Electric Power Systems Research 214 (2023) 108900

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

An adaptive protection coordination strategy utilizing user-defined characteristics of DOCRs in a microgrid

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A R T I C L E I N F O

Keywords:
Distributed generation
DOCR
Relay coordination
Optimization
Hybrid GA-NLP

A B S T R A C T

The value of plug setting (PS) as well as time multiplier setting (TMS) of Directional Overcurrent Relay (DOCR) is used to achieve the relay coordination conventionally. With the emergence of Numerical DOCR, four settings of the relay, namely, PS, TMS, A and B are utilized for the relay coordination. This numerical DOCR make the coordination strategy adaptive for any contingencies. In this paper, four setting coordination strategy is proposed for Grid connected and for different contingencies in the network topology considering near end and far end fault locations. This coordination problem is formulated and solved using Hybrid GA-NLP approach. The proposed strategy is validated on the meshed distribution system. It also investigates the impact of DG penetration. The proposed method is also compared with the conventional strategy. The relay coordination problem has been tested on the meshed distribution system of IEEE 6-bus, modified 14-bus and IEEE 30-bus test systems which are penetrated with synchronous based DGs. The computed results show that the user-defined approach of selecting inverse time relay characteristic has significant potential in minimizing the overall operating time of the Numerical based DOCR. Hence, making it an effective and reliable option for meshed distribution system with DG.

1. Introduction

IN Order to operate a power system with maximum reliability, the most important thing is to have a proper protection coordination scheme. A reliable protection scheme during fault removes only faulty part of the power system for keeping intact the healthy portion of the feeder [1, 2]. During fault condition, a proper protection scheme will ensure maximum utilization of power with minimum loss by disconnecting only faulted section from the main supply. For an efficient protection scheme, there must be minimum coordination time interval between the primary relay and the backup relay. This may ensure primary protection to respond as quickly as possible and island a faulty part from healthy part of the power system network [3]. Therefore, a proper coordination between protective devices has become a mandatory requirement for ensuring reliable power supply. During failure of primary protection, backup relay must operate in order to clear the fault which may unnecessarily trip the larger part of the network [4].

Directional Overcurrent Relays (DOCRs) has been considered as a basic protective relaying equipment due to its low cost, effective and efficient operation during unwanted network condition. The inverse time current characteristic type of relays is employed frequently in the protection of distribution networks. Further, the optimum relay settings are selected to achieve enhanced relay coordination for ensuring fast, selective and reliable operation of the relay during faulty condition [5].

Conventional relays such as electromechanical based relays were less sensitive, required more maintenance, were not flexible and had moving parts. Therefore, numerical based relays are presently used in the distribution system as it provides effective, robust protection with much more attributes than electromechanical relays like greater flexibility and compactness, simplicity of interfacing with measuring instruments like Current Transformer(CT) and Potential Transformer(PT), time synchronization with GPS system, storage of fault recorder data, adaptive relaying, self-checking facility, Immune to variations in parameters of components, reliability and dependability[6]. Conventional relay coordination problem has been defined by many researchers using Plug setting and Time Multiplier setting [3,7]. The minimization of sum of operating time of all primary relay is considered as the relay coordination problem [8]. Further, the operating time of backup relay is also considered along with the primary relay operating time [9,10].

The developments in the relay technology has motivated the protection engineers to upgrade the conventional power grids into Smart Grid. Furthermore, one of the important attribute of the smart grid is to

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https://doi.org/10.1016/j.epsr.2022.108900
Received 4 August 2022; Received in revised form 28 September 2022; Accepted 13 October 2022
Available online 20 October 2022

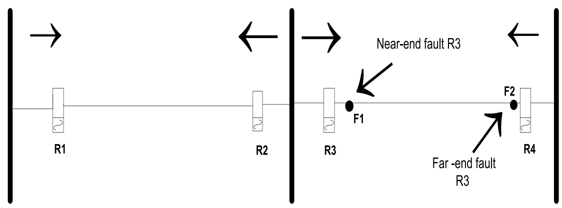

Fig. 1. Near end and far end fault points for relay R3.

be resilient to any increase in DG penetration at distribution levels [11, 12]. Continuous increase in the level of DG penetration level distribution system causes an adverse impact on the protection coordination due to bidirectional flow of current [7,13]. Further, there are two types of DGs commonly used namely, Synchronous based and the other one is inverter based. The synchronous based DGs generate higher fault current than the inverter based DGs [14]. Maloperation of relays due to CTI constraint violation with DG penetration has an adverse impact on relay coordination [15].

In addition, a flexible settings approach that will be optimum and provide a considerable time reduction as compared to the traditional techniques. This approach will provide a user-defined characteristics of the Numerical DOCRs according to the system conditions. Many commercial numerical based relays provide an option to select the operating characteristics of the relay. Authors in [9,16–19], have also suggested the potential option of use of the user defined curves. In [20], piecewise linear characteristic of numerical relay has been utilized for different relay characteristic. Hybrid GA-NLP algorithm has been utilized in the present study as it utilizes the advantages of both GA and NLP technique for obtaining global optimum solution. The GA algorithm converges to solution which are not optimum and the NLP algorithm gets trapped in local optimum and depends on the initial choice Therefore, in order to overcome this drawback and utilize the advantages of both the methods a Hybrid GA-NLP algorithm is utilized [8].

The motivation to the present study is to provide enhanced coordination for any dynamic changes in the network topology. Most of the literatures discuss the relay coordination for mid-point faults with conventional inverse time current characteristics [7,8]. Some of the researchers have also utilized near end and far end fault location for the analysis [21–23]. The probability of occurrence of the fault on the feeder depends on the length of the line. Therefore, practically faults may occur at any distance from the relay under consideration. Consequently, the magnitude of fault current may change as it depends on the length of the line. For achieving this, near end and far end fault locations with user defined inverse time current characteristics have been considered for relay coordination which ensures relay sensitivity for minimum fault and speed of operation for maximum fault current. The novelty of this research is to propose an adaptive protection coordination strategy for any contingencies with near end and far end fault locations and utilizing user defined inverse time current relay characteristics.

This paper is organized as follows: Relay coordination problem is formulated in Section 2 followed by proposed optimization algorithm applied in Section 3. All the steps involved to solve the adaptive relay coordination problem is presented in Section 3 and their results tested on IEEE 6 and modified 14 bus distribution system are discussed in Section 4. Section 5Section 5 concludes the paper.

2. Problem formulation

Conventional DOCR coordination problem is aimed to find the sum of operating time of all the relay. The operating time of a relay is a function of two variables, namely, Time Multiplier Setting (TMS) and Plug Setting (PS) of the relay. As per standard IEC 60,255 [24], the operating time of the relay t_{op}, is represented as

$$t_{op} = \frac{A(TMS)}{\left(I_{sc,3ph}/I_{pickup}\right)^{B} - 1} \tag{1}$$

where A and B are constant coefficients for different types of overcurrent relay; $I_{SC,3\ pH}$ is the three phase fault current seen by the relay at the CT secondary; I_{pickup} is the minimum value of the current for which the relay is at the verge of operation and mathematically defined as

$$I_{pickup} = PS \times CT_{secrated} \tag{2}$$

where, $CT_{sec\ rated}$ is the rated value of the secondary side of the current transformer.

Conventional Coordination problem can be solved for a given placement of different conventional characteristics of DOCRs. The value of A and B are kept fixed for a given relay. The intermediate values of A and B are not considered in the conventional problem. With the inception of numerical based DOCRs, the relay coordination problem considers TMS, PS, A and B over a given range. In the proposed relay coordination problem, the total time of operation of all the relays is optimized considering both near end and far end faults for each type of relays. For four continuous variables, namely, TMS, PS, A and B and is formulated as [9]:

$$Min\ T = \sum_{j=1}^{M}\left\{\sum_{i=1}^{NR}\left(t_{pij} + \sum t_{bij}\right) + \sum_{i=1}^{FR}\left(t_{pij} + \sum t_{bij}\right)\right\} \tag{3}$$

where, M is the total number of relays in the system. NR and FR denotes the total number of near end fault locations and far end fault locations, respectively. For i^{th} fault location, the operating time of j^{th} primary and backup relay is represented by t_{pij} and t_{bij} respectively.

For the optimal relay coordination, TMS, PS, A and B of all the relays in the test system are considered as variables. In a relay coordination problem of system consisting of N relays, the variable TMS, PS, A and B are defined by [X_1, X_2.....X_N], [X_{N+1},X_{N+2}.....X_{2N}], [X_{2N+1},X_{2N+2},.....X_{3N}] and [X_{3N+1},X_{3N+2},.....X_{4N}] respectively. Hence, for a system with N relays, there are 4*N variables for optimum relay coordination.

For relay R3, the fault point F1 and F2 act as near end fault and far end fault, respectively as shown in Fig. 1. For relay R3, the minimum and maximum fault current seen by the respective relay will occur at near end and far end respectively [25,26]. In this paper, the user has been provided with an option for adjusting four relay settings, namely, TMS, PS, A and B for each DOCR in order to achieve the relay coordination. The proposed coordination problem is modelled as a non-linear problem where the four relay variables are determined optimally. For optimal coordination, the objective function defined by (3) must be optimized along with the constraints.

2.1. Operating time constraint of the relay and time multiplier setting

The primary relay should operate within specified time duration for an effective and reliable protection of the network. The upper range allowed for time delay is 4.0 s and lower value should be more than minimum predefined time of 0.1 s considering transient conditions [27] and can be denoted as:

$$t_{i,k\ min} \le t_{i,k} \le t_{i,k\ max} \tag{4}$$

where, $t_{i,k\ min}$ /$t_{i,k\ max}$ are the minimum /maximum limits on the relay operating time at any location *i* for fault in *k*th protection zone respectively. With the given limit on operating time of relay defined by (4), the bound on TMS will be given by:

$$TMS_{i,k\ min} \le TMS_{i,k} \le TMS_{i,k\ max} \tag{5}$$

where, $TMS_{i,k\ min}$/$TMS_{i,k\ max}$ are the minimum/maximum values of TMS of relay at any location *i* respectively. In this work, the range of TMS is considered as [0.025, 1.2].

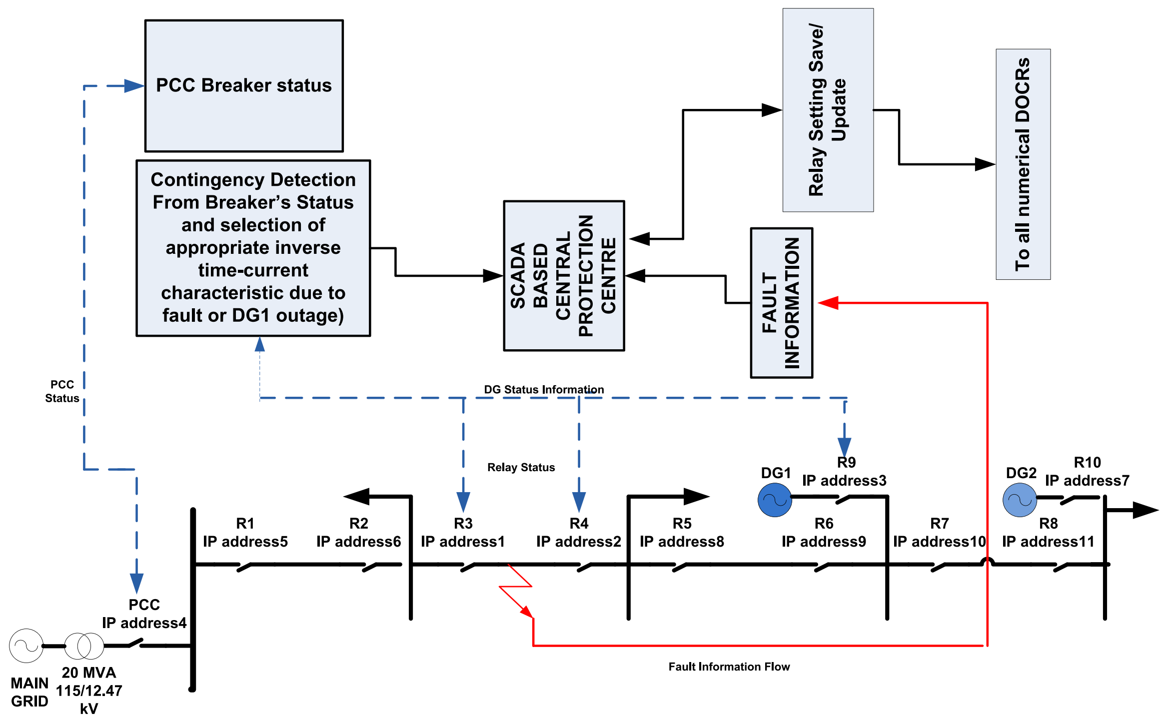

Fig. 2. Adaptive protection scheme.

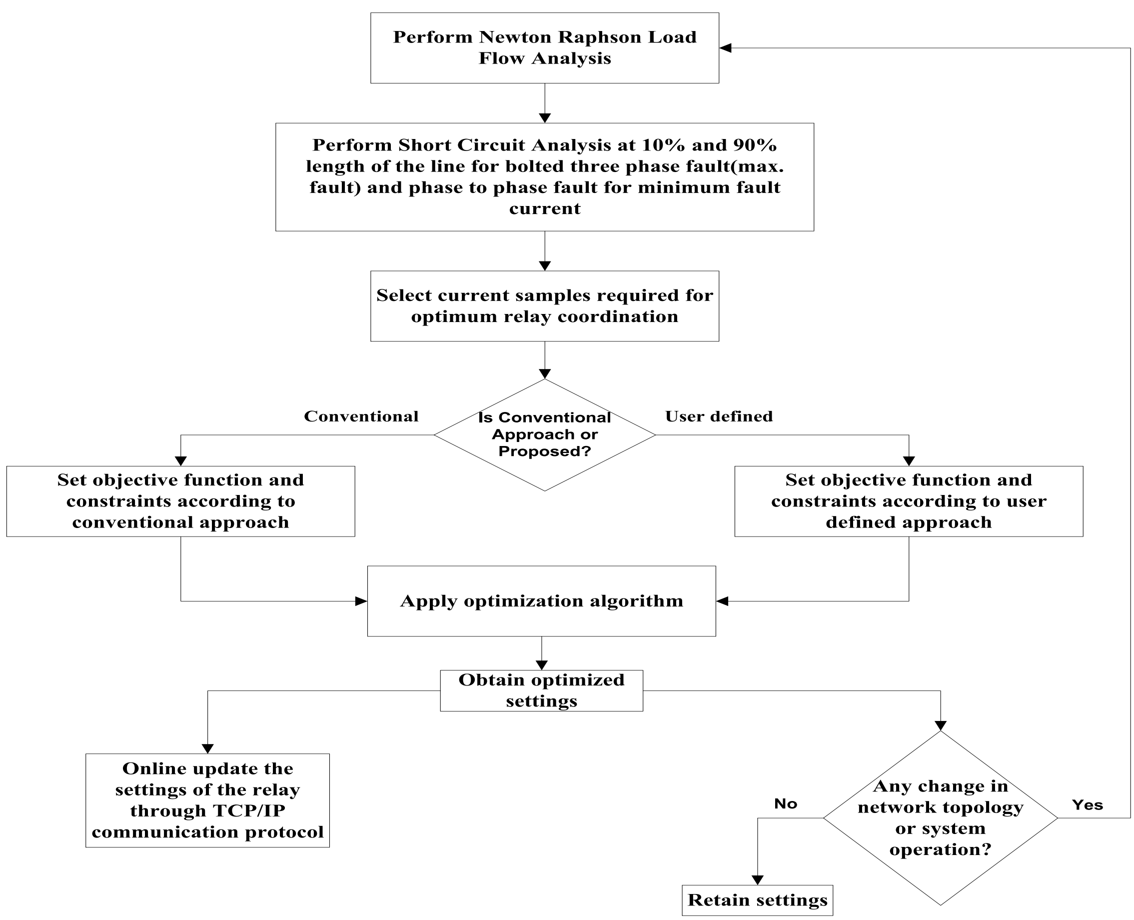

Fig. 3. Flow chart of proposed methodology.

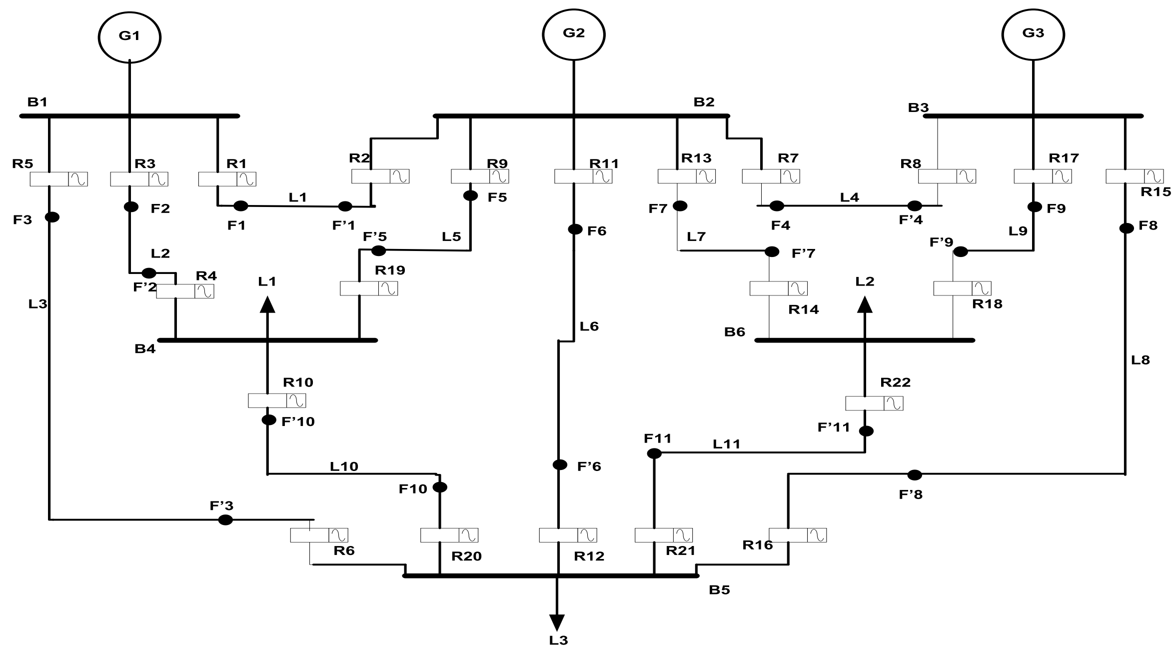

Fig. 4. IEEE 6 bus distribution system.

Table 1
System parameters of 6 bus system.

System quantities	Values
Generators G1, G2, G3	6.3 KV, 6 MVA, $X_d^{'} = 0.2$ p.u
Loads at buses B4, B5and B6	2.4 MVA, 0.9 pf
Line Impedance	0.08+j0.16 Ω/km, all lines are 500 m long

2.2. Limit on coordination time interval (CTI)

The backup relay should respond to a fault if the primary relay fails to clear it in a given specified time. The time difference between the operation of backup and primary relay is referred to coordination time interval (CTI). It is expressed as [28].

$$t_{bi,k} - t_{i,k} \geq \Delta t \tag{6}$$

where, $t_{i,k}$ is the operating time of ith primary relay and $t_{bi,k}$ is the operating time of the backup relay for fault at any location k on the feeder. Δt is the minimum value of the CTI taken as 0.2 s[29]. For any distribution system the total number of primary-backup relay pair is identified and the corresponding number of CTI constraints are incorporated as a non-linear function for solving relay coordination issue.

2.3. Bounds on plug setting

The plug setting of the DOCRs is considered as one of the variables associated with the relay coordination problem of the microgrid. The optimum value of this variable is obtained by formulating the relay coordination problem and setting its lower and upper bounds. The range

Table 2
CT ratio of each relay for 6 bus system.

Relay	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}
CT ratio	1200/5	1200/5	1200/5	1000/5	800/5	600/5	800/5	400/5	1600/5	1000/5	600/5
Relay	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}
CT ratio	1200/5	800/5	400/5	400/5	400/5	1000/5	500/5	300/5	300/5	400/5	300/5

Table 3
Fault current seen by the relay for bolted three phase fault of 6-bus system.

Fault location	Primary relay		Backup relay							
	PR_1	PR_2	BU_1				BU_2			
F_1	R_1 4126	R_2 4298	R_4 219	R_6 422	–	–	R_8 1236	R_{10} 191	R_{12} 361	R_{14} 919
F_2	R_3 4367	R_4 3389	R_2 1086	R_6 757	–	–	R_9 2628	R_{20} 703	–	–
F_3	R_5 3012	R_6 2416	R_2 498	R_4 303	–	–	R_{11} 585	R_{15} 92	R_{19} 287	R_{22} 607
F_4	R_7 2391	R_8 1312	R_1 1386	R_{10} 916	R_{12} 103	R_{14} 392	R_{16} 632	R_{18} 802	–	–
F_5	R_9 5527	R_{10} 3372	R_1 2017	R_8 869	R_{12} 602	R_{14} 778	R_3 2761	R_{20} 592	–	–
F_6	R_{11} 1956	R_{12} 1701	R_1 872	R_8 135	R_{10} 486	R_{14} 64	R_5 916	R_{15} 293	R_{19} 314	R_{22} 192
F_7	R_{13} 2827	R_{14} 1362	R_1 1528	R_8 279	R_{10} 1012	R_{12} 114	R_{17} 922	R_{21} 601	–	–
F_8	R_{15} 1124	R_{16} 1604	R_7 712	R_{18} 652	–	–	R_5 933	R_{11} 408	R_{19} 375	R_{22} 119
F_9	R_{17} 1388	R_{18} 1795	R_7 954	R_{16} 822	–	–	R_{13} 1139	R_{21} 607	–	–
F_{10}	R_{19} 1204	R_{20} 1098	R_3 701	R_9 583	–	–	R_5 502	R_{11} 187	R_{15} 333	R_{22} 218
F_{11}	R_{21} 1559	R_{22} 1096	R_5 902	R_{11} 293	R_{15} 152	R_{19} 337	R_{13} 714	R_{17} 509	–	–

Table 4
Optimized settings using proposed four setting coordination strategy for 6 bus system.

Relay No.	GA-NLP			
	TMS	PS	A	B
R_1	1.2	0.5	45	1.3
R_2	1.2	0.8	46	2
R_3	0.15	2	47	1.8
R_4	1	1.4	48	2
R_5	1.2	0.5	49	1.4
R_6	1.2	0.7	50	1.8
R_7	0.12	2.2	50.4	1.3
R_8	0.42	1.5	52	1.9
R_9	0.15	1.7	53	1.2
R_{10}	1.2	0.9	54	2
R_{11}	0.12	1.6	52	1.2
R_{12}	1.2	1.25	55	1
R_{13}	1.2	0.7	56	1.8
R_{14}	0.15	0.6	57	1.6
R_{15}	0.16	1.6	58	1.3
R_{16}	1.2	2.3	56	1.45
R_{17}	0.16	0.5	61	1.45
R_{18}	0.15	2.2	63	1.9
R_{19}	1.2	0.5	64	1.4
R_{20}	0.23	1.75	66	1.25
R_{21}	1.2	1.6	66	1.3
R_{22}	0.12	1.6	67	1.25

of plug setting is expressed as:

$$PS_{min} \leq PS \leq PS_{max} \tag{7}$$

where, PS_{min}/PS_{max} are the lower/upper limits of plug setting, respectively. In this study, the minimum range of PS is considered to be 50% and the maximum value as 250% of the CT secondary rated respectively. The lower and upper bounds for this variable is set as [0.5, 2.5] in relay coordination problem.

2.4. Bounds on continuous variables (A and B)

In the conventional formulation approach A and B are considered as constants associated with the relay characteristic curve of DOCRs. In the proposed approach both these constants A and B are considered as variables in the relay coordination problem. The continuous variables are computed in order to provide greater flexibility within numerical DOCRs by providing operation with a wider range of characteristics not limited to conventional time-current characteristics.

The optimum values of these variables is obtained by setting the upper and lower limits in the formulated problem. The lower/upper limits of both the variables are defined between the constants associated with conventional relay characteristics as:

$$A_{jmin} \leq A_j \leq A_{j\ max} \tag{8}$$

$$B_{j\ min} \leq B_j \leq B_{j\ max} \tag{9}$$

where, A_{jmin}/A_{jmax} are the minimum/maximum values of continuous variable A, respectively. In this work the range of A has been considered as [0.14,80]. B_{jmin}/B_{jmax} are the minimum/maximum values of continuous variable B, respectively. In this work the range of B has been considered as [0.02,2].

In order to solve the complex relay coordination problem the lower and upper bound of all the relays are arranged as [TMS^{lb1},TMS^{lb2},…..,TMS^{lbN},PS^{lb1},PS^{lb2},…..,PS^{lbN}, A^{lb1}, A^{lb2},…..,A^{lbN}, B^{lb1},B^{lb2}…..B^{lbN}] and [TMS^{ub1},TMS^{ub2},…..,TMS^{ubN}, PS^{ub1},PS^{ub2},…..,PS^{ubN}, A^{ub1}, A^{ub2},…..,A^{ubN}, B^{ub1},B^{ub2}…..B^{ubN}] respectively. Where, lbN/ubN are the lower/upper bounds of the variable parameters associated with N^{th} relay.

Table 6
CTI using proposed and conventional approach for 6 bus system.

Conventional approach		Proposed approach	
Value of CTI calculated	Obtained values	Value of CTI calculated	Obtained values
Maximum	4	Maximum	4
Minimum	0.5	Minimum	0.2
Average	1.364	Average	1.246

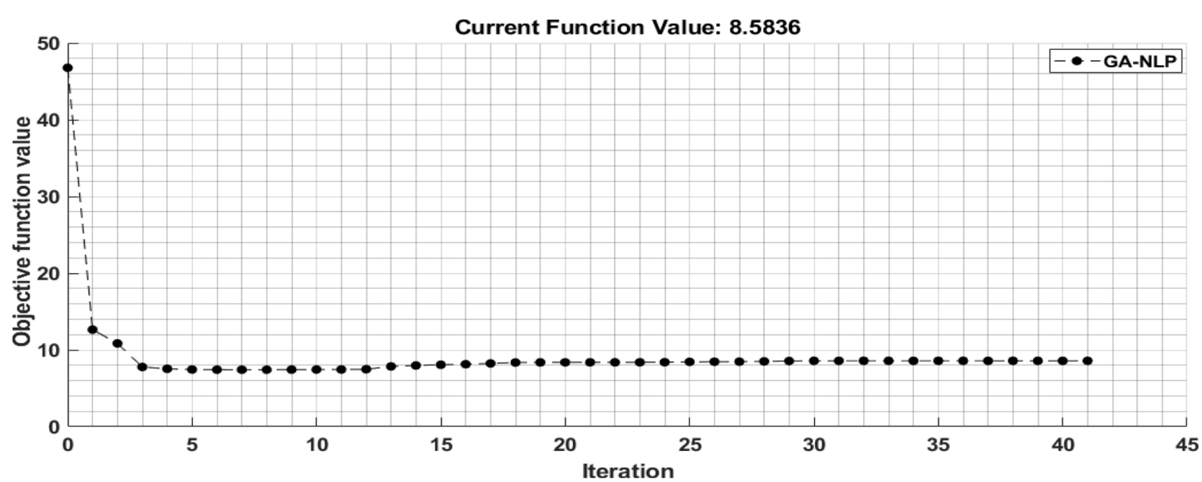

Fig. 5. Convergence curve with GA-NLP using proposed approach for 6 bus system.

Table 5
Comparison between conventional and proposed approach using different optimization technique for 6 bus system.

Optimization technique	Conventional approach			Proposed approach		
	Objective function	Simulation time(s)	No. of iterations	Objective function	Simulation time(s)	No. of iterations
GA	15.3528	17.51	51	11.2246	16.36	48
NLP	12.9847	14.58	47	10.8582	14.19	42
GA-NLP	8.67148	13.41	44	8.5836	13.37	41

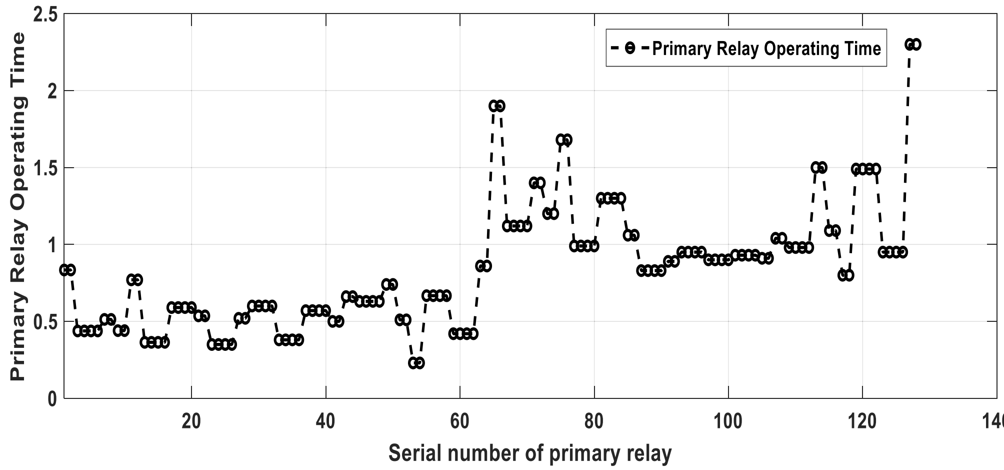

Fig. 6. Primary relay operating time for proposed approach for IEEE 6-bus system.

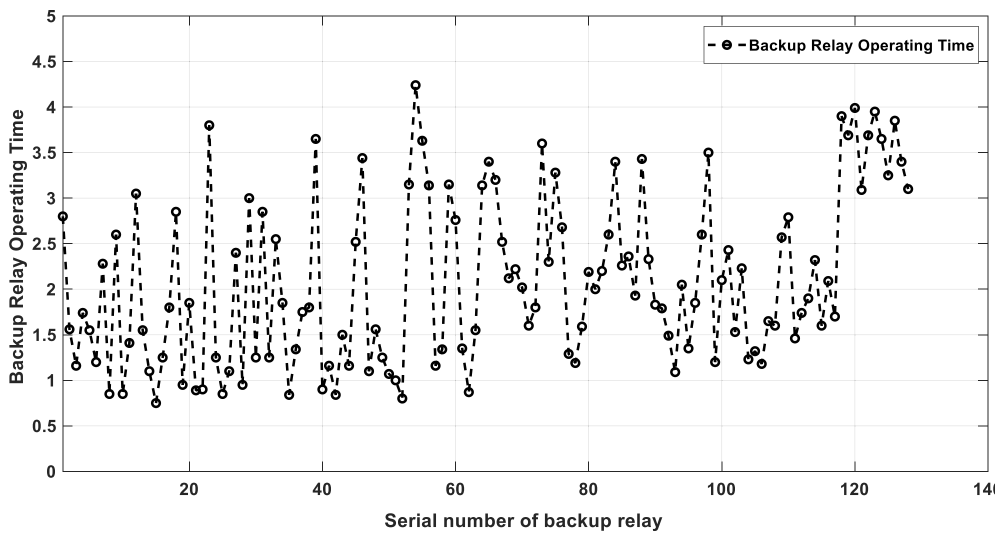

Fig. 7. Backup relay operating time for proposed approach for IEEE 6-bus system.

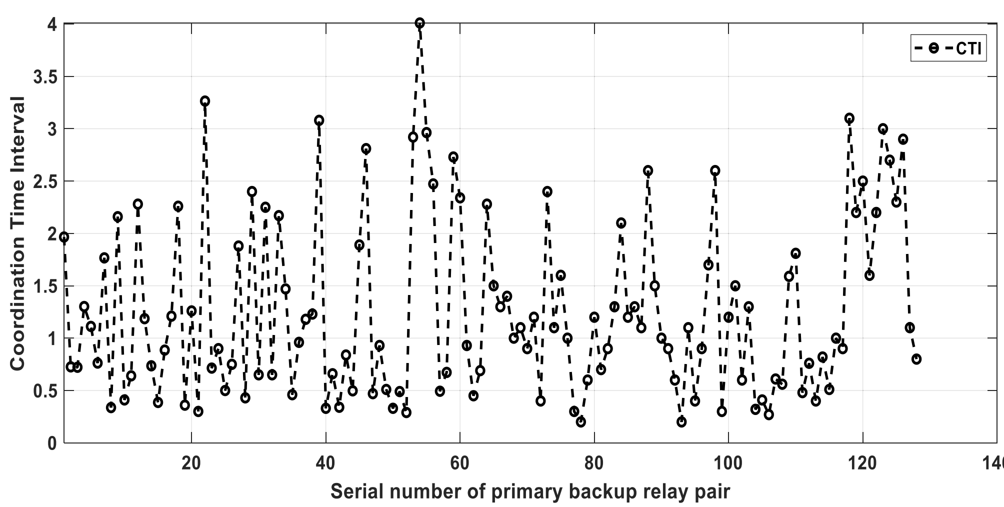

Fig. 8. CTI of primary backup relay pair for proposed approach for IEEE 6-bus system.

3. Proposed adaptive protection coordination approach

This approach is a online activity based on real time settings update of DOCRs for avoiding any mal operation of relays [30,31]. This process is necessary because of dynamic changes in the system like variation in fault currents with time due to change in generation and topology.

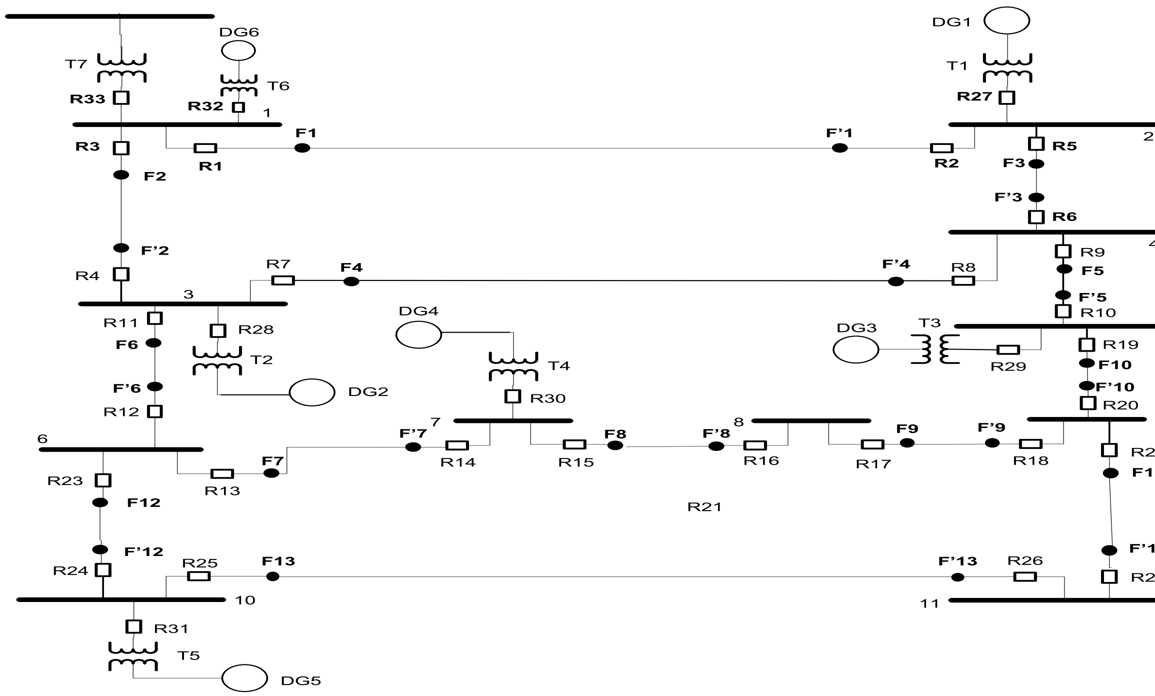

Fig. 9. Modified 14 bus system.

Table 7
System parameters of modified 14-bus system.

System quantities	Values	System quantities	Values
Main grid	120 KV, Short-circuit MVA = 200	**Transformer T_7**	40 MVA, 120/20 KV, X_t = 0.1 p.u
Line impedance	0.08+j0.16 Ω/km, all lines are 500 m long	**DGs**	6.3 KV, 6 MVA, X_d'' = 0.2 p.u
Transformer T_1-T_6	8 MVA, 20/6.3 KV,X_t = 0.1 p.u	**Loads at buses 1 to 11**	2.4 MVA, 0.9 pf

Further, this requires a real time adjustment in relay settings in order to achieve minimum operating time of all the relays and simultaneously maintaining the minimum coordination time constraints [32,33]. In order to update the settings of the relay online according to the changing system conditions, proper communication of the field devices with the relays are essential.

In this approach, real time information of the system like current, load, voltage, status of circuit breaker and generation are needed. Each relay in the system is denoted by a unique IP address for real time information exchange. For any contingency in the network, the fault current is recalculated. Further, for the new fault current and existing relay settings, Protection coordination status is checked. If there is any miscoordination, the relay settings are recomputed and updated accordingly.

In the test system under study, Numerical DOCRs have been considered for complete protection under any contingency. In addition, the settings of the DOCRs can be updated online through the data received from the field devices like Intelligent Electronic Devices (IEDs) by communication links [34,35]. In order to completely implement this scheme TCP/IP communication protocol can be used.

In this scheme for any contingency like DG outage, fault on the feeder etc. the appropriate inverse time-current characteristic has to be selected and applied to the Numerical DOCRs for overall protection of the microgrid. Further, in the quest of adaptive relay coordination a robust, highly efficient and fast processor is needed in the computer system of Central Protection Centre and for effective Human Machine Interface, SCADA system has to be installed.

The adaptive protection scheme has been explained through a five bus distribution system with 10 number of Numerical DOCRs in Fig. 2. Each component of the system like relays, DGs etc. are denoted by a unique IP address for effective communication to and from the SCADA based central protection centre. Further, it can be observed from the figure that during DG1outage, breaker at relay R9 denoted by IP address3 communicates its status information to the central control centre. Moreover, for a fault point the breaker status information at Relay R3 and Relay R4 having IP address1 and IP address2 respectively is passed on to the control centre for further update. In addition, the Point of Common Coupling (PCC) status information is communicated to the PCC breaker status through TCP/IP communication protocol through IP address4. The updated relay settings and appropriate inverse time-characteristic are loaded to all the Numerical DOCRs through the central protection centre. The pre-loaded settings and characteristics are erased from the memory of the DOCRs.

Table 8
CT ratio of each Relay of modified 14-bus system.

Relay	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}
CT ratio	1200/5	1200/5	1200/5	1000/5	800/5	600/5	800/5	400/5	1600/5	1000/5	600/5
Relay	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}
CT ratio	1200/5	800/5	400/5	400/5	400/5	1000/5	500/5	300/5	300/5	400/5	300/5
Relay	R_{23}	R_{24}	R_{25}	R_{26}	R_{27}	R_{28}	R_{29}	R_{30}	R_{31}	R_{32}	R_{33}
CT ratio	1200/5	800/5	400/5	400/5	400/5	1000/5	500/5	300/5	300/5	400/5	300/5

Table 9
Minimum and maximum fault current seen by the relays for 6 DGs of modified 14-bus system.

Fault location	Min. fault current (I_{fmin})	Max. fault current (I_{fmax})	Fault location	Min. fault current (I_{fmin})	Max. fault current (I_{fmax})
R_1	1672	5300	R_{18}	1072	5669
R_2	1986	5220	R_{19}	1154	5200
R_3	1729	4819	R_{20}	1315	5134
R_4	1472	5400	R_{21}	1187	4416
R_5	1502	5390	R_{22}	1347	3156
R_6	1123	5627	R_{23}	1023	5310
R_7	1402	3781	R_{24}	1283	3258
R_8	1103	4986	R_{25}	1682	3875
R_9	1373	3216	R_{26}	1892	4243
R_{10}	1721	2839	R_{27}	1101	2981
R_{11}	989	5804	R_{28}	1053	2785
R_{12}	1034	5497	R_{29}	1298	3265
R_{13}	1156	5692	R_{30}	1349	3641
R_{14}	1379	3689	R_{31}	1478	4527
R_{15}	1632	4761	R_{32}	1163	4735
R_{16}	1739	5121	R_{33}	1461	4874
R_{17}	1537	3997	-		

Table 10
Optimized settings using proposed four setting coordination strategy for modified 14-bus system.

Relay No.	GA-NLP TMS	PS	A	B
R_1	0.18	1.40	67	1.1
R_2	0.18	2.50	68	1.84
R_3	0.30	1.30	69	1.98
R_4	0.28	1.40	70	1.82
R_5	0.23	1.20	71	1.76
R_6	0.19	0.70	72	1.9
R_7	0.10	1.60	69.6	1.99
R_8	0.10	0.50	74	1.46
R_9	0.12	1.70	75	1.88
R_{10}	0.32	1.00	76	1.82
R_{11}	0.34	0.60	77	1.81
R_{12}	0.12	0.80	78	1.84
R_{13}	0.50	1.40	79	1.86
R_{14}	0.13	1.43	78.8	1.7
R_{15}	0.14	1.38	79	1.61
R_{16}	0.12	1.00	79	1.82
R_{17}	0.21	1.48	79	1.81
R_{18}	0.14	1.30	79	1.78
R_{19}	0.13	1.36	79	1.6
R_{20}	0.15	1.60	79	1.62
R_{21}	0.14	1.30	79	1.72
R_{22}	0.13	1.00	79	1.38
R_{23}	0.36	2.00	78.8	1.8
R_{24}	0.20	1.40	79	1.81
R_{25}	0.18	1.50	79	1.94
R_{26}	0.20	1.30	79	1.91
R_{27}	1.2	1.60	79	1.43
R_{28}	0.17	0.53	79	1.9
R_{29}	0.13	1.3	79	1.3
R_{30}	0.13	0,95	79	1.8
R_{31}	0.20	0.90	78.8	1.9
R_{32}	0.13	1.10	78.8	1.73
R_{33}	0.13	1.30	78.8	1.82

However, it has to be pointed out that the present study focusses on the computation of relay settings under different conditions of system operation. The detailed study of communication system is not the part of the current work. As adaptive protection coordination approach is a real time online operation therefore a superior algorithm has to be utilized in order to compute the optimum relay settings. In Fig. 3, the step by step procedure adopted for the proposed methodology has been pictorially represented. Newton Raphson load flow analysis is carried out followed by short circuit analysis at 10% and 90% length of the feeder. Further, for phase to phase fault inception minimum fault current is obtained and for three phase fault inception maximum fault current is obtained. In the present study, a Hybrid Genetic algorithm-Non Linear Programming (GA-NLP) approach was used in order to compute the optimum settings of DOCRs.

3.1. Hybrid GA-NLP

This algorithm is exploited to achieve the optimal relay coordination as it provides global optimum solution and do not get trapped in local optimum. It overcomes the drawback present in multi-objective GA (MOGA) of non-convergence to optimum solution. Further, NLP method is a single point search algorithm, therefore, it has the drawback of searching a small solution space and getting trapped in local optimum. Moreover, if the initial choice is properly selected then, this algorithm gives global optimum solution. Further, GA is a multi-point search method and it searches a large solution space. Therefore, Hybrid GA-NLP approach is utilised as it uses the advantages of the MOGA and NLP techniques [8].

A Nonlinear Programming Problem approach is adapted to solve the DOCRs coordination problem. In this approach initial point is determined by executing GA for few generations for obtaining TMS, PS, A and B values and utilising the obtained value as initial choice in nonlinear programming method. Moreover, for obtaining the initial choice the objective function, time constraints and coordination constraints are written and incorporated in the optimization toolbox with proper syntax. The constraints on TMS, PS, A and B are incorporated in the lower and upper bounds present in the toolbox. The solver is selected from the toolbox as multi objective genetic algorithm and the program is executed.

The computed values through MOGA technique is then utilised as the initial point in the NLP algorithm. Moreover, similar to MOGA method the upper and lower limits of TMS, PS, A and B are incorporated. The non-linear coordination constraint, objective function are written in two separate files and called in the toolbox with proper syntax. Number of variables in the toolbox is four times the number of relays in the test system. Further, the algorithm selected in this method is interior point. The obtained optimized value through this algorithm is global optimum.

4. Results and discussions

The protection strategy proposed for Numerical DOCR coordination based on user defined characteristic has been tested on 6-bus and modified 14-bus test systems. The optimized values of TDS, PS, A and B have been evaluated using Hybrid GA-NLP technique for user defined numerical DOCR and compared with the conventional DOCR coordination approach. Further, relay operating time with coordination time interval is also calculated and investigated for constraint violation.

4.1. Section I: 6 bus test system

The 6-bus test system under study consists of three generators connected at buses 1, 2 and 3. This system consists of 22 Numerical DOCRs having 64 combinations of Primary-backup relay pair as shown in Fig. 4.

A total of 11 near end fault locations at 10% length of the line and the same number of far end fault locations at 90% length of the line are identified on the test system as F_1, F_2,……F_{11} and F_1',F_2',……F_{11}'. For a line between bus B_1 and B_2, fault point F_1 is regarded as fault at the near end and at the far end for relay R_1 and R_2 respectively. Similarly, fault point F_1' is considered to be far end and near end fault for relay R_1 and R_2 respectively. The relays R_4 and R_6 act as a backup protection for relay R_1. Similarly, the relay R_8, R_{10}, R_{12} andR_{14} provide backup protection for relay R_2.

For the given 6 bus test system, the system parameters are listed in Table 1 [36]. For all 22 relays, CT ratios have been tabulated in Table 2.

Bolted three phase faults are created at different fault points on the

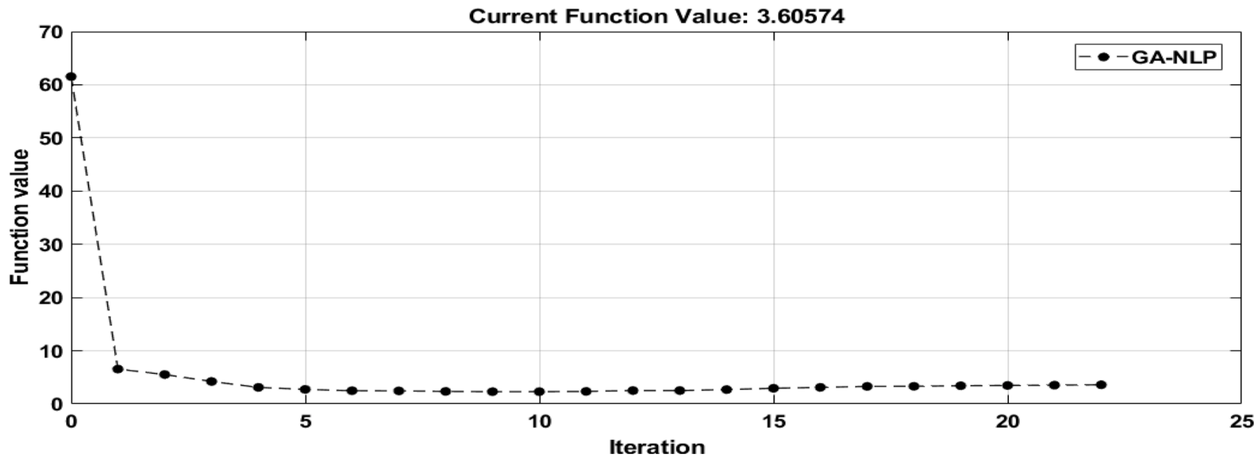

Fig. 10. Convergence curve with GA-NLP for proposed approach for 6 DGs of modified 14-bus system.

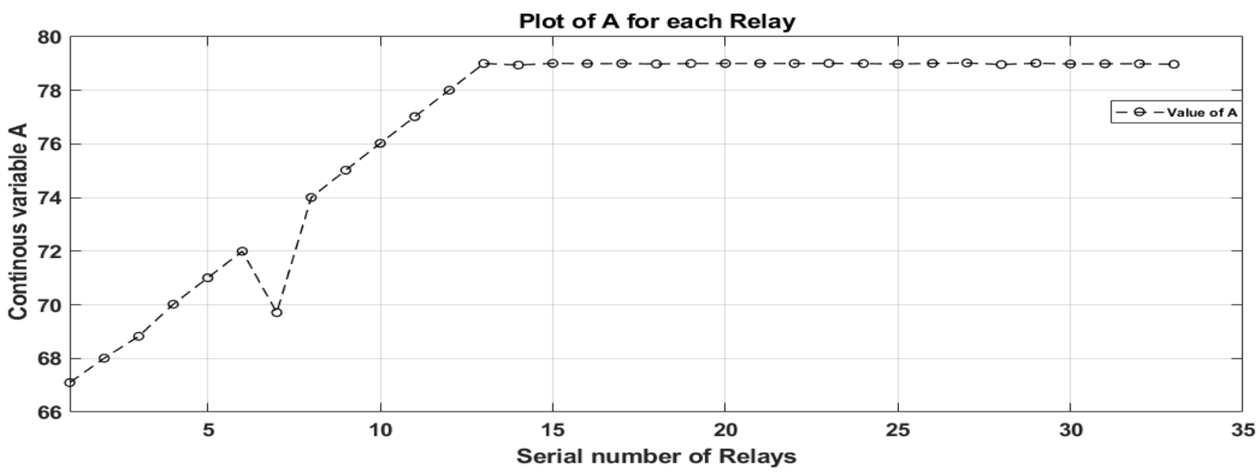

Fig. 11. Variation of continuous variable A for each relay of modified 14-bus system with 6 DGs.

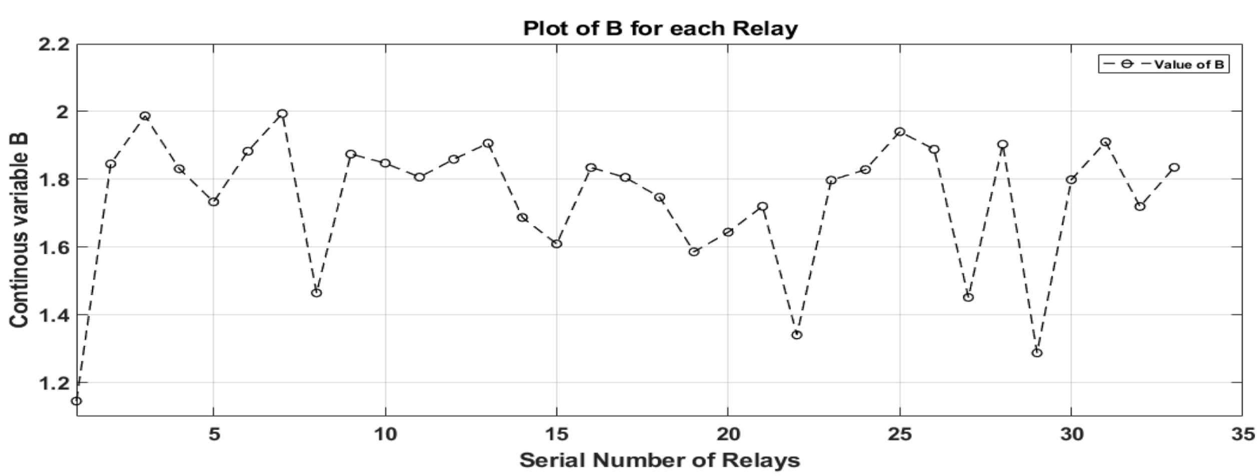

Fig. 12. Variation of continuous variable B for each relay of modified 14-bus system with 6 DGs.

feeder of the test system under study F_1, F_2,……F_{11} and F_1',F_2',……F_{11}'. Further, Newton-Raphson load flow followed by short circuit analysis on DIg SILENT Power Factory Software is carried out on the test system for obtaining maximum fault seen by each relay. Fault current magnitudes of all the primary and backup relay pair have been listed in Table 3 for the fault location F_1, F_2,……F_{11}. However, for relay coordination, both the fault locations F_1, F_2,……F_{11} and F_1', F_2', ……F_{11}' have been considered in (3).

The proposed DOCR coordination method has estimated the value of TMS, PS, A and B optimally using GA-NLP technique and these values are listed in Table 4.

The value of objective function represented by (3) is calculated using

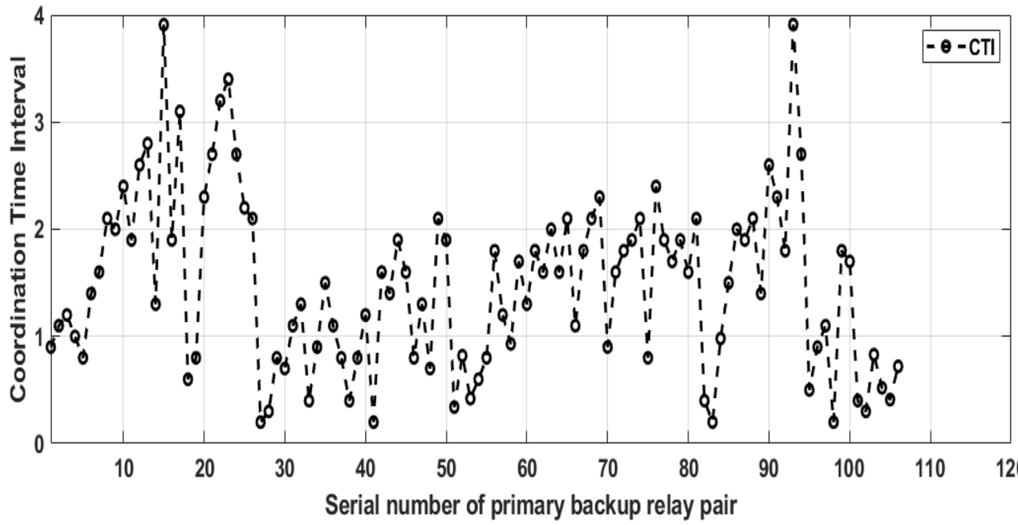

Fig. 13. CTI for primary backup relay pair for proposed approach for modified 14-bus System.

Table 11
Comparison between Conventional and Proposed approach using different optimization technique for modified 14 bus system.

Optimization technique	Conventional approach Objective function	Simulation time(s)	No. of Iterations	Proposed approach Objective Function	Simulation Time(s)	No. of iterations
GA	11.7296	21.76	46	8.2246	21.31	41
NLP	8.1837	18.39	38	6.8582	17.92	33
GA-NLP	7.83291	15.23	31	3.60574	14.97	22

Table 12
CTI using conventional and proposed approach for modified 14-bus system.

Conventional approach Value of CTI calculated	Obtained Values	Proposed approach Value of CTI Calculated	Obtained values
Maximum	4	Maximum	3.91
Minimum	0.53	Minimum	0.2
Average	1.681	Average	1.483

Table 13
Effect of DG penetration on modified 14 bus test system.

DG penetration level	Objective function value (Conventional strategy) GA-NLP	Objective function value (Proposed strategy) GA-NLP
DG rated 8MVA@bus 1,2,3,5,7,10	17.89	4.76
DG rated 6MVA@bus 1,2,3,5,7,10	16.92	3.60
DG rated 6MVA@bus 2,3,5,7	16.14	3.26
DG rated 6MVA@bus 1,2	14.78	2.97

proposed method for the optimal setting as given in Table 4. The optimal coordination of DOCRs using proposed method is converged in 41 iterations and the value of objective function is found to be 8.5836 s as shown in Fig. 5.

The proposed method of DOCR coordination is compared with the conventional method. The conventional method considers 22 relays (R_1, R_2,……..R_{21},R_{22}) to be of IDMT characteristic and provide the optimal coordination using GA-NLP techniques [8,36].

It can be observed from Table 5 that the objective function value obtained with Hybrid GA-NLP approach is the least for conventional as well as proposed approach as compared to GA and NLP methods. Moreover, the simulation time taken in the execution of the algorithm and the number of iterations performed for convergence to optimum solution is also less for proposed approach than to conventional approach. From this data, it can be inferred that the proposed approach is effective and robust in obtaining enhanced relay coordination.

In Table 6 the maximum, minimum and average value of Coordination time interval has been listed for conventional and proposed approach. It is evident from the data obtained that the average and minimum value of CTI obtained for proposed approach is less as compared to conventional approach. Hence, it can be inferred that the backup relay operating time obtained for proposed approach is less than for conventional approach. Consequently, it leads to less value of CTI and subsequently, objective function value obtained is also less. It can be inferred from the CTI data that the calculated values listed in Table 5 follow the constraints in (5).This clearly shows that with proposed approach the time involved in backup protection is reduced for enhanced relay coordination as compared to the conventional approach.

In Figs. 6 and 7, primary and backup relay operating time obtained by Hybrid GA-NLP for all the 128 combinations of primary-backup relay pair (1–64 for near end fault and 65–128 for far end fault) has been shown. It is evident from Fig. 6 that for any faulty condition on the distribution system the primary relay operates quickly to remove the faulty section. Further, from Fig. 7 it can be observed that the corresponding backup relays placed in the system operate after a minimum time gap allowing the primary relay to operate first. Hence, it can be pointed out that the essential requirement of selectivity for relay coordination is maintained. Furthermore, in Fig. 8, the corresponding values of coordination time interval (CTI) obtained for each pair of relays has been shown. It can be examined from this figure that the CTI values obtained for all 128 combinations of relay pair maintains the minimum time interval necessary for relay coordination. Moreover, it can also be inferred from Fig. 8 that the relays coordinate for far end fault. Hence, it

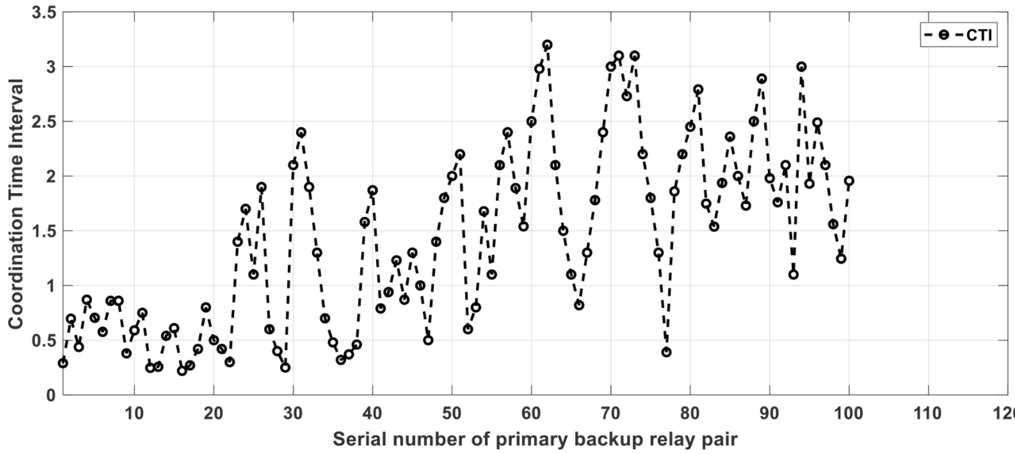

Fig. 14. CTI for primary backup relay pair using proposed approach with GA-NLP for IEEE 30-bus system.

Table 14
Performance of proposed approach for IEEE 30 bus system.

Optimization technique	Proposed approach Objective function	Simulation time (s)	No. of iterations
GA-NLP	10.6057	13.64	34

can be observed from Fig. 8 that the relays are sensitive enough to operate for minimum fault.

4.2. Section II: modified 14 bus test system

Modified 14 bus test system as shown in Fig. 9, has been also utilized to validate the proposed method. In this system six synchronous based DGs (DG1, DG2, DG3, DG4, DG5 and DG6) are connected through six transformers (T1,T2,T3,T4,T5 and T6) to form microgrid. Further, 33 Numerical inverse-time characteristic based DOCRs having the capability to choose the desired characteristic (A and B) are also connected to this system through 33 CTs.

This system is connected to main grid through transformer T7 near bus B1. The system parameters for the test system are listed in Table 7. The CT ratios of all 33 CTs connected to network are also listed in Table 8.

In this test system, 26 bolted three phase near end (at 10% length of the line) and phase to phase far end faults (at 90% length of the line) have been created as $F_1, F_2, \ldots, F_{13}$ and F'_1, $F'_2, \ldots, F'_{13}$ in order to investigate the proposed method. For all the 13 near end fault locations, the current seen by all 33 relays are calculated for bolted three phase fault and for the other 13 far end fault locations, the current seen by all 33 relays are calculated for phase to phase faults. Using these values, the maximum and minimum fault current seen by all 33 relays are listed in Table 9.

Network data presented in Table 7 and CT ratios in Table 8 is utilized to obtain minimum and maximum values of fault current as seen by each relay for n-1 contingency and has been listed in Table 9. Further, Newton Raphson Load flow analysis followed by short circuit analysis on DIg SILENT Power Factory 2021 software for 6 DGs at buses 1,2,3,5,7,10 has been carried out in order to obtain the parameters listed in above table. Moreover, for minimum fault current values phase to phase fault has been considered and in order to obtain maximum fault current values for each relay bolted three phase fault has been incorporated.

In Table 10 the maximum, minimum and average value of Coordination time interval has been listed for conventional and proposed approach. It is evident from the data obtained that the average and minimum value of CTI obtained for proposed approach is less as compared to conventional approach. Hence, it can be inferred that the backup relay operating time obtained for proposed approach is less than for conventional approach. Consequently, it leads to less value of CTI and subsequently, objective function value obtained is also less. It can be inferred from the CTI data that the calculated values listed in Table 10 follow the constraints in (5). This clearly shows that with proposed approach the time involved in backup protection is reduced for enhanced relay coordination as compared to the conventional approach.

Fig. 10 shows the convergence plot of modified 14-bus system obtained for proposed approach with Hybrid GA-NLP technique. It can be observed from the figure that the function value converges to optimum at 22nd iteration and the optimum value obtained is 3.60574 s. Further, in Figs. 11 and 12 the optimum values obtained for continuous variables A and B has been shown. It can be pointed out from this figure that the values obtained follows the constraint in (8) and (9) respectively. In Fig. 13 it can be inferred that with the proposed approach the relays coordinate for both near end (Serial number 1 to 53) and far end fault (Serial number 54 to 106).

Further, the data calculated in Table 10 has been utilized for computation of settings listed in Table 11 and Table 12. It can be observed from Table 11 that the objective function value obtained with Hybrid GA-NLP approach is the least for conventional as well as proposed approach as compared to GA and NLP methods. Moreover, the simulation time taken in the execution of the algorithm and the number of iterations performed for convergence to optimum solution is also less for proposed approach than to conventional approach. From this data, it can be inferred that the proposed approach is effective and robust in obtaining enhanced relay coordination.

Further, in Table 12 comparison of minimum, maximum and average values of CTI between conventional and proposed approach has been listed. It is evident from the obtained data that the proposed approach gives better results in terms of different CTI values. It can be inferred from Table 12 that the computed values of backup relay operating time is less as compared to conventional approach. Consequently, the CTI values obtained for proposed approach is less and hence the total relay operating time is less.

Further, the procedure adopted for calculation of the parameters listed in Table 10 and computation of optimized settings in Table 11 and Table 12 has been utilized for computation of the objective function value listed in Table 13. In addition, contingencies has been created in the network topology and the response of the Proposed and conventional approaches has been observed. For a better analysis of the advantages of proposed strategy over conventional approach the computed data has been listed in Table 13. It can be pointed out from this table that the optimized value computed for different contingencies achieves a global optimum with the proposed strategy and there is a drastic time reduction.

The proposed approach using GA-NLP technique has also been validated for its effectiveness on IEEE 30 bus system [9]. The performance of the proposed approach has been listed in Table 14. Further, the obtained values of CTI has been shown for primary-backup relay pair for near and far end faults (2 × 50=100) in Fig. 14.

5. Conclusion

The objective of this research was to propose a novel user defined adaptive relay coordination strategy at the near-end as well as at the far-end faults in the line. In the present study, user defined four-settings numerical DOCRs have been employed for the grid-connected microgrid operation on IEEE 6, modified 14 bus and IEEE 30 bus test system. Also, the relay coordination strategy using GA-NLP is compared with GA and NLP algorithms for conventional as well as proposed approach and GA-NLP technique is more efficient as compared to GA or NLP techniques. Further, the effect of DG penetration has been investigated using the conventional as well as proposed approach on modified 14 bus test system and it is found that the proposed method is more effective in handling relay coordination with increased DG penetration. In the context of relay coordination it is evident from the obtained results that the proposed approach is more suitable in handling the complex coordination problem by providing greater flexibility in choosing the characteristic amongst the available option.

CRediT authorship contribution statement

Jayant Mani Tripathi: Conceptualization, Methodology, Software, Visualization, Investigation, Validation, Data curation, Writing – original draft. **Sanjeev Kumar Mallik:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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