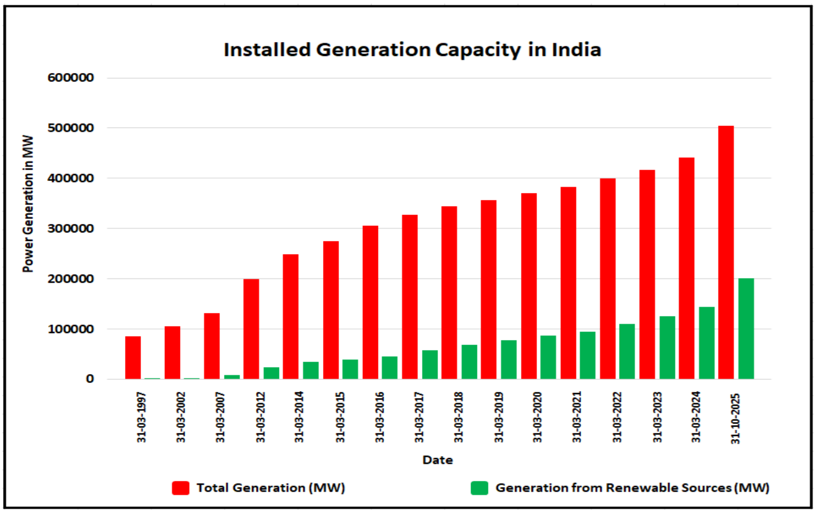

Figure 1. Total power generation capacity (MW) in India

Most of the DERs are integrated at load end, giving advantages like reduction in cost of constructing new overhead power lines, reducing power loss and voltage drop and improving voltage regulation as well as system reliability [3]-[8]. Key parameters affecting protection coordination in distribution networks (DNs) [8]-[13] include type, capacity and location of DERs, fault characteristics (fault type and fault resistance), system topology and settings of protection device like relay (Figures 2 and 3). Factors like bidirectional power flow and continuous variable power generation [14]-[19] also influence the performance of protection schemes. Continuous variable power generation will vary system parameters like voltage (should be within ±10% range) and frequency (should be within range of 49.5 Hz-50.2 Hz [20]). Optimization of these parameters is very much important for mitigating issues such as miscoordination, nuisance tripping or failure to detect faults, which can lead to equipment damage and power outages.

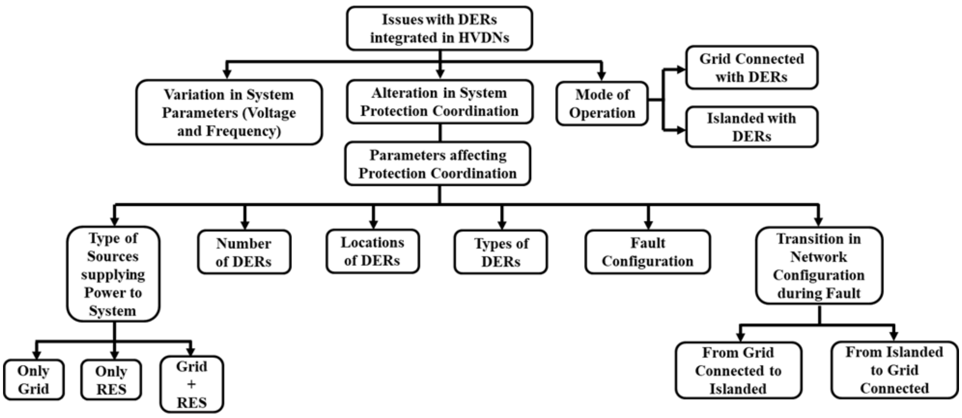

Figure 2. Issues with integration of DERs in HVDNs

This article is aiming to systematically analyses the parameters affecting protection coordination in HVDNs with DERs. By examining their impact through theoretical analysis and simulation studies, this work seeks to provide insights into adaptive protection strategies and coordination techniques that enhance the reliability of modern DNs. The findings are intended to help system designers in designing robust protection schemes which accommodate increasing penetration of DER while ensuring efficient system operation.

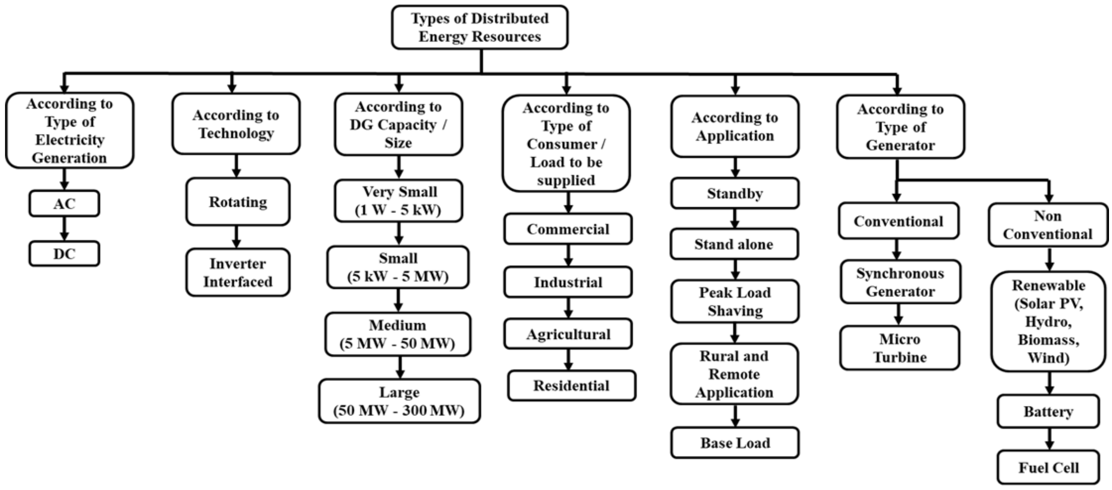

Figure 3. Types of DERs

2. FACTORS AFFECTING PROTECTION COORDINATION

Integrating DERs mainly affect protection coordination [21]-[42] provided for reliable protection of HVDNs. DER sources increase normal as well as fault current in DN which lead to undesired operation of relay even though fault is not present and protection scheme may lose selectivity. Presence of these sources also decrease fault current contribution from grid which may cause relay blinding. Fault impedance is also one of the parameters result in protection miscoordination. Integrating DERs in DN increases number of relays and switchgear devices increasing overall cost and complexity of protection scheme.

2.1. Distributed energy resource types

Various types of DER cause numerous effects on DN like voltage unbalance or flickering, harmonics generation and insertion and other power quality related issues [43]-[50]. Voltage instability is created when less number of large capacity or large number of less capacity wind power generators (induction generator (IG)) are connected in DN because of their reactive power requirement. Majority of DERs like solar PV generate DC power and to integrate them with AC system, converters are required to convert generated DC power into AC. Rotating type DERs like wind power generation systems are also connected to system through converter system. This process generates reactive power requirement which also results in voltage unbalance as voltage and reactive power have direct proportionate relation. Voltage unbalance also affects real power transfer in system as real power transfer is directly proportional to the square of the voltage as in (1). Apart from this, variable generation from DERs and load demand also affect power flows (both real and reactive as shown in (2) and (3) in DN.

$$P = \frac{V_S V_R}{X_L} \sin\delta \tag{1}$$

where, V_S, V_R are sending and receiving end voltages (kV) respectively, X_L is line reactance (Ω), and δ is load angle (°).

$$P = P_{grid} + \sum_i P_{DER,i} - \sum_i P_{Load,i} \tag{2}$$

$$Q = Q_{grid} + \sum_i Q_{DER,i} - \sum_i Q_{Load,i} \tag{3}$$

where, P, Q are real and reactive power in DN, P_{grid}, Q_{grid} are real and reactive power supply from grid, $P_{DER,i}$, $Q_{DER,i}$ are real and reactive power supply from DERs at bus I, and $P_{Load,i}$, $Q_{Load,i}$ are real and reactive power demand at bus i.

$$I_f = I_{f,grid} \tag{4}$$

$$I_f' = I_{f,grid} + \sum_i I_{f,DER,i} \tag{5}$$

where, I_f is fault current in DN in absence of DERs and I_f' is fault current in DN when DERs are present.

$$I_{f,grid} = \frac{V_{grid}}{Z_{grid} + Z_{line} + Z_{fault}}$$

$$I_{f,DER,i} = \frac{V_{DER}}{Z_{DER} + Z_{line,\ DER} + Z_{fault}}$$

where, $I_{f,grid}$ is fault current contribution from grid, $I_{f,DER,i}$ is fault current contribution from DERs at bus I, V_{grid}, V_{DER} are grid and DER bus voltages respectively, Z_{grid}, Z_{DER} are source impedance (grid and DER), Z_{line} is impedance of line between grid and fault location, $Z_{line,DER}$ is impedance of line between DER and fault location, and Z_{fault} are fault impedance.

With wind power generation (IG) system, capacitor banks are connected for fulfilling reactive power requirements. If cable is used for distribution of power, it increases capacitance further as well as chances of resonance (with harmonic frequencies). As mentioned before, DERs increases fault current magnitude as in (4) and (5). During fault in the DN, fault current contribution is different from various types of DERs. In faulty condition, fault current contribution is the highest from synchronous generator (SG). Fault current contribution from IG (simple IG<doubly fed induction generator (DFIG)) is less than SG and it is the least for solar PV [51]-[54].

2.2. System operating modes

High HVDN with DERs is known as microgrid which can operate in two different modes viz; grid connected and islanded. When microgrid is connected with main grid, power can either flow from main grid to microgrid (when in microgrid, load demand is higher than power generation from DERs) or from microgrid to main grid (when in microgrid, power generation from DERs is higher than load) as Figure 4 and load demand is fulfilled from grid and DERs both as in (6). Because of any fault or abnormal condition in main grid, microgrid will get disconnected from main grid and start working in islanded mode [12]-[14], [16] as shown in Figure 5 and only DERs will fulfil load demand as in (7).

$$I_{Load} = I_{grid} + \sum_i I_{DER,i} \tag{6}$$

$$I_{Load} = \sum_i I_{DER,i} \tag{7}$$

When unintentional islanding occurs, there is huge variation in system parameters like voltage and frequency which can damage equipments. There are three condition that can be considered in case of islanding viz; i) generation from DERs is less than load demand (frequency less than 50 Hz), ii) generation from DERs is higher than load demand (frequency more than 50 Hz), and iii) generation from DERs is same as load demand. Detection of islanding is one of the most important tasks for the protection of microgrid in case of islanding. Islanding detection (ID) becomes little difficult when generation from DERs and load demand are nearly the same.

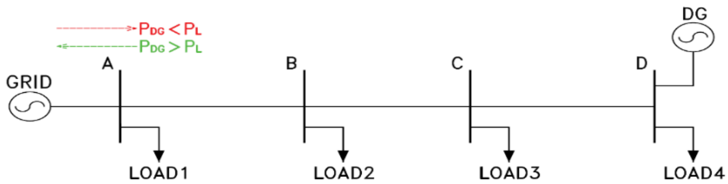

Figure 4. DN supplied through grid and DG source (grid connected mode)

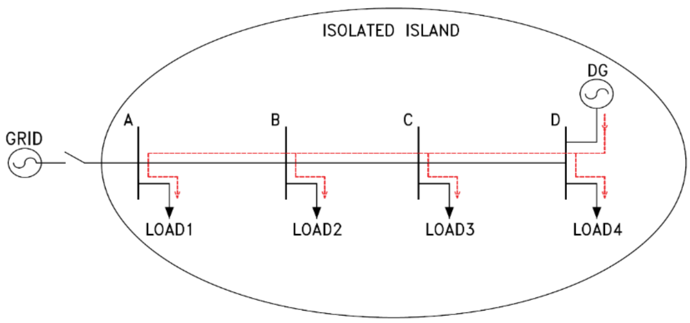

Figure 5. DN supplied through DG source (islanded mode)

2.3. High voltage distribution network with one source

In this section, effect of numerous parameters on protection coordination of DN fed through one source is discussed. In first case, it is considered that radial distribution network (RDN) is fed through utility grid only (Figure 6) and in other, effect of types of DER is analysed for standalone system supplied only through DERs like wind (IG) and small hydro (SG) power generation (Figure 7). For DN, mainly overcurrent protection is used. For analysing the effects, IEC-60255 standard [55] is followed with inverse definite minimum time (IDMT) characteristic for overcurrent relays (OCR). In (8) is followed for relay operating time.

$$T_{op} = \left(\frac{A}{M^{P} - 1}\right) TDS + B \quad (8)$$

where, TDS is time dial setting or time multiplier setting (TMS), M is plug setting multiplier (PSM), and A, B, P are constants according to IDMT characteristics as per IEC 60255 (Table 1).

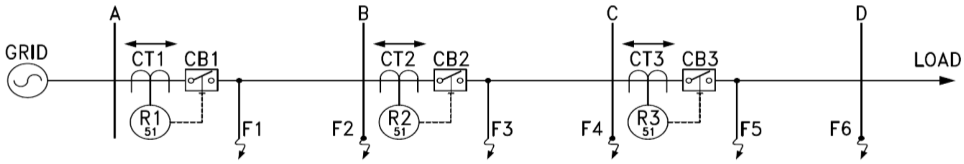

Figure 6. RDN fed at one end (through utility grid only)

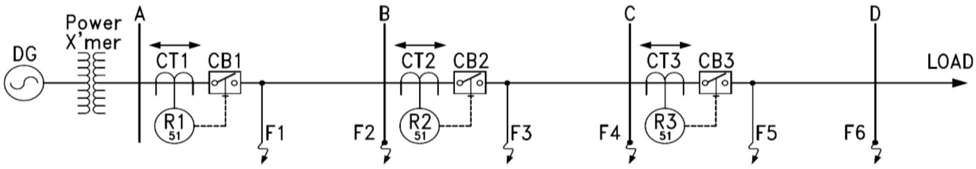

Figure 7. RDN fed at one end (through DG source only-standalone system)

Table 1. Constant for calculating relay operating time

Characteristics	A	P	B
IDMT	0.14	0.02	0.00
Very inverse	13.5	1.00	0.00
Extremely inverse	80.0	2.00	0.00
Long inverse	120	1.00	0.00

For the protection of RDN with three sections, three non-directional type OCR are required as no matter where fault occurs, curent flow is always unidirectional (forward or from source to load). Modified IEEE 4-bus RDN is prepared using PSCAD/EMTDC 4.5 software (as shown in Figure 8) with system voltage of 12.47 kV, each feeder section with 20 km length (with resistance 0.363 Ω/km and inductive reactance 1.323 Ω/km) and load demand of 6 MW. Inverse time OCR (51) with IDMT characteristic is coordinated for protection.

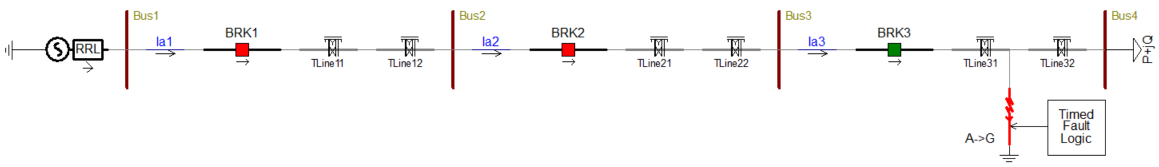

Figure 8. RDN fed at one end (through utility grid only-prepared in PSCAD 4.5)

Fault parameters: for analysing the effect of fault parameters on protection coordination, fault resistances, fault types and fault locations are taken into account. Fault location affects protection coordination of distribution network. The relay setting should be as such that wherever a fault occurs in the system, the designated relay should operate. Fault locations are considered at midpoint (10 km (F1), 30 km (F3), and 50 km (F5) from the source) and the end (20 km (F2), 40 km (F4), and 60 km (F6) from the source) of each line section as presented in Figures 6 and 8. LG and LL type of faults are considered for analysing the effect of fault types on protection coordination. As fault resistance has considerable effect on protection coordination, its effect as well is taken into account. Fault resistances of 0 Ω, 4 Ω, 8 Ω, and 12 Ω are considered for analysing their effect on protection coordination.

System with different voltage levels (system with transformer): protection coordination is going to be affected [56] if transformer is included in the DN (as shown in Figure 9) as the system is being operated at two different voltages which changes current levels on both the sides of transformer. 6.3 MVA, 12.47/4.16 kV transformer is included in the system. For this case, 7 fault locations are considered as shown in Figure 9.

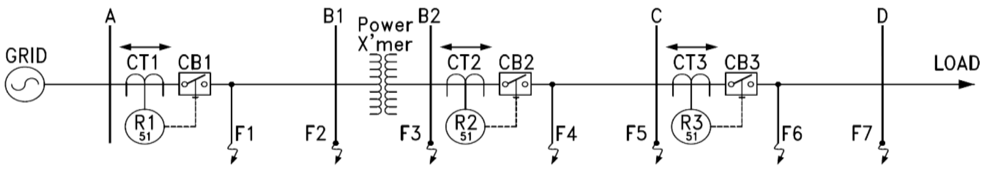

Figure 9. RDN fed at one end (operating at two different voltage levels)

Different cases as shown in Table 2 are considered for analysing effect on protection coordination of HVDN with DERs. Fault current contribution from different types of sources is presented in Figure 10 (cossidering fault location F1) and effect on protection coordination (considering LL fault because of seviour effect compared to LG fault) is represented in terms of change in relay current setting (in Ampere) (keeping relay operating time nearly same) in Table 3.

Table 2. Cases for analysis of effect on protection coordination (system with one source)

Case no.	Description
1	Radial feeder without transformer (system fed at one end (grid only))
2	Radial feeder with transformer (system fed at one end (grid only))
3	Radial feeder without transformer (system fed at one end (SG only))
4	Radial feeder without transformer (system fed at one end (IG only))

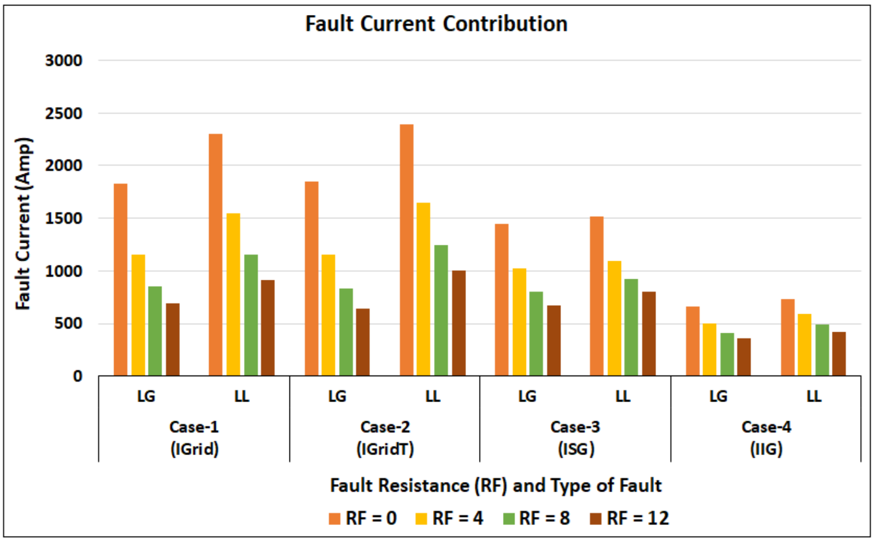

Figure 10. Fault current contribution from different types of sources (system with one source)

2.4. High voltage distribution network with more than one source

Fault parameters: to analyse the effect of fault parameters on protection coordination of HVDN with more than one source (grid+DERs), fault resistances (Rf) of 4 Ω, and 12 Ω are considered. Fault locations (considering LG fault) are considered at 10 km (F1), 20 km (F2), 30 km (F3), 40 km (F4), and 50 km (F5) from source-1 (Figures 11 and 12). Radial distribution fed at two ends is prepared in PSCAD 4.5 as shown in Figure 13.

Table 3. Relay current settings (Ip) for different cases (system with one source)

Fault resistance	Relay	Relay current settings (Ip) (A)			
		Case-1	Case-2	Case-3	Case-4
RF=0	R1	0.25	0.06	0.22	0.17
	R2	0.2	0.11	0.2	0.11
	R3	0.15	0.07	0.17	0.09
RF=4	R1	0.24	0.05	0.21	0.14
	R2	0.19	0.08	0.19	0.09
	R3	0.15	0.06	0.16	0.08
RF=8	R1	0.185	0.04	0.17	0.13
	R2	0.18	0.07	0.17	0.09
	R3	0.15	0.06	0.15	0.08
RF=12	R1	0.16	0.03	0.15	0.12
	R2	0.16	0.07	0.15	0.085
	R3	0.14	0.06	0.14	0.08

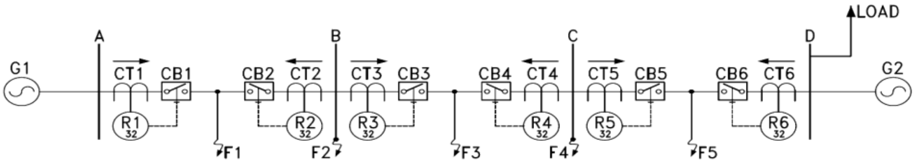

Figure 11. Radial DN fed at two ends (through utility grid only)

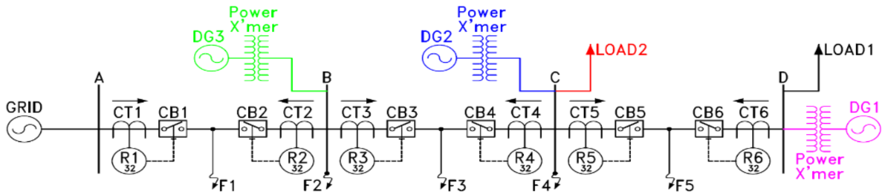

Figure 12. Radial DN fed from more than two sources (one utility grid and three DG source) with load increment (figure for Case 3 to Case 10)

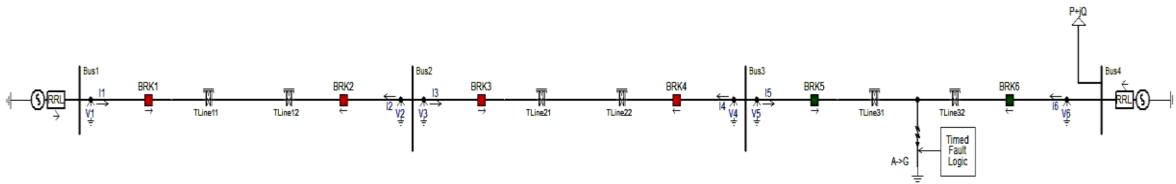

Figure 13. Radial DN fed at two ends (through utility grid only-PSCAD 4.5)

Multiple sources: effect of implementing DERs is analysed with DER sources of either different or same types (SG, IG, and solar PV) and capacity. As mentioned before, fault current contribution is different from SG, IG, and solar PV which affects protection coordination. Effect will be more prone when distribution network is having only wind power generation or solar PV or both as DERs.

Various cases for analysing the effects on relay coordination are discribed in Table 4. Effect on protection coordination (in terms of change in relay current setting) is presented in Table 5 considering different fault resistances.

System topology: protection coordination varies with different distribution system topologies. For radial distribution systems with branches or ring main distribution networks, protection coordination is different. For ring main distribution network, power flow in various branch is different. These systems demand more relays and switchgear devices that make the task of protection coordination a little complex. Because of fault, change in system topology may also happen that modifies protection coordination. A modified IEEE 9-bus ring main distribution network is shown in Figure 14, where it is represented that if fault occurs at location F, circuit breakers 7 and 8 will be open and whole system will get converted into radial. Protection coordination should be able to adopt system changes and protect the reminder of healthy part of the system.

Table 4. Cases for analysis of effect on protection coordination (system with more than one sources)

Case no.	Description SG and IG
1	Radial feeder (system fed at two ends (grid only)
2	Radial feeder (system fed at two ends (grid only) with load increment by 1 MW)
3	Radial feeder fed at two ends (grid and SG (1 MW)
4	Radial feeder fed at three ends (grid and two SG (1 MW) with load increment by 1 MW)
5	Radial feeder fed at three ends (grid and two SG (1 MW and 0.7 MW) with load increment by 1 MW)
6	Radial feeder fed at three ends (grid, one SG (1 MW) and one IG (1 MW) with load increment by 1 MW)
7	Radial feeder fed at three ends (grid, one SG (1 MW) and one solar PV (1 MW) with load increment by 1 MW)
8	Radial feeder fed at four ends (grid, one SG (1 MW), one IG (1 MW) and one solar PV (1 MW)) with load increment by 1 MW)
9	Radial feeder fed at four ends (grid, three SG (1 MW) with load increment by 1 MW)
10	Radial feeder fed at four ends (grid, two SG (1 MW), one IG (1 MW) with load increment by 1 MW)

Table 5. Relay current settings (Ip) for different cases (system with more than one sources)

Fault resistance	Relay	Relay current settings (Ip) (A)									
		Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7	Case-8	Case-9	Case-10
RF=0	R1	0.45	0.40	0.42	0.38	0.40	0.28	0.28	0.28	0.32	0.30
	R2	0.07	0.12	0.12	0.08	0.40	0.12	0.17	0.16	0.14	0.17
	R3	0.20	0.225	0.19	0.26	0.24	0.18	0.18	0.13	0.28	0.20
	R4	0.22	0.225	0.16	0.20	0.16	0.14	0.16	0.16	0.22	0.22
	R5	0.09	0.21	0.18	0.135	0.20	0.16	0.18	0.195	0.16	0.15
	R6	0.45	0.45	0.26	0.26	0.26	0.22	0.24	0.20	0.32	0.20
RF=4	R1	0.42	0.38	0.36	0.34	0.38	0.24	0.26	0.24	0.30	0.28
	R2	0.05	0.11	0.12	0.07	0.30	0.11	0.15	0.16	0.12	0.16
	R3	0.19	0.19	0.18	0.22	0.20	0.14	0.14	0.12	0.24	0.16
	R4	0.20	0.22	0.16	0.16	0.14	0.14	0.15	0.145	0.20	0.22
	R5	0.085	0.19	0.16	0.13	0.18	0.16	0.15	0.16	0.16	0.15
	R6	0.41	0.35	0.23	0.20	0.22	0.18	0.20	0.17	0.26	0.17
RF=8	R1	0.35	0.30	0.30	0.28	0.32	0.15	0.22	0.18	0.26	0.20
	R2	0.018	0.10	0.08	0.06	0.26	0.10	0.12	0.16	0.10	0.15
	R3	0.165	0.16	0.17	0.20	0.16	0.12	0.13	0.10	0.16	0.12
	R4	0.14	0.15	0.15	0.12	0.12	0.12	0.14	0.135	0.16	0.16
	R5	0.082	0.18	0.14	0.12	0.16	0.14	0.14	0.15	0.14	0.15
	R6	0.32	0.28	0.18	0.16	0.18	0.13	0.14	0.14	0.17	0.14
RF=12	R1	0.30	0.25	0.24	0.18	0.20	0.13	0.20	0.16	0.22	0.14
	R2	0.012	0.10	0.04	0.05	0.24	0.10	0.08	0.14	0.08	0.15
	R3	0.16	0.14	0.165	0.15	0.135	0.105	0.12	0.09	0.12	0.10
	R4	0.12	0.13	0.13	0.09	0.105	0.11	0.13	0.13	0.12	0.132
	R5	0.08	0.15	0.12	0.10	0.14	0.125	0.13	0.12	0.10	0.15
	R6	0.22	0.22	0.16	0.15	0.16	0.10	0.12	0.12	0.12	0.12

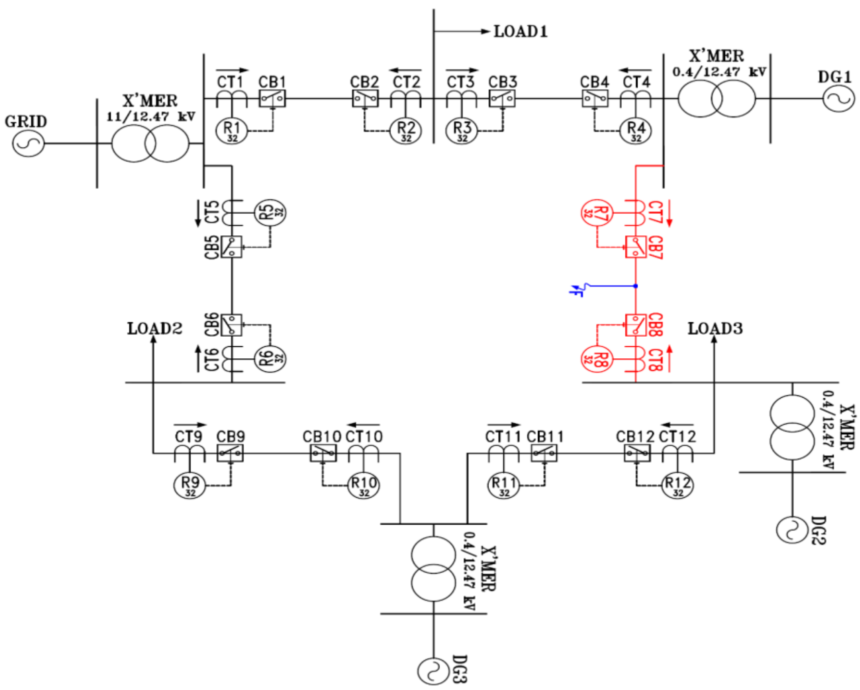

Figure 14. Modified IEEE 9-bus system with DG sources

3. DISCUSSION

This article represents comprehensive analysis of different variables influencing protection coordination of HVDN while integrating DERs. In absence of DERs, only utility grid will supply fault but in presence of DERs, both utility grid as well as DERs will supply fault. In later case, fault current contribution from utility grid will reduce which leads to protection blinding. Fault current contribution from different types of sources is presented in Figure 10 (for distribution network supplied through one source and cossidering fault location F1) and Table 6 (for distribution network supplied through more than one sources including grid and DERs and considering fault location F3). It is observed that current contribution from various types of sources is different (I_{SG}>I_{IG}>I_{PV}) which also has impact on protection coordination as fault current level will be different with various combination of DERs.

Table 6. Fault current contribution from different types of sources (system with more than one sources)

Current contribution from different sources (A)	Case-1	Case-2	Case-3	Case-4	Case-5	Case-6	Case-7	Case-8	Case-9	Case-10
IGrid1	616	643	625	468	501	657	627	646	478	462
IGrid2	1517	1563	-	-	-	-	-	-	-	-
ISG1	-	-	993	976	981	963	980	943	888	939
ISG2	-	-	-	918	667	-	-	-	908	878
ISG3	-	-	-	-	-	207	-	-	979	-
IIG	-	-	-	-	-	-	-	207	-	178
IPV	-	-	-	-	-	-	151	149	-	-

For investigating effect on protection coordination, OCR and directional overcurrent relays (DOCR) with standard IEC 60255 are considered as they are mainly used for distribution network protection. With integration of DERs in distribution network, fault current is increased by 10-20% and grid current contribution reduced by 10-15%. These results are variable subjected to different points like type of source, capacity of source and combination of different sources. This demands modification in relay settings (Tables 3 and 5). For more than two sources, it is also observed that protection will be affected more if IG and solar PV are used as DERs because of their constantly variable power generation and lesser fault current contribution compared to SG. In case of fault when three different DERs along with grid (Figure 13 and considering Case-8) are integrated, contribution from SG, IG, and solar PV are 48%, 11%, and 8% respectively (subjected to vary with capacity and other parameters). If transformer is added in distribution network, there is huge variation in current of different sections and relay current settings (referring Table 3). Location of DERs in distribution network also play pivotal role in alteration of relay coordination.

Network topology also proved instrumental, with ring main configuration which exhibits better system reliability compared to radial system. However, this benefit is offset by increment in number of relays required for its protection and complexity in its setting, where improper DOCR adjustments result in nuisance tripping during higher DER penetration. Apart from this, change in system topology is one of the major issues. In ring main system, if fault occurs in one of the section, respective relays will sense it, send trip command to breakers and isolate the faulty section which will convert ring main system into radial system. There will be drastic change in system parameters and relay should be able to adopt changes in the system. All these discussions above align with observations that increased DER integration causes redistribution of power flow, change in direction of power flow and increment in faulty as well as current, necessitating adaptive protection strategy (as proposed algorithm shown in Figure 15 (in Appendix)) to maintain protection selectivity and reliability.

4. CONCLUSION

Integration of DERs in HVDN brings both opportunities and challenges. The literature review and simulational analysis highlights key factors like fault current contribution from DERs, network topology, DER penetration level and dynamic behaviour of DERs significantly impact the efficacy of protection coordination. When DERs are integrated, protection coordination is also affected by DER location, fault types, fault location, and fault resistance. Increased penetration level of DERs also intriduces challanges like bidirectional power flow which results in altration of protection coordination settings.

With detail simulational analysis performed through PSCAD/EMTDC 4.5 software, effect of these parameters on protection reliability and speed is evaluated. Analysis demonstrated in this article along with understanding of parameters which affects protection coordination will be helpful in its optimization and having reliable and secure operation of DN. Results shows that integrating DERs in distribution system can lead to change in normal as well as fault currents and alteration of protection parameters which necessitates adaptive and robust protection scheme. This analysis will also be hepful in preparing advanced fault detection and classification algorithm which can increase the reliability of developed protection scheme further. Researchers should focus on developing dynamic protection strategies with machine learning techniques to enhance protection coordination in DER-integrated DN that ensures robustness of distribution systems.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ishan Desai	✓	✓	✓		✓	✓	✓	✓	✓		✓			
Nilesh Chothani	✓	✓		✓	✓	✓				✓		✓		
Paul Jacob	✓	✓			✓					✓				

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The author(s) declare(s) that there is no conflict of interest regarding the publication of this manuscript.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article. The data that support the findings of this study are available from the corresponding author [NC], upon reasonable request.

REFERENCES

[1] W. El-Khattam and M. M. A. Salama, "Distributed generation technologies, definitions and benefits," *Electric Power Systems Research*, vol. 71, no. 2, pp. 119–128, Oct. 2004, doi: 10.1016/j.epsr.2004.01.006.

[2] Central Electricity Authority, "Monthly Installed Capacity Reports," [Online]. Available: https://cea.nic.in/installed-capacity-report/?lang=en. (Accessed Aug. 08, 2025).

[3] S. A. Salimon, G. A. Adepoju, I. G. Adebayo, H. O. R. Howlader, S. O. Ayanlade, and O. B. Adewuyi, "Impact of Distributed Generators Penetration Level on the Power Loss and Voltage Profile of Radial Distribution Networks," *Energies*, vol. 16, no. 4, 2023, doi: 10.3390/en16041943.

[4] P. Pokharel and L. Poudel, "Impact of Distributed Generation in Distribution Network Losses and Voltage Profile," *International Journal of Engineering and Applied Sciences (IJEAS)*, vol. 6, no. 10, Oct. 2019, doi: 10.31873/ijeas.6.10.06.

[5] J. Liu, J. Zhang, and D. Zhang, "Effect of distributed generation on power supply reliability of distribution network," in *Proceedings - 8th International Conference on Grid and Distributed Computing (GDC) 2015*, Nov. 2016, pp. 32–35, doi: 10.1109/GDC.2015.13.

[6] A. T. Mohamed, A. A. Helal, and S. M. E. Safty, "Distribution System Reliability Evaluation in Presence of DG," in *Proceedings - 2019 IEEE International Conference on Environment and Electrical Engineering and 2019 IEEE Industrial and Commercial Power Systems Europe, EEEIC/I and CPS Europe 2019*, Jun. 2019, pp. 1–6, doi: 10.1109/EEEIC.2019.8783657.

[7] B. Singh and P. K. Dubey, "Distributed power generation planning for distribution networks using electric vehicles: Systematic attention to challenges and opportunities," *Journal of Energy Storage*, vol. 48, 2022, doi: 10.1016/j.est.2022.104030.

[8] H. Kuang, S. Li, and Z. Wu, "Discussion on advantages and disadvantages of distributed generation connected to the grid," in *2011 International Conference on Electrical and Control Engineering, ICECE 2011 - Proceedings*, pp. 170–173, 2011, doi: 10.1109/ICECENG.2011.6057500.

[9] Z. E. Idrissi, F. E. Mariami, A. Belfqih, and T. Haidi, "Impact of distributed power generation on protection coordination in distribution network," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 23, no. 3, pp. 1271–1280, 2021, doi: 10.11591/ijeecs.v23.i3.pp1271-1280.

[10] S. A. Hosseini, H. A. Abyaneh, S. H. H. Sadeghi, F. Razavi, and A. Nasiri, "An overview of microgrid protection methods and the factors involved," *Renewable and Sustainable Energy Reviews*, vol. 64, pp. 174–186, 2016, doi: 10.1016/j.rser.2016.05.089.

[11] S. A. M. Javadian, M. R. Haghifam, M. F. Firoozabad, and S. M. T. Bathaee, "Analysis of protection system's risk in distribution networks with DG," *International Journal of Electrical Power and Energy Systems*, vol. 44, no. 1, pp. 688–695, Jan. 2013, doi: 10.1016/j.ijepes.2012.08.034.

[12] P. T. Manditereza and R. Bansal, “Renewable distributed generation: The hidden challenges - A review from the protection perspective,” *Renewable and Sustainable Energy Reviews*, vol. 58, pp. 1457–1465, 2016, doi: 10.1016/j.rser.2015.12.276.

[13] A. Yazdaninejadi, A. Hamidi, S. Golshannavaz, F. Aminifar, and S. Teimourzadeh, “Impact of inverter-based DERs integration on protection, control, operation, and planning of electrical distribution grids,” *Electricity Journal*, vol. 32, no. 6, pp. 43–56, 2019, doi: 10.1016/j.tej.2019.05.016.

[14] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, and W. D’haeseleer, “Distributed generation: Definition, benefits and issues,” *Energy Policy*, vol. 33, no. 6, pp. 787–798, 2005, doi: 10.1016/j.enpol.2003.10.004.

[15] L. L. Lai, S. W. Chan, P. K. Lee, and C. S. Lai, “Challenges to implementing distributed generation in area electric power system,” in *2011 IEEE International Conference on Systems, Man, and Cybernetics*, Oct. 2011, pp. 797–801, doi: 10.1109/ICSMC.2011.6083750.

[16] J. I. D. Cisneros-Saldana, S. Samal, M. M. Begovic, and S. R. Samantaray, “On Protection Schemes for AC Microgrids: Challenges and Opportunities,” *IEEE Transactions on Industry Applications*, vol. 60, no. 3, pp. 4843–4854, 2024, doi: 10.1109/TIA.2024.3353721.

[17] H. A. Abdel-Ghany and A. M. Azmy, “Defining the practical constraints of inserting DG units in distribution systems regarding protection schemes,” *International Transactions on Electrical Energy Systems*, vol. 25, no. 12, pp. 3618–3629, 2015, doi: 10.1002/etep.2056.

[18] H. Takele, “Distributed generation adverse impact on the distribution networks protection and its mitigation,” *Heliyon*, vol. 8, no. 6, 2022, doi: 10.1016/j.heliyon.2022.e09624.

[19] M. Karimi, H. Mokhlis, K. Naidu, S. Uddin, and A. H. A. Bakar, “Photovoltaic penetration issues and impacts in distribution network - A review,” *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 594–605, 2016, doi: 10.1016/j.rser.2015.08.042.

[20] Central Electricity Regulatory Commission, “Indian Electricity Grid Code,” Available Online: https://www.cercind.gov.in/Current_reg.html. (Accessed Mar. 01, 2026).

[21] A. Kamel, M. A. Alaam, A. M. Azmy, and A. Y. Abdelaziz, “Protection coordination for distribution systems in presence of distributed generators,” *Electric Power Components and Systems*, vol. 41, no. 15, pp. 1555–1566, 2013, doi: 10.1080/15325008.2013.835361.

[22] A. A. Akila, A. Helal, and H. Eldesouki, “Protection of Active Distribution Systems with DGs,” *International Journal of Emerging Electric Power Systems*, vol. 16, no. 5, pp. 399–411, 2015, doi: 10.1515/ijeeps-2015-0033.

[23] C. B. A. Christy and J. S. Savier, “Impact Assessment of DG in Radial Distribution Networks,” in *2018 20th National Power Systems Conference (NPSC) 2018*, 2018, doi: 10.1109/NPSC.2018.8771792.

[24] S. Conti, “Analysis of distribution network protection issues in presence of dispersed generation,” *Electric Power Systems Research*, vol. 79, no. 1, pp. 49–56, 2009, doi: 10.1016/j.epsr.2008.05.002.

[25] J. C. Gomez and S. M. Nesci, “Effect of the presence of distributed generation on the studies of overcurrent protection coordination,” in *IET Conference Publications*, 2013, vol. 2013, no. 615 CP, doi: 10.1049/cp.2013.0792.

[26] F. Motabarian, M. A. Golkar, and S. Hajiaghasi, “Surveying the effect of distributed generation (DG) on over current protection in radial distribution systems,” in *EPDC 2013 - 18th Electric Power Distribution Network Conference*, 2013, doi: 10.1109/epdc.2013.6565955.

[27] H. Zayandehroodi, A. Mohamed, H. Shareef, and M. Mohammadjafari, “Impact of distributed generations on power system protection performance,” *International Journal of Physical Sciences*, vol. 6, no. 16, pp. 3999-4007, 2011, doi: 10.5897/IJPS11.674.

[28] S. P. George, S. Ashok, and M. N. Bandyopadhyay, “Impact of distributed generation on protective relays,” in *Proceedings - 2013 International Conference on Renewable Energy and Sustainable Energy (ICRESE) 2013*, 2014, pp. 157–161, doi: 10.1109/ICRESE.2013.6927806.

[29] A. A. Eladl, A. N. Sheta, M. A. Saeed, V. Bureš, and B. E. Sedhom, “Assessing the impact of distributed energy resources on overcurrent protection in microgrids for enhanced effectiveness,” *Results in Engineering*, vol. 25, 2025, doi: 10.1016/j.rineng.2025.104461.

[30] M. Dahal, A. K. Jha, and R. M. Ghimire, “Impact of Renewable Distributed Generation on Protection Coordination of Distribution System,” *International Journal of Engineering and Applied Sciences (IJEAS)*, vol. 6, no. 4, 2019, doi: 10.31873/ijeas/6.4.2019.17.

[31] Y. Firouz, S. Farhadkhani, J. Lobry, F. Vallée, A. Khakpour, and O. Durieux, “Numerical comparison of the effects of different types of distributed generation units on overcurrent protection systems in MV distribution grids,” *Renewable Energy*, vol. 69, pp. 271–283, 2014, doi: 10.1016/j.renene.2014.03.035.

[32] S. E. Razavi *et al.*, “Impact of distributed generation on protection and voltage regulation of distribution systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 105, pp. 157–167, May 2019, doi: 10.1016/j.rser.2019.01.050.

[33] K. Malmedal, B. Kroposki, and P. K. Sen, “Distributed energy resources and renewable energy in distribution systems: Protection considerations and penetration levels,” in *Conference Record - IAS Annual Meeting (IEEE Industry Applications Society)*, 2008, doi: 10.1109/08IAS.2008.148.

[34] T. S. Zhan, C. L. Su, Y. D. Lee, J. L. Jiang, and J. T. Yu, “Adaptive OCR coordination in distribution system with distributed energy resources contribution,” *AIMS Energy*, vol. 11, no. 6, pp. 1278–1305, 2023, doi: 10.3934/ENERGY.2023058.

[35] Y. Pan, I. Voloh, and W. Ren, “Protection issues and solutions for protecting feeder with distributed generation,” in *2013 66th Annual Conference for Protective Relay Engineers (CPRE) 2013*, 2013, pp. 92–111, doi: 10.1109/CPRE.2013.6822030.

[36] G. Kaur and Y. M. Vaziri, “Effects of Distributed Generation (DG) interconnections on protection of distribution feeders,” *2006 IEEE Power Engineering Society General Meeting, PES*, 2006, doi: 10.1109/pes.2006.1709551.

[37] L. Ndahepele and S. Chowdhury, “Impact of Distributed Generation on Traditional Protection in Distribution and Transmission Systems: A Review,” *2020 IEEE PES/IAS PowerAfrica, PowerAfrica 2020*, 2020, doi: 10.1109/PowerAfrica49420.2020.9219840.

[38] B. Fani, H. Bisheh, and I. Sadeghkhani, “Protection coordination scheme for distribution networks with high penetration of photovoltaic generators,” *IET Generation, Transmission and Distribution*, vol. 12, no. 8, pp. 1802–1814, 2018, doi: 10.1049/iet-gtd.2017.1229.

[39] Y. M. Nsaif, M. S. H. Lipu, A. Ayob, Y. Yusof, and A. Hussain, “Fault Detection and Protection Schemes for Distributed Generation Integrated to Distribution Network: Challenges and Suggestions,” *IEEE Access*, vol. 9, pp. 142693–142717, 2021, doi: 10.1109/ACCESS.2021.3121087.

[40] M. Singh, “Protection coordination in distribution systems with and without distributed energy resources- a review,” *Protection and Control of Modern Power Systems*, vol. 2, no. 1, 2017, doi: 10.1186/s41601-017-0061-1.

[41] V. Telukunta, J. Pradhan, A. Agrawal, M. Singh, and S. G. Srivani “Protection challenges under bulk penetration of renewable energy resources in power systems: A review,” *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 365–379, 2017, doi: 10.17775/cseejpes.2017.00030.

[42] A. S. N. Huda and R. Živanović, “Large-scale integration of distributed generation into distribution networks: Study objectives, review of models and computational tools,” *Renewable and Sustainable Energy Reviews*, vol. 76, pp. 974–988, 2017, doi: 10.1016/j.rser.2017.03.069.

[43] L. I. Dulău, M. Abrudean, and D. Bică, “Effects of Distributed Generation on Electric Power Systems,” *Procedia Technology*, vol. 12, pp. 681–686, 2014, doi: 10.1016/j.protcy.2013.12.549.

[44] Z. Klaić, G. Knežević, M. Primorac, and D. Topić, “Impact of photovoltaic and biogas power plant on harmonics in distribution network,” *IET Renewable Power Generation*, vol. 14, no. 1, pp. 110–117, 2020, doi: 10.1049/iet-rpg.2019.0528.

[45] E. P. Madruga, D. P. Bernardon, R. P. Vieira, and L. L. Pfitscher, “Analysis of transient stability in distribution systems with distributed generation,” *International Journal of Electrical Power and Energy Systems*, vol. 99, pp. 555–565, 2018, doi: 10.1016/j.ijepes.2018.01.039.

[46] J. A. Martinez and J. Martin-Arnedo, “Impact of distributed generation on distribution protection and power quality,” *2009 IEEE Power and Energy Society General Meeting, PES ’09*, 2009, doi: 10.1109/PES.2009.5275777.

[47] B. Hussain, S. M. Sharkh, and S. Hussain, “Impact studies of distributed generation on power quality and protection setup of an existing distribution network,” in *SPEEDAM 2010 - International Symposium on Power Electronics, Electrical Drives, Automation and Motion*, Jun. 2010, pp. 1243–1246, doi: 10.1109/SPEEDAM.2010.5545061.

[48] M. Khederzadeh, H. Javadi, and S. M. A. Mousavi, “Source type impact of Distributed Generation (DG) on the distribution protection,” in *IET Conference Publications*, 2010, no. 558 CP, doi: 10.1049/cp.2010.0299.

[49] M. S. Thomas and P. P. Terang, “Interconnection issues for distributed resources in a smart distribution system,” in *India International Conference on Power Electronics, IICPE*, 2012, doi: 10.1109/IICPE.2012.6450446.

[50] S. C. Reddy, G. Saritha, and N. Vikas, “Effect of distributed generation on distribution systems during faults,” in *Proceeding of the IEEE International Conference on Green Computing, Communication and Electrical Engineering (ICGCCEE) 2014*, 2014, doi: 10.1109/ICGCCEE.2014.6922356.

[51] M. Meskin, A. Domijan, and I. Grinberg, “Impact of distributed generation on the protection systems of distribution networks: Analysis and remedies – review paper,” *IET Generation, Transmission and Distribution*, vol. 14, no. 24, pp. 5816–5822, 2020, doi: 10.1049/iet-gtd.2019.1652.

[52] K. H. Oon, C. K. Tan, A. H. A. Bakar, H. S. Che, H. Mokhlis, and H. A. Illias, “Establishment of fault current characteristics for solar photovoltaic generator considering low voltage ride through and reactive current injection requirement,” *Renewable and Sustainable Energy Reviews*, vol. 92, pp. 478–488, 2018, doi: 10.1016/j.rser.2018.05.001.

[53] T. M. Masaud and R. D. Mistry, “Fault current contribution of Renewable Distributed Generation: An overview and key issues,” in *2016 IEEE Conference on Technologies for Sustainability (SusTech) 2016*, 2017, pp. 229–234, doi: 10.1109/SusTech.2016.7897172.

[54] N. Nimpitiwan, G. T. Heydt, R. Ayyanar, and S. Suryanarayanan, “Fault Current Contribution From Synchronous Machine and Inverter Based Distributed Generators,” *IEEE Transactions on Power Delivery*, vol. 22, no. 1, pp. 634–641, 2007, doi: 10.1109/TPWRD.2006.881440.

[55] International Electrotechnical Commission, “Measuring relays and protection equipment,” *IEC 60255-1:2022*, 2022.

[56] R. N. Bhargavi, P. R. Kumar, M. L. Swarupa, and C. Shravani, “Effect of Transformer connections in Distributed Generation system,” in *Proceedings of the 2020 International Conference on Renewable Energy Integration into Smart Grids: A Multidisciplinary Approach to Technology Modelling and Simulation (ICREISG) 2020*, 2020, pp. 95–98, doi: 10.1109/ICREISG49226.2020.9174506.

APPENDIX

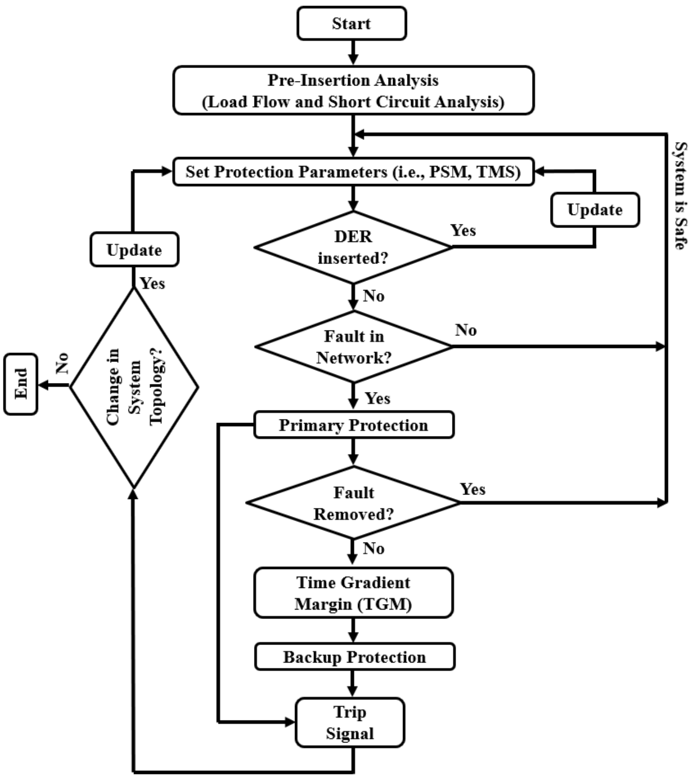

Figure 15. Proposed algorithm for protection of distribution network with DERs

BIOGRAPHIES OF AUTHORS

Ishan Desai received his BE degree from Gujarat University, Ahmedabad, Gujarat, India in 2010, MTech from Nirma University, Ahmedabad, Gujarat, India in 2012 and currently pursuing Ph.D. degree from Gujarat University, Ahmedabad, Gujarat, India in the field of Electrical Engineering. He is working as Assistant Professor in Department of Electrical Engineering, Parul University, Vadodara, India. His area of interest are power system protection, electrical substation design and power system transmission, and distribution. He has published more than five papers in international and national journal as well as conferences. He can be contacted at email: ishandesai31081988@gmail.com.

Nilesh Chothani received his BE degree from Saurashtra University, Rajkot, Gujarat, India in 2001, ME from Sardar Patel University, V. V. Nagar, Gujarat, India in 2004 and Ph.D. degree from Sardar Patel University, V. V. Nagar, Gujarat, India in 2013 in the field of Electrical Engineering. He is working as Assistant Professor in Department of Electrical Engineering, Pandit Deendayal Energy University, Gandhinagar, India. His area of interest is power system protection and power system. He has published more than 50 papers in various national and international journals as well as conferences. He can be contacted at email: chothani_nilesh@rediffmail.com.

Paul Jacob received Diploma in Electrical Engineering in 1997 before B.Tech. in Electrical Engineering from The Institution of Engineers (India) in 2012 and M.Tech. in Electrical Engineering at Parul Institute of Engineering and Technology in 2022. He has gained engineering projects, operations and maintenance expertise from professional life of 25 years in different types of facilities and in different regions. He is a Chartered Engineer and Corporate Member of IEI (India), a fellow member of IHEEM-UK and PMP-USA Certified Professional. Present responsibilities as executive director, engineering and facilities management include managing a very large hospital complex for its power generation, distribution and entire maintenance management as certified authorized person (AP) of HTM 06-02 (LV) and HTM 06-03 (HV). As executive member of other professional bodies, actively pursuing papers in seminars, souvenirs and journals other than working as train to trainer to his organization. He can be contacted at email: pauljacob771@gmail.com.