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An Optimization-based Protection Strategy in an Active Distribution Network using Double Dual-Setting Directional Overcurrent Relays to Increase DG Penetration

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ABSTRACT

Coordination between protection devices is one of the important issues in any protection scheme of an electrical power system. The tendency to increasingly use distributed generation has jeopardized the selectivity of overcurrent relays in active distribution networks. To increase the penetration level of distributed generation in these networks, an increase in the Protection Coordination Index (PCI) of the network is a must. For this purpose, in this paper, voltage-current-time characteristics and Dual Setting Directional Overcurrent Relays are used. In this case, coordination is not a trivial task and imposes further complexity. Since Dual Setting Directional Overcurrent Relays are capable to break current in both directions with separate tuning, they have the flexibility to improve the protection coordination index. Moreover, voltage-current-time characteristics employ voltage in the operation of relays. This capability can also be used in reducing the optimization of the protection scheme and provides more flexibility in coordination procedures. Afterward, the protection scheme is developed by user-adjustable voltage-current-time characteristics to improve the PCI as much as possible. The proposed scheme is modelled as a nonlinear programming approach which is solved by a Genetic Algorithm (GA).

1. Introduction

The purpose of the power system is to generate, transmit, and distribute electrical energy and deliver it to consumers. The importance of the distribution sector in the electricity industry is not hidden from anyone. The share of the distribution network from a total investment made in the electricity industry is significant. Hence, optimal planning, design, and operation of this system are very important to meet the economic performance and targets set by the investors. Customer satisfaction with acceptable power quality, ensuring technical stability and continuity of service, promoting economic productivity, and maintaining distribution network security are examples of consumer services that are offered by distribution companies. Meanwhile, paying enough attention to protection issues is crucial to guarantee the safe and secure operation of distribution networks.

Two-way power flow in a ring distribution network is effective in the structure of complex protection designs, compared to one-way currents. This complexity increases with increasing network size and scale. In addition, this situation becomes more complex if the network structure is multi-feed or the penetration of distributed generation is considerable. Since radial distribution systems with one-way power flow are considered, only one backup relay is sufficient for each of them. However, this is not the case for multidirectional multi-feed networks. In these

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networks, two or more backup relays are required to ensure the performance of a reliable protection scheme. To deal with this problem, directional overcurrent relays have been proposed as a suitable and effective solution. In this regard, the optimal coordination of these relays is still a challenging part for researchers. In this regard, finding a protection solution to increase the penetration of distributed generation can be interesting for network operators.

Ref. [1] considers the application of the new voltage-current-time characteristic in grid-connected operating modes and microgrid islands. The coordination plan of adaptive protection with the presence of wind farms has been investigated in [2]. In [3], a protection relay scheme based on the combined coordination of Dual Setting Directional Overcurrent Relays (D-DOCRs) and distance relays in distribution networks is described which can cover the possible N-1 states as a complex problem. Ref. [4] presents the microgrid protection scheme, which is divided into four levels including load, a loop path, feeder, and microgrid. In [5], a new algorithm for directional overcurrent relay has been introduced which uses only current signals to determine the direction of fault. In [6], a protection coordination scheme of directional overcurrent relays in ring networks has been proposed based on an interpolation method to minimize the operating time of the main and backup relays simultaneously with a new objective function. Also, in [7], a method for improving the objective function of minimizing the operating time of overcurrent relays has been proposed. Ref. [8] discusses the relationship between protection coordination and reactive power issues. In [9], the protective coordination of overcurrent relays has been studied using the combined PSO-GSA algorithm and considering wind and solar sources to achieve optimal coordination by considering the effect of environmental factors on the optimal settings of the relays. Ref. [10] provides an optimization-based method using NSGA II for coordinating directional overcurrent relays in order to reduce the number of times the main and backup relays are out of alignment. Ref. [11] investigates the optimal coordination of directional overcurrent relays using the SOS algorithm. In [12], a hybrid optimization algorithm based on Gravitational Search Algorithm-Sequential Quadratic Programing (GSA-SQP) is used for optimal coordination of directional overcurrent relays. Ref. [13] provides a method that, in addition to synchronizing overcurrent relays, specifies the minimum unsatisfied constrained as Broken Constraints (BC). In [14], a new mathematical expression is proposed that considers transient stability constraints to determine the optimal relay settings. To solve the optimization model of directional overcurrent relay settings, five types of modified differential evolution have been applied [15]. In [16], the protection coordination problem is solved to determine the optimal relay settings by considering N-1 scenarios dues to the outage of a transmission line, a DG unit, or a substation. In [17], a method to ensure the performance of the protection system by considering a power system planning approach and the future expansion capabilities of DG in the network is proposed. The new scheme proposed in [18] is to what extent the impedance value of FCL below its critical value can be reduced by resetting only one adaptive relay (relative to the original settings) to obtain relay coordination.

In [19], a multi-objective model is developed based on the maximum total capacity of DGs, voltage increase, power loss reduction, and fault current level. Assessing the maximum usable capacity of distributed generation resources for overcurrent relays, Dual Setting Directional Overcurrent Relays based on the use of voltage-current-time characteristic curve have been performed in [20]. In [21], Dual Setting Directional Overcurrent Relays are equipped with two reverse time-current characteristics where, the settings of which will depend on the direction of the fault in such a way that they are able to function in both forward and reverse directions, but with different settings. Ref. [22] provides the characteristic of Dual-Inverse Overcurrent Relay (DIOCR) to provide proper coordination and maintain DG stability.

Increasing the penetration of distributed generation to maximize their benefits along with meeting network protection constraints is considered the ideal goal of the paper, which leads to a sustainable power supply and improves reliability in power distribution networks.

Using the new protection scheme and optimal coordination of relays, we will attempt to improve the penetration of distributed generation by defining an indicator to achieve the goals of sustainable power supply and improving the reliability of power distribution networks. In this regard, in this paper, the following points have been highlighted as the contribution:

- Introduce a new protection strategy in active distribution networks using Dual-Setting and double Inverse OCR (DS-DIOCR),
- Increase the penetration of DGs by meeting protection-related constraints,
- Optimal equipment coordination to provide rapid protection.

The paper is organized into four sections: First, with a comprehensive introduction, the need to study the research topic is explained. The description of the study scenario and the detailed description of the problem of their optimization are examined in the second section. In the following, the research is performed in two phases of protection coordination studies in the context of the implementation of the proposed model. In order to evaluate the effectiveness of the proposed method, a numerical comparison of results and their analysis is considered in the fourth section. Finally, the analytical results of this study and the recommendations for future research are presented.

2. Mathematical Modeling of the problem

In order to achieve the purpose of paper, optimization is performed in two steps according to Fig. 1.

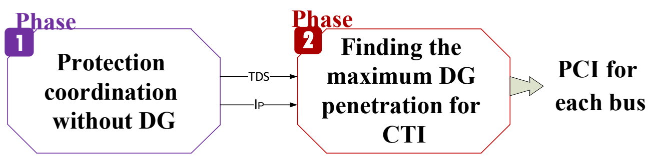


Fig. 1. Two stage proposed approach

A. Phase 1: Modeling protection Coordination

In the following, the coordination strategy based on the voltage-current-time characteristic is presented and the proposed method is developed based on the user-defined coordination approach. The DOCR characteristic is expressed as follows:

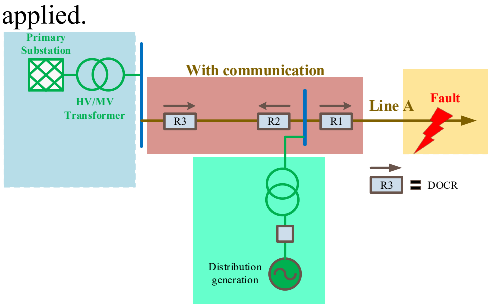
$$t = \frac{TDS_i \times A}{(W)^B - 1} \tag{1}$$

$$W = \frac{I_{SC}}{Ip} \tag{2}$$

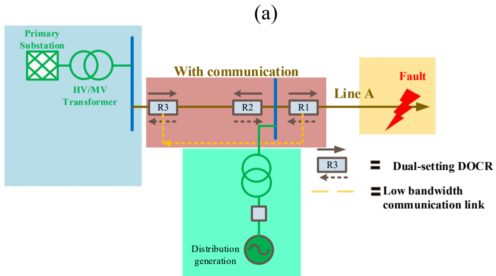
Where:
t: Relay operation time
i: Relay counter
TDS: Time Dial Setting
TDS_i: Time Dial Setting for i^{th} relay
A, B: Relay constants
Isc: Fault current seen by relay
Ip: Pickup current relay
To improve performance of relay (time operation minimization), according to equation (1), two features added:

- group setting (dual-setting) in Fig. 2 and 3,
- Time–current–voltage characteristics in Fig. 4

are applied.

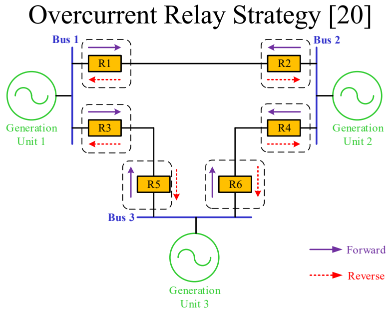


(a)

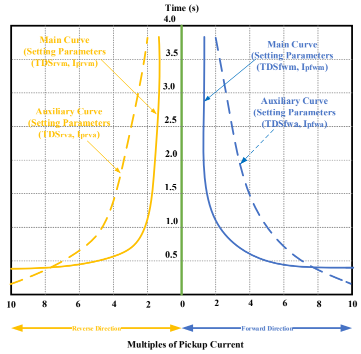


(b)

Fig. 2. Active distribution network with (a) classical protection design (b) Dual Setting Directional Overcurrent Relay Strategy [20]



(a)



(b)

Fig. 3. (a) protection with Dual-setting directional Overcurrent relay, (b) DS-DIOCR time-current characteristics

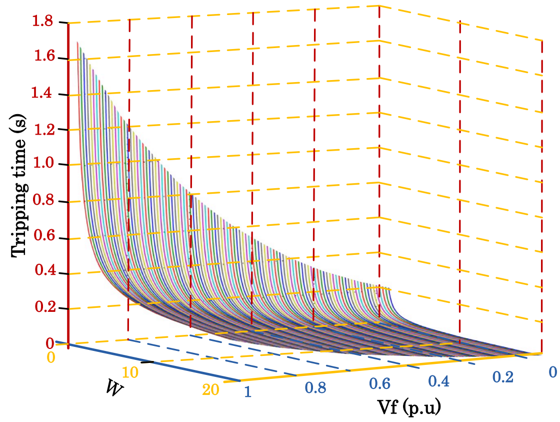


Fig. 4. Time–current–voltage characteristics [20]

Because VTs are part of directional overcurrent relays, the characteristics of these relays can be updated by the voltage indicator. The voltage-current-time characteristic of the DS-DIOCR relay is rewritten in the following equation:

$$t=\left(\frac{1}{e^{1-V_f}}\right)^K TDS \frac{A}{\left(\frac{I_{SC}}{Ip}\right)^B - 1} \tag{3}$$

Where:
K: This characteristic adds a voltage amplitude as a new dimension in the relay operation characteristic (constant regulating parameter of the relay)
V_f: Fault voltage range measured by the corresponding relay (prionite)

$$t_{ijlfwm} = \left(\frac{1}{e^{1-V_{fijlfwm}}}\right)^K TDS_{fwmi} \frac{A}{\left(\frac{I_{scfwmij}}{I_{pfwmi}}\right)^B - 1} \tag{4}$$

$$t_{ijlfwa} = \left(\frac{1}{e^{1-V_{fijlfwa}}}\right)^K TDS_{fwai} \frac{A}{\left(\frac{I_{scfwaij}}{I_{pfwai}}\right)^B - 1} \tag{5}$$

$$t_{ijlrvm} = \left(\frac{1}{e^{1-V_{fijlrvm}}}\right)^K TDS_{rvmi} \frac{A}{\left(\frac{I_{scrvmij}}{I_{prvmi}}\right)^B - 1} \tag{6}$$

$$t_{ijlrva} = \left(\frac{1}{e^{1-V_{fijlrva}}}\right)^{K} TDS_{rvai} \frac{A}{\left(\frac{I_{scrvaij}}{I_{prvai}}\right)^{B} - 1} \quad (7)$$

The voltage-current-time characteristics of the relay for DS-DIOCR is shown in the forward-reverse and main-auxiliary directions according to the following equations:

Where:

t: Relay operation time
j: Fault type counter
l: Fault location
t_{ijlfwm}: The time of disconnection of the 1st relay due to the fault of the 1st counter in the position of the 1st counter in the direction of the main-curve
t_{ijlrvm}: The time of disconnection of the 1st relay due to the fault of the 1st counter in the location of the 1st counter in the opposite direction - the main curve
t_{ijlfwa}: Im relay disconnection time due to jm counter fault at lm counter location in auxiliary-curve direction
t_{ijlrva}: Im relay disconnection time due to jm counter fault at lm counter location in reverse- auxiliary curve direction
V_{fijl}: Equivalent prionite is the phase fault voltage measured at the 1st meter relay for the 1st meter fault at the 1st meter location
$V_{fijlfwm}$: Equivalent prionite phase fault voltage measurement, measured at the 1st meter relay for the 1st meter fault at the 1st meter position in the direction of the main-curve
$V_{fijlfwa}$: Equivalent prionite phase fault voltage measurement, measured at the 1st meter relay for the 1st meter fault at the 1st meter position in the auxiliary -curve direction
$V_{fijlrvm}$: Equivalent prionite phase voltage voltage measurement, measured at the 1st meter relay for the 1st meter fault at the 1st position in the opposite direction - main curve
$V_{fijlrva}$: Equivalent prionite phase fault voltage measurement, measured at the 1st meter relay for the 1st meter fault at the 1st meter in the opposite direction - auxiliary curve
$I_{scfwmij}$: Short-circuit current measured in the secondary winding of the transformer. Relay current of the 1st meter
$I_{scfwaij}$: Short-circuit current measured in the secondary winding of the transformer. Relay current of the 1st meter
$I_{scrvmij}$: Short-circuit current measured in the secondary winding of the transformer. Relay current of the 1st meter
$I_{scrvaij}$: Short-circuit current measured in the secondary winding of the transformer. Relay current of the 1st meter
The main objective of first phase is to minimize relay operation time. The objective function of the first phase (protection coordination) is:

$$Minimize\,T = \sum_{j=1}^{M}\sum_{l=1}^{L}\left(\left(\sum_{i=1}^{N} t_{fwij} + \sum_{k=1}^{N} t_{rvkj}\right) + \left(\sum_{x=1}^{X}\left(t_{ijlfw}^{x_{ijl}} + t_{ijlrv}^{x_{ijl}}\right)\right)\right) \quad (8)$$

Where:

$\sum_{i=1}^{N} t_{fwij}$: i^{th} relay operation time in duration j^{th} fault by forward direction
$\sum_{k=1}^{N} t_{rvkj}$: k^{th} relay operation time in duration j^{th} fault by reverse direction
$\left(\sum_{x=1}^{X}\left(t_{ijlfw}^{x_{ijl}} + t_{ijlrv}^{x_{ijl}}\right)\right)$: i^{th} backup relay operation time in duration j^{th} fault at l^{th} location by forward direction
T: Total time of relay operation
N: Total number of relays
M: The total number of types of Faults studied
L: Total number of Fault locations
x: Backup counter
bx: X^{th} backup relay
X: Total number of backup relays for each main relay
t_{fwij}: Time of disconnection of the i-th relay during the j-th fault in the forward direction
t_{rvkj}: Time to disconnect the km relay during the jm fault in the reverse direction
$t_{ijlfw}^{x_{ijl}}$: Time of disconnection of the i-th support relay due to the j-th fault in the l-th position in the forward direction
$t_{ijlrv}^{x_{ijl}}$: Time to disconnect the 1st support relay due to the 1st fault in the 1st position in the reverse direction
t_{jl}^{bx} : Xm counter backup relay operation time for jm counter type fault at lm counter location
t_{jl}^{p}: Main operating relay time for j m counter type fault at l m counter location

This objective function is optimized subject to the following constraints:

$$t_{rvkjl}^{bx} - t_{fwijl}^{p} \geq CTI, \forall i,j,k,\{l,x\} \quad (9)$$

Where:
CTI : Coordination time interval

$$TDS_{i\text{-}min} \leq TDS_{fwmi} \quad (10)$$

$$TDS_{i\text{-}min} \leq TDS_{fwai} \quad (11)$$

$$TDS_{rvmi} \leq TDS_{i\text{-}max} \quad (12)$$

$$TDS_{rvai} \leq TDS_{i\text{-}max} \quad (13)$$

Where:

TDS_i: Timing relay timing of the i-th counter
TDS_{fwmi}: Timing adjustment of the i-counter counter relay in the direction of the main-curve
TDS_{fwai}: Timing adjustment of the i-counter counter relay in the auxiliary-curve direction
TDS_{rvmi}: Timing adjustment of the i-counter counter in the reverse direction - the main curve
TDS_{rvai}: Timing adjustment of the i-counter relay in the reverse direction - auxiliary curve
$TDS_{i\text{-}min}$: Low limit TDS adjustment relay
$TDS_{i\text{-}max}$: High limit TDS relay setting

$$I_{pi\text{-}min} \geq I_{pfwmi} \quad (14)$$

$$I_{pi\text{-}min} \geq I_{pfwai} \tag{15}$$

$$I_{prvmi} \leq I_{pi\text{-}max} \tag{16}$$

$$I_{prvai} \leq I_{pi\text{-}max} \tag{17}$$

Where:

$I_{pi\text{-}min}$: Lower limit of main relay pickup current setting

$I_{pi\text{-}max}$: High limit setting of the main relay pickup current

I_{pfwmi}: Pickup current (minimum amount of current for which the 1st relay will operate) in the direction of the main-curve

I_{pfwai}: Pickup current (the minimum amount of current for which the 1st relay will operate) in the direction of auxiliary -curve

I_{prvmi}: Pickup current (minimum amount of current for which the i relay will operate) in the reverse direction - the main curve

I_{prvai}: Pickup current (the minimum amount of current for which the i relay will operate) in the reverse direction - auxiliary curve

$$A_{min} \leq A_{fwm,i} \leq A_{max} \quad \forall i \tag{18}$$

$$A_{min} \leq A_{fwa,i} \leq A_{max} \quad \forall i \tag{19}$$

$$A_{min} \leq A_{rvm,i} \leq A_{max} \quad \forall i \tag{20}$$

$$A_{min} \leq A_{rva,i} \leq A_{max} \quad \forall i \tag{21}$$

$$B_{min} \leq B_{fwm,i} \leq B_{max} \quad \forall i \tag{22}$$

$$B_{min} \leq B_{fwa,i} \leq B_{max} \quad \forall i \tag{23}$$

$$B_{min} \leq B_{rvm,i} \leq B_{max} \quad \forall i \tag{24}$$

$$B_{min} \leq B_{rva,i} \leq B_{max} \quad \forall i \tag{25}$$

Where:

$A_{fwm,i}$: Constant parameter of the relay that changes in the direction of operation of the main curve of the relay i

$A_{fwa,i}$: A constant parameter of a relay that changes in the direction of the auxiliary -curve operation of the i-relay

A_{min}: The lower limit of the constant parameter A

A_{min}: The upper limit of the constant parameter A

$A_{rvm,i}$: Relay constant parameter that changes in the reverse direction - main curve of relay i

$A_{rva,i}$: A constant parameter of a relay that changes in the reverse direction of the auxiliary-curve operation of relay i

$B_{fwm,i}$: Constant parameter of the relay that changes in the direction of operation of the main curve of the relay i

$B_{fwa,i}$: A constant parameter of a relay that changes in the direction of the auxiliary -curve operation of the i-relay

B_{min}: The lower limit of the constant parameter B

B_{min}: The lower limit of the constant parameter B

$B_{rvm,i}$: Relay constant parameter that changes in the reverse direction - main curve of relay i

$B_{rva,i}$: A constant parameter of a relay that changes in the reverse direction of the auxiliary -curve operation of relay i

$$1 \leq K_{fwm} \leq 5 \tag{26}$$

$$1 \leq K_{fwa} \leq 5 \tag{27}$$

$$1 \leq K_{rvm} \leq 5 \tag{28}$$

$$1 \leq K_{fwa} \leq 5 \tag{29}$$

Where:

K_{fwm}: Adjustment parameter K in the direction of operation according to the main curve relay

K_{fwa}: Adjustment parameter K for the operation of the auxiliary-curve relay

K_{rvm}: Adjustment parameter K in the opposite direction of the main-curve relay

K_{rva}: Adjustment parameter K for reverse operation of auxiliary -curve relay

Which in above relations:

- equation (9): Selectivity constraint,
- equation (10-14): *TDS* constrains,
- equation (14-17): I_P constrains,
- equation (18-25): relay's constant parameters constraints,
- In addition, equation (26-29): *k* related constraints.

B. Phase 2: Maximizing usable capacity

In this section, the PCI is defined to evaluate the ability of the protection scheme in the acceptable penetration capacity of DG resources. Afterward, a proposed protection scheme based on voltage-current-time characteristics for Dual Setting Directional Overcurrent Relays is presented. Finally, it is expanded based on a user-defined coordination strategy.

The main objective function in the first stage of optimization of this paper is to minimize the operating time of the protection system and the main objective function in the second stage of optimization is to find the maximum usable capacity of DG resources while maintaining protective coordination in the first stage.

PCI is calculated in proportion to the optimal CTI according to the optimal changes in the level of penetration. If the rated DG capacity in bus b is considered S_b^{DG} in terms of megavolt-amps, the DG penetration rate is obtained from the following equation:

$$P = \sum_{b \in B} S_b^{DG} \tag{30}$$

Where:

P: DG capacity in MVA

DG penetration causes a change in the admittance matrix, which of course will also change the impedance matrix. Therefore, during the fault process, different currents pass through the relays at the same points. As a result, it can be inferred that the IFs function of DG capacity is expressed as follows:

$$IF = f(S_b^{DG}) \tag{31}$$

In the PCI calculation process, the P value is calculated for different CTI values. The following equation can be used to calculate PCI:

$$PCI = -\frac{\Delta P}{\Delta CTI} \tag{32}$$

Where:

ΔP : Rate of change P

CTI : Coordination time interval

ΔCTI : CTI change rate

The objective function of the second phase for finding the maximum usable capacity of DG is expressed as follows:

$$Maximize\ P = \sum_{b \in B} S_b^{DG} \tag{33}$$

Where:
b: Bus counter
B: Total number of busbars
S_b^{DG} : DG capacity can be installed in bus *b* (in MVA)

As mentioned earlier, the fault currents change with any change in the level of DG penetration. The currents observed by the relay are calculated by the following equation:

$$I_{scsf}=f\left(S_{DGk}\right)=\frac{V_s}{Z_{sff}}=\frac{1}{\left(Y\left(s.s\right)+\frac{1}{Z_{DG}}\right)^{-1}} \quad (34)$$

Where:
I_{scsf}: Short circuit current in the presence of Sth source due to fault occurrence
S_{DGk}: DG capacity to be installed in each location
$S_{DGk\text{-}max}$: High DG capacity limit can be installed in each bus
V_s: DG voltage level
Z_{sff}: The diagonal element of the fth matrix of the equivalent impedance matrix in the presence of the source Sth
Y(s,s): The Norton equivalent admittance associated with the busbore where the Sth source is located
Z_{DG}: DG Impedance

DG capacity constraint is considered in the following:

$$0 \le S_{DGk} \le S_{DGk\text{-}max}, \forall k \quad (35)$$

Finally, the PCI value is obtained by the following equation (32).

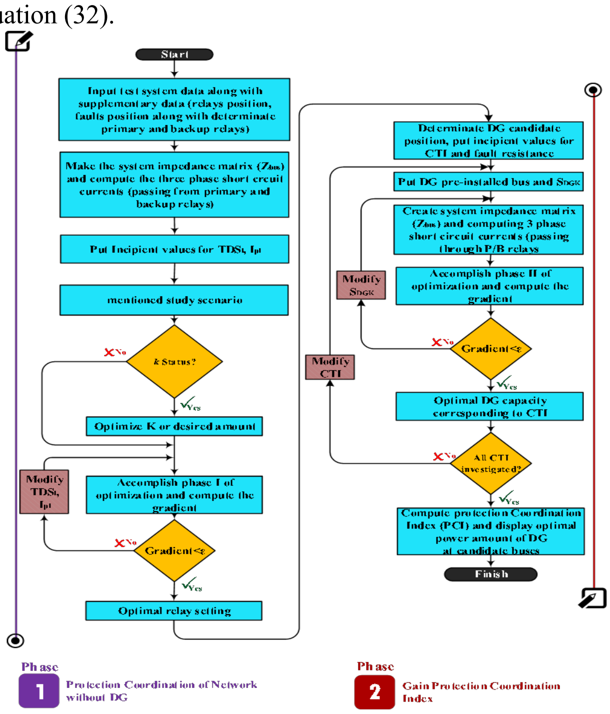


Fig. 5. Flowchart of the proposed approach

3. Conclusion

In this paper, after investigating the effect of dual control protection on PCI, the voltage-current-time characteristic was added to the protection design. The proposed Strategy increased PCI to maximize the penetration level of distributed generation in distribution networks. DS-DIOCRs protect both directions. In addition, the voltage-current-time characteristic provides more flexibility in the coordination process. To evaluate the performance of the proposed PCI. To evaluate the performance of the proposed method, two scenarios were considered in the study. User-definable current-time was evaluated in a two-dimensional dual protection method to improve PCI. In this study, not only the operating time of the protection relays but also the PCI index was improved by using dual-mode relays to maximize DG penetration. It is noted that observance of selectivity and sensitivity constraints in this research has been one of the main priorities in most cases this issue has been observed in the results. Also, in this paper, the proposed dual-voltage protection based on voltage-current-time characteristics is provided. The results showed that the PCI improved significantly. The proposed approach is able to be implemented in real-world software and hardware platform.

4. Tests and Results

The IEEE 30-bus test system is considered as a case study with 28 pairs of DS-DIOCR relays, 52 pairs of relays, 18 communication lines and three-way power supply.

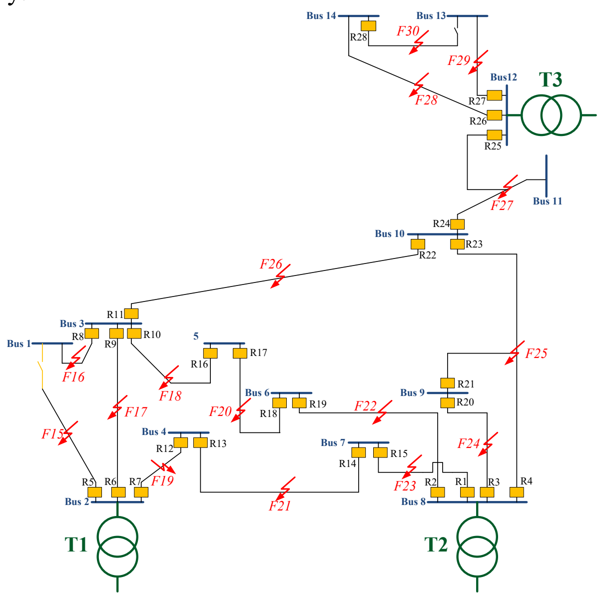


Fig. 6. IEEE 30-bus test system

The proposed method scenario is evaluated using the voltage-current-time characteristic for DS-DIOCR. In addition to the TDS and Ip adjustment parameters, it also includes parameters A, B, and K.

The complete results of the algorithm are presented in the appendix. So that table 1 shows the optimal adjustment parameters of relay main curve. Also, Table 2 shows the optimal adjustment parameters of relay auxiliary curve. Table 3 shows the optimal disconnection times of the main and backup relays and Table 4 shows the PCI values. It is understood from the results that the operation time of the relays has been reduced along with the improvement of PCI value. This indicates the scalability of the proposed method. Also figure 7 and 8 show PCI values and Variation of DG penetration in CTI=0.3 for IEEE 30-bus test system respectively.

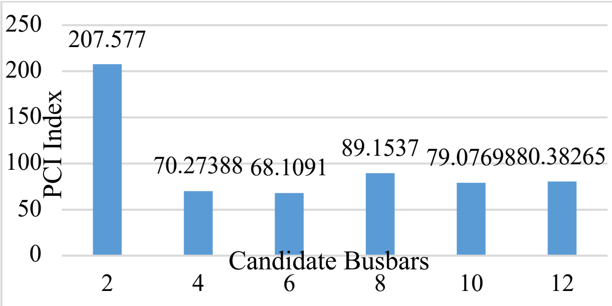


Fig. 7. PCI values for IEEE 30-bus test system

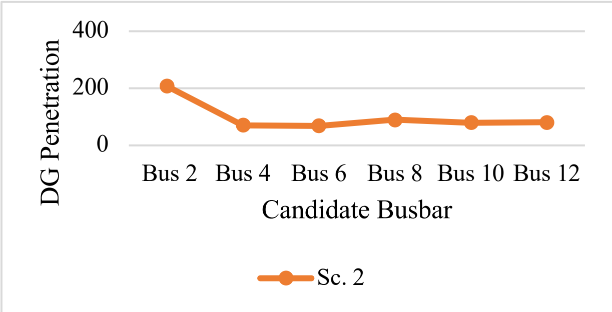


Fig. 8. Variation of DG penetration in CTI=0.3 for IEEE 30-bus test system

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Appendix

Table. 1 Optimal tuned parameters of relay in IEEE 30-bus test system- Main curve

Relay Counter	Adjusted parameters (k, A, and B)									
	TDS_{fwm}	TDS_{rvm}	I_{pfwm}	I_{prvm}	A_{fwm}	A_{rvm}	B_{fwm}	B_{rvm}	K_{fwm}	K_{rvm}
1	0.1246	0.3670	0.2283	0.0185	0.0999	0.0880	0.0150	0.0306	2.3427	1.9914
2	0.1234	0.2101	0.1257	0.0543	0.1087	0.1074	0.0189	0.0324	2.4884	1.8804
3	0.0924	0.6617	0.1625	0.0037	0.1006	0.1155	0.0137	0.0152	2.4624	2.1888
4	0.0984	0.6380	0.1651	0.0025	0.1149	0.0979	0.0194	0.0208	2.9364	2.0863
5	0.1101	0.3971	0.1050	0.3142	0.0992	0.0918	0.0234	0.0175	2.6448	2.0452
6	0.1195	0.1865	0.1470	0.0893	0.1055	0.0967	0.0225	0.0279	2.4001	2.0901
7	0.1186	0.1752	0.1101	0.1128	0.0962	0.1078	0.0211	0.0404	2.3848	2.0860
8	0.1667	0.3945	1.3049	0.3188	0.1113	0.1180	0.0207	0.0215	2.3165	1.8385
9	0.1162	0.7421	0.0521	0.2706	0.1108	0.1020	0.0186	0.0337	2.6817	1.1074
10	0.1303	1.9115	0.1116	0.0489	0.1135	0.1156	0.0246	00257	2.7864	1.8763
11	0.1402	1.3581	0.5007	0.1352	0.0820	0.0826	0.0229	0.0212	2.5453	1.8919
12	0.2447	1.3244	0.6295	0.3960	0.0788	0.0979	0.0197	0.0431	2.5254	2.1754
13	0.2478	1.2829	0.6131	0.4427	0.1070	0.1008	0.0221	0.0143	2.5249	2.1787
14	0.2478	1.7797	0.3522	0.6320	0.1322	0.1038	0.0214	0.0254	2.3758	2.0024
15	0.3115	0.7955	0.7588	0.3585	0.1351	0.1078	0.0229	0.0370	2.5547	2.1006
16	0.2522	1.6474	0.7004	0.5147	0.1197	0.1119	0.0208	0.0171	2.6030	2.2085
17	0.2926	1.4317	0.6327	0.4787	0.1068	0.1115	0.0201	0.0136	2.4288	2.0612
18	0.2800	1.6602	0.5612	0.5324	0.1157	0.0888	0.0163	0.0218	2.4544	2.1187
19	0.2827	1.6507	0.7200	0.5433	0.1204	0.1142	0.0153	0.0174	2.3926	1.8951
20	0.3093	1.8716	0.4859	0.6209	0.1296	0.1003	0.0150	0.0299	2.3980	1.9858
21	0.2889	1.8376	0.3420	0.6060	0.1239	0.1094	0.0237	0.0271	2.7170	2.2396
22	0.1417	0.8210	0.6301	0.1181	0.1079	0.1003	0.0219	0.0275	2.5557	2.1427
23	0.1312	0.4733	2.1504	0.2353	0.1196	0.1143	0.0206	0.0357	2.5208	1.5089
24	0.1477	0.4826	0.4642	0.2749	0.1006	0.0927	0.0223	0.0417	2.5894	2.0276
25	0.1052	0.1702	0.0381	0.1311	0.0940	0.964	0.0168	0.0395	2.5387	2.2160
26	0.1049	0.4252	0.0412	0.2956	0.0856	0.1110	0.0155	0.0346	2.7249	2.1131
27	0.1101	0.4478	0.0434	0.2978	0.0891	0.1038	0.0219	0.0456	2.4662	2.0242
28	0.3417	0.4406	05299	0.2991	0.1069	0.0988	0.0206	0.0368	2.3945	2.3287

Table. 2 Optimal tuned parameters of relay in IEEE 30-bus test system- auxiliary curve

Relay Counter	Adjusted parameters (*k*, *A*, and *B*)									
	TDS_{fwa}	TDS_{rva}	I_{pfwa}	I_{prva}	A_{fwa}	A_{rva}	B_{fwa}	B_{rva}	K_{fwa}	K_{rva}
1	0.1367	0.3849	0.3207	0.0281	0.1109	0.1058	0.0161	0.0319	2.2376	1.8725
2	0.1362	0.2248	0.1699	0.0779	0.1201	0.1289	0.0198	0.0304	2.4510	1.6190
3	0.1034	0.6430	0.2276	0.0052	0.1024	0.1360	0.0142	0.0160	2.5939	2.0149
4	0.0973	0.6248	0.2002	0.0040	0.1333	0.1310	0.203	0.0215	2.6061	1.8925
5	0.1194	0.4107	0.1488	0.4591	0.1113	0.1120	0.0227	0.0174	2.4877	1.8440
6	0.1213	0.1896	0.1933	0.1349	0.1254	0.1244	0.0299	0.0289	205288	1.8745
7	0.1236	0.1824	0.1535	0.1503	0.1038	0.1275	0.0224	0.0413	2.4410	1.9759
8	0.1713	0.4387	0.6594	0.4615	0.1246	0.1474	0.0195	0.0225	2.3073	1.6321
9	0.1304	0.7729	0.0935	0.3664	0.1255	0.1330	0.0189	0.0341	2.6130	1.8404
10	0.1518	2.695	0.8274	0.0756	0.1365	0.1411	0.0233	0.0255	2.6217	1.6183
11	0.1470	1.3843	0.8081	0.1898	0.0863	0.1056	0.0242	0.0231	2.5262	1.8105
12	0.2483	1.3074	0.7313	0.6555	0.0915	0.1271	0.0197	0.0412	2.4418	1.9800
13	0.2438	1.2266	0.6696	0.6827	0.1184	0.1218	0.220	0.0146	2.4099	2.0166
14	0.2132	1.5894	0.4415	0.8932	0.1433	0.1432	0.0225	0.0247	2.3727	1.9866
15	0.3119	0.8459	1.0070	0.4958	0.1403	0.1363	0.0210	0.0358	2.4744	1.8090
16	0.2591	1.5667	0.8973	0.8030	0.1448	0.1470	0.0226	0.0179	2.4950	1.9618
17	0.3117	1.3842	0.8541	0.6956	0.1116	0.1413	0.0208	0.0141	2.5820	1.9755
18	0.2890	1.5313	0.8059	0.8625	0.1274	0.1096	0.0154	0.0223	2.4167	1.9796
19	0.3176	1.5561	0.9608	0.7633	0.1377	0.1467	0.0148	0.0175	2.2453	1.5487
20	0.3250	1.7014	0.5960	0.9268	0.1567	0.1272	0.0141	0.0320	2.3850	1.7082
21	0.2855	1.6205	0.4231	0.8289	0.1383	0.1366	0.0225	0.0272	2.7448	1.9658
22	0.1498	0.7767	0.5616	0.1686	0.1258	0.1177	0.0231	0.0300	2.5502	1.9269
23	0.1286	0.4140	0.2855	0.3864	0.1370	0.1376	0.0213	0.0372	1.8557	1.7973
24	0.1532	0.4568	0.5481	0.3897	0.1184	0.1136	0.0237	0.0416	2.5069	1.8579
25	0.1151	0.1618	0.0481	0.1726	0.1031	0.1136	0.0165	0.0403	2.4826	2.0720
26	0.1209	0.3919	0.0505	0.4770	0.0925	0.1326	0.0160	0.0365	2.5019	1.8008
27	0.1160	0.4326	0.0623	0.4693	0.0965	0.1380	0.0224	0.0452	2.5207	1.6927
28	0.3661	0.4065	0.7001	0.4719	0.1232	0.1209	0.0219	0.0367	2.3647	2.0110

Table. 3 The optimal downtime of main and backup relays in the IEEE 30-bus test system

FP	RN/TT	p	b_1	b_2	b_3	FP	RN/TT	p	b_1	b_2	b_3
		Relays tripping time (s)						Relays tripping time (s)			
F15	RN	5	6	7	-	F23	RN	1	2	3	4
	TT	0.157	0.464	0.754	-		TT	0.127	0.464	0.858	0.942
F16	RN	8	9	10	11		RN	15	14	-	-
	TT	0.136	0.449	0.740	1.043		TT	0.107	0.426	-	-
F17	RN	6	5	7	-	F24	RN	3	1	2	4
	TT	0.160	0.456	0.749	-		TT	0.084	0.397	0.478	0.768
	RN	9	8	10	11		RN	20	21	-	-
	TT	0.032	0.330	0.636	0.925		TT	0.106	0.415	-	-
F18	RN	10	8	9	11	F25	RN	4	1	2	3
	TT	0.101	0.402	0.698	0.992		TT	0.109	0.402	0.689	0.982
	RN	16	17	-	-		RN	21	20	-	-
	TT	0.120	0.419	-	-		TT	0.080	0.380	-	-
F19	RN	7	5	6	-	F26	RN	23	22	24	-
	TT	0.167	0.458	0.757	-		TT	0.081	0.390	0.722	-
	RN	12	13	-	-		RN	11	8	9	10
	TT	0.115	0.418	-	-		TT	0.131	0.436	0.723	1.022
F20	RN	17	16	-	-		RN	22	23	24	-
	TT	0.103	0.388	-	-		TT	0.137	0.446	0.747	-
	RN	18	19	-	-	F27	RN	24	22	23	-
	TT	0.114	0.415	-	-		TT	0.180	0.484	0.776	-
F21	RN	13	12	-	-		RN	25	26	27	-
	TT	0.124	0.410	-	-		TT	0.152	0.443	0.729	-
	RN	14	15	-	-	F28	RN	26	25	27	-
	TT	0.136	0.441	-	-		TT	0.174	0.479	0.787	-
F22	RN	2	1	3	4	F29	RN	27	25	26	-
	TT	0.221	0.512	0.823	1.119		TT	0.156	0.468	0.729	-
	RN	19	18	-	-	F30	RN	28	-	-	-
	TT	0.116	0.411	-	-		TT	0.187	-	-	-

FP: fault location counter, RN: relay counter, TT: interrupt time, TTT: Total interrupt time, P: Main, b_1: Backup 1, b_2: backup 2, b_3: backup 3

Table. 4 PCI values for IEEE 30-bus test system

DG Candidate Busbar	*PCI* Index	DG Candidate Busbar	*PCI* Index
2	207.577	8	89.1537
4	70.2738	10	79.0769
6	68.1091	12	80/2836