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Design and analysis of power distribution systems for optimum over-current relay coordination using voltage component of fault current limiters

Shanker D. Godwal[1*], Kartik S. Pandya[2], Akhilesh A. Nimje[3] and Vipul N Rajput[4]
Research Scholar, Department of Electrical Engineering, Charotar University of Science and Technology, Changa, Gujarat, India[1]
Department of Electrical Engineering, M.S. University of Baroda, Vadodara, Gujarat, India[2]
Department of Electrical Engineering, Institute of Technology, Nirma University, Ahmedabad, Gujarat, India[3]
Department of Electrical Engineering, Charotar University of Science and Technology, Changa, Gujarat, India[4]

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Abstract

Several challenges are posed by the escalating complexities of modern power systems, including increased fault levels and fault currents. One efficient solution to the fault current issue is the superconducting fault current limiter (SFCL), which can prevent further increases in fault current caused by the growth in power generation and consumption. The SFCL has a faster response time and can minimize fault current using its quench features. However, relay operation is adversely affected due to delayed tripping time, leading to mis-coordination among primary and backup relays. To address this issue, the voltage component available across the fault current limiters (FCL), which offers a large reactance, is utilized as an input parameter to modify relay characteristics. This helps to reduce tripping time and avoid mis-coordination. Relay characteristics using voltage components derived from SFCL are implemented to tackle this problem. The operational characteristic of the overcurrent relay is changed using this voltage component. In this paper, a new objective function, based on reported relay characteristics, was proposed. A prototype of the ring mains distribution system was developed to evaluate the effectiveness of the reported characteristics and proposed objective function. Furthermore, the reported characteristic and proposed objective function were examined on a 9-bus distribution system. It was found that the application of voltage components in the relay characteristic and proposed objective function was fruitful and did not delay the relay tripping time also there is no miscoordination found in case of reported characteristic and proposed objective functions. To achieve optimum setting of overcurrent relay parameters, a genetic algorithm(GA) was used.

Keywords

Fault current, Fault current limiter (FCL), Over-current relay (OCR), Voltage component, Protection devices, Power distribution system.

1.Introduction

The electric power demand has been increasing due to various reasons such as rapid growth in industrialization, increased population and improved standard of living. The large-scale deployment of distributed generation has therefore gained momentum to cater the need of increased power demand [1]. The penetration of distributed generation resources results in higher fault mega volts amperes (MVA) thereby increasing the magnitude of fault current [2].

The superconducting fault current limiter (SFCL) has been identified as the favorable protective devices to solve the increasing fault current or fault level in a power distribution system caused by its interconnected operation of the generators with bigger capacities. The implementation of the SFCL into power distribution system may leads to the malfunction or non-operation of the protective relay's coordination. As a result, research on the protection coordination of protective relays with regard to the use of SFCL is required. Due to SFCL quicker response time and ability to use their quench features to minimize the fault current, SFCL can be used to reduce the fault current in a network. In addition to its quench property, it also improves the power system's transient stability. SFCLs are series linking

*Author for correspondence

components which is undetectable to the system when it is functioning normally and during fault it minimize the short circuit current.

The changes in fault level requires replacement of the existing circuit breakers with higher fault levels capacity. It is practically uneconomical to replace circuit breakers. The fault levels can otherwise be confined by using fault current limiter (FCL) that can be bypassed during normal operation and are inserted in the circuit during fault conditions [3]. FCL has quick response within a quarter cycle. This proven technology of FCL has been commercially adopted by the utility across the world. The use of the FCL may have an impact on the protection device's performance, which is particularly reliant on the fault current's amplitude.

One of the usual protection devices in the power distribution system is over current relay (OCR) have its operational parameters reset. The OCR and FCL must be properly coordinate otherwise during fault conditions, OCR operating time will increase as FCL will reduce the fault level. The insertion of FCL reduces the magnitude of fault current thus delaying the inverse definite minimum time (IDMT) relay tripping time and gives rise to miscoordination among the primary and back up relays. The delay in tripping time can be compensated by taking voltage component across the FCL to modify the relay characteristic and have been reported in several recent literatures. The technique that protects the power distribution system with the SFCL by employing the voltage component as the OCR's effective parameter.

In the work done by the authors, a prototype of ring mains distribution system has been developed in the laboratory. In this prototype model and other test systems it is found that overcurrent relay characteristic using voltage component is more appropriate as compared to previous coordination methods. The optimization studies have been done by researchers in the recent past to compute the optimum values of time multiplier settings and plug settings (PS) to avoid miscoordination problem among the primary and back up relays.

The objective of this paper is to find the optimum relay setting parameters for new objective function and reported characteristics.

In this paper, through new objective function and voltages component-based relay characteristic, optimum overcurrent relay coordination is achieved. Further, the said combination is evaluated on prototype ring main distribution system , ring main distribution system & 9 bus distribution system.

This paper is divided into five sections. In section 1 the introduction of OCR coordination and brief summary of the paper is discussed. Section 2 discuss the literature survey part of the research work. Section 3 present problem formulation of OCR coordination and issues related to conventional objective function and relay characteristic. Further, in same section reported relay characteristic with voltage component is discussed. In section 4, experimental setup ring main distribution system is discussed. Section 5 covers the results and discussion part of the research work.

2.Literature survey

In the present era, the penetration through distributed generation (DGs) has increased significantly. It is imperative to see that a higher capacity DGs can also be connected in the distribution network. With this, the fault level abruptly increases thus requires the replacement of the existing circuit breakers which is economically unfeasible. As the DGs are included with the conventional grid, it escalates the short-circuit level thereby increasing the fault current into distribution systems. It has a major impact on the protective system performance and may reverse the direction of power flow. In order to reduce the short-circuit current, FCLs are used [4]. Both FCLs and DGs alter the protective equipment settings. Inverse time relay characteristics and the set points are influenced by the fault clearing time (FCT) and the pick-up current. In order to secure all the equipment, it is necessary to implement the optimization method to reduce the FCTs, PS and time setting multiplier (TMS) of primary and backup relays (BR). During normal operation, the FCLs are bypassed by the system currents due to high reactance. Under fault conditions, it helps to reduce the fault MVA and thus the fault current. The introduction of FCL alters the system admittance matrix. This affects the PS and TMS necessary to establish the relay coordination [4]. A given SFCL deployment is not regarded as a technically viable alternative if the maximum fault current is not constrained below the capacity of the protective devices. Additionally, if the location of FCL is improperly selected, it may lead to relay miscoordination [5–8]. Apart from the optimum settings of the overcurrent relays, it also depends on few constraints and the objective function. In literature, many authors have proposed modifications in the objective function as conventional objective function does not incorporate the operating time of backup relay and coordination time interval (CTI). Further, the various soft computing techniques can be used to achieve optimum setting of overcurrent relays. These soft-computing techniques are genetic algorithm(GA), binary GA, particle swarm optimization, differential evolution, harmony search, honey bee algorithm, sequential quadratic programing etc. [9–12]. Further, major issues in overcurrent relay coordination of microgrid is that when these grids are in islanded mode, it works as intended. However, with integration of grid, the fault current level and direction may get changed. This creates problem in coordination [13–15]. The fault current can be minimized by using FCL but the operating time of OCR will be higher comparatively system without FCL and it leads to miscoordination as each relay is associated with its nearby backup relays. If the conventional objective function is used with the system having FCL there may be high chances of miscoordination. To avoid such situations, the objective function reported in [5] and the relay characteristics reported in [1] have been used. This objective function reduces the secondary or backup relay's time of operation. In continuation of this, many standard and non-standard relay characteristics have been reported in the literature. Authors have utilized the voltage component across clearing time (CT) and potential transformer (PT). Using this voltage component, the operating time of the relay can be reduced to avoid the miscoordination. For regaining the initial settings of the directional overcurrent relay (DOCR) for relay coordination, the investigations revealed that insertion of FCL is crucial to restrict the short circuit current resulted from addition of DG into the existing network. The system has been tested in a network in the absence of DG, a network with DG and FCL and in the absence FCL. The results revealed that the FCL has better potential to limit the fault current and brings back the initial setting of DOCR. A suitable option to change the relay settings when DGs are involved is the adaptive protection strategy [16–19]. For the sake of working out the relay coordination in a network with the conventional sources accompanied with DG, two methods namely adaptive and non-adaptive strategies have been devised. It is the process of picking up the few relays, their position and altogether a new-settings. While a non-adaptive technique calls for computing FCL specifications in order to restrict the heavy short circuit current and return the relay to its initial setting. Software called as general algebraic modeling system (GAMS) and MATLAB code are used to model the network [20–24]. The non-adaptive protection approach requires added hardware FCL in the network. Whereas the adaptive protection anticipates on activating and upgrade the relay configuration without additional expenses. The end results demonstrate that the adaptive scheme is the best suited, however it is constrained by the relay group settings. For accurate findings, the work might be recreated using electromagnetic transients program (EMTP) reliability verification (RV) software and compared. The dynamic model of the overcurrent relays is used for this purpose based on GA. In contrast to earlier steady state methods, the method provides workable and efficient solutions for optimal coordination in the actual power system networks. For better performance, an adaptive protection method for updating relay settings in a network with DG can be developed and compared to a non-adaptive protection scheme for designing FCL [25–30]. A method for DOCR coordination called the GA is one that takes non-standard inverse time curves and many levels of fault currents into account. After a reasonable time, adequate protection settings are attained. The system creates a unique time current characteristic for each relay, altering coordination without requiring compatibility between curves. An alternative to the GA is a new optimization algorithm. A unique time-current voltage tripping characteristic for DOCRs is developed in order to reduce the overall operating time of relays in mesh distribution networks. The protective coordination problem is handled as a limited nonlinear programming problem to start the ideal relay settings. The proposed characteristic is tested using the power distribution systems of the IEEE-14 bus and IEEE-30 bus with inverter-based and synchronous-based DG units [30–34]. The findings of this experiment demonstrate that, in comparison to the conventional characteristic, the novel tripping characteristic for DOCRs drastically decreases the operation time of all relays. The relay can be constructed with non-standard features for the shortest possible operating time [35–40]. The absence of relay sensitivity during relay coordination is addressed in this article through the use of non-standard inverse time curves. When considering distance relays, the overcurrent relay model takes five convertible settings into account to improve coordination. The suggested approach decreases the number of relays that are not coordinated, allowing for improved implementation of results. According to the findings, overcurrent relay coordination has improved in various intricately linked IEEE test systems. To address the sensitivity issues of relays during the coordination process, the adaptive relay curve can be constructed utilizing the fuzzy interface system (FIS) method [39]. The nonstandard inverse time curves presented in this work can be used to compare the results as well. The study provides a concise summary of few important ideas regarding the coordination of directional overcurrent protection.

The addition of the affected parameters on the relay coordination is not yet available according to the present literature review. Since the network conditions may prevent the standard characteristics from resolving the coordination issue, they should be taken into account for the discussion. The research illustrates how fault location and overcurrent characteristics affect DOCR coordination. The relay curve types that have been evaluated for improved performance of optimal coordination are extremely inverse, normal inverse, and very inverse. When compared to results with normal inverse curves, results with very inverse curves are roughly 16 times faster. In few circumstances, choosing extremely inverse curves could be a preferable option for striking a balance between getting quick operating times. Solid faults at two locations were simulated to find the influence of the fault location. As the fault site changes, the adaptive relay curve can be designed in a way that highlights the traits of the widely used standard curves. In this study, a coordination technique that takes into account the transient state through network simulation employing an accurate elemental model and equations is proposed. The proposed method prevented 23 and 94 miscoordinations, respectively, in the IEEE 8-bus and IEEE 30-bus networks that were caused by the conventional method of coordination. Miscoordination is prevented by taking into account transient situations while choosing the operating times. While applying an optimization strategy, the relay characteristics and TMS should be taken into account.

This study recommends employing a GA in MATLAB to enhance the TMS for the tripping features. An electrical transient and analysis program (ETAP) simulated on international electrotechnical commission (IEC) microgrid benchmark network is used to assess the method. The suggested strategy produced appropriate and satisfactory outcomes for an effective and long-lasting OCR coordination. The work offers a new technique for protection coordinating in microgrids that makes use of the unusual features of DOCR. The optimal coordination problem was solved using shuffling frog leaping, teaching learning-based optimization, evolutionary algorithms, and particle swam optimization (PSO). Every time, the suggested approach discovered shorter coordination times, demonstrating its applicability and effectiveness [40].

3.Problem formulation

This section discusses the objective function and related constraints which affect the relay coordination.

Objective function

To find the optimum value of relay settings, objective function defined in Equation (1) is used. As per relay coordination, sum of all primary relays operating time must be minimum [4]. The conventional objective function is defined as per Equation 1.

$$OF_1 = \sum_{i=1}^{m} w_i t_i \tag{1}$$

where, t_i is the operating time of relay R_i when fault occurs in its zone, m is the total number of PR, and w_i is the weight factor that controls individual relay operating time. The operating time of individual relay is defined in Equation 2.

$$t_i = \frac{0.14 \, x \, TDS_i}{\left(\left(\frac{I_f}{PS_i}\right)^{0.02} - 1\right)} \tag{2}$$

where TDS_i and PS_i are relay settings of R_i relay respectively and I_f is the relay current.

Coordination Constraints

As PR and circuit breaker takes some time to operate, it is essential that backup relay must wait for that much time. Hence, there must be one constraint which must be satisfied. This constraint is defined as per Equation 3. As per this constraint, the operating time of backup relay must be greater than PR by certain time interval which is known as CTI.

$$\Delta t = OT_{backup} - OT_{primaty} - CTI \tag{3}$$

where, Δt is the discrimination time, $OT_{primary}$ and OT_{backup} are the operating time of primary and backup relay respectively the operating time of PR [5].

Constraint on relay operating time

Each relay takes at least minimum time t_{min} to respond. Similarly, it is not intended to take time greater than t_{max}.

$$t_{min} \leq t \leq t_{max} \tag{4}$$

Constraints of time and current settings

It is preferred to set a predefined delay in each primary and backup relay for their operation. This delay is set using TMS. This constraint is expressed as:

$$TMS_i^{min} \le TMS_i \le TMS_i^{max} \quad (5)$$

Similarly, each relay is set for different pickup value i.e., once, the fault current exceeds the pickup current, relay issues trip signal to the circuit breaker [6]. This constraint is expressed as:

$$PS_i^{min} \le PS_i \le PS_i^{max} \quad (6)$$

3.1Issues related to conventional objective function and relay characteristic

Conventional Objective Function

The main issue related to conventional objective function is, it does not optimize the operating time of backup relay and further mis-coordination problem may arise due to this. To overcome this problem, it is required to modify this objective function. The proposed objective function (POF) is expressed as per Equation 7.

$$POF = \gamma_1 \sum_{i=1}^{m} t_i + \gamma_2 \sum_{k=1}^{n} (\Delta t_{pbk} - |\Delta t_{pbk})^2 + \gamma_3 \sum_{k=1}^{n} (\Delta t_{pbk} + (|\Delta t_{pbk}| \quad)\Delta t_{pbk}{}^2 \quad (7)$$

The constant γ_1, γ_2, γ_3 are the weight factor which control terms 1,2 and 3. For simplicity, the values of said constants are considered 1. Further, t_i is operating time of PR and Δt_{pbk} is discrimination time and defined as:

$$\Delta t_{pbk} = t_{bk} - t_{pk} - CTI \quad (8)$$

where, t_{bk} operating time of k^{th} pairs backup relay. t_{pk} is operating time k^{th} pair PR and CTI varies from 0.2 to 0.3s. *Figure 1* depicts the two-bus system with protective zone A and B. For zone A, the primary relay R_b is assigned to clear the fault and for zone B, the primary relay R_p is assigned to clear the fault. Further, if fault takes place in zone B and relay R_p does not respond due to some reason, the relay R_b acts as backup relay for fault at point Q. Thus, as per overcurrent relay coordination, the objective function comprises as sum of operating time of both primary relays and it is defined as per Equation 9.

$$Zsum = t_p + t_{bp} \quad (9)$$

where, t_p and t_{bp} are the operating times of R_p and R_b relays respectively when they are working as primary relays. *Table 1* depicts the comparative analysis of both objective functions. It is seen from case 1 and 2, that OF is insensitive towards the miscoordination situation in both the cases, OF is equal to the sum of both relays working as primary relay. Further, in both cases of OF, each relay takes 6.25 cycles to operate whereas for both cases (case1 and case2) of POF the operating time is 0.26s and 0.34s respectively working differently in case of miscoordination (case 2) as it has larger sum of operating time as compared to OF and similarly in case 1, where miscoordination is not observed, POF performs more or less as OF. At the same time, POF optimizes backup relay's operating time.

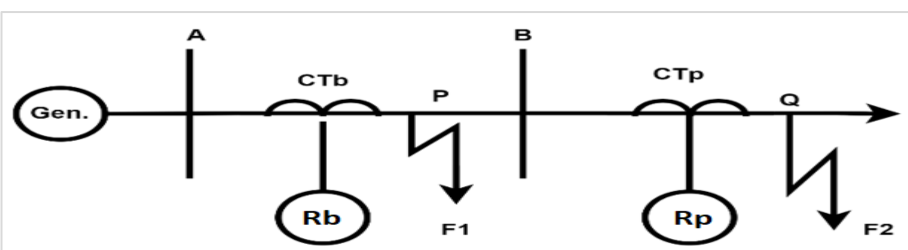

Figure 1 Two bus radial system

Table 1 Comparative analysis of both objective functions

Case	t_p	t_b	Δt_{pb}	t_{bp}	POF	OF	N_1 cycle	N_2 cycle
1	0.15s	0.55s	0.20s	0.1s	0.26s	0.25s	6.25	6.65
2	0.15s	0.2s	−0.15s	0.1s	0.34s	0.25s	6.25	8.5

3.2Conventional IEC standard overcurrent relay characteristic

To obtain the desired time current characteristic, various standard and non-standard relay characteristics have been reported in the literatures [7]. Researchers have adopted the over current relay characteristics as given below:

$$t_i = \frac{A \times TMS}{(M)^p - 1} + B;\ M = \frac{I_f}{PS} \quad (10)$$

where, t_i is time of operation of over current relay;; A, p and B are the constants.

3.3Overcurrent relay characteristics using voltage component (Reported Characteristic)

Figure 2 shows a section of radial distribution system with OCR using voltage component of FCL. Upon occurrence of the fault, FCL carries the fault current. It is worth noting that if the fault current is reduced due to insertion of FCL, the operating time of the relay increases and thus it needs to be reduced. The voltage component across FCL at the instant of fault inception is derived and used to reduce the operating time of the relay.

$$t_i = \frac{A \times TDS}{(M')^p - 1} \quad (11)$$

$$M' = \frac{I_f + \alpha \times V_{FCL}}{PS} \quad (12)$$

where, α is the coefficient of voltage component across FCL. V_{FCL} is the voltage across FCL at the instant of fault occurrence. Further, *Figure 3* depicts the block diagram of overall Structure of trigger type SFCL. SFCL has superconducting module connected in series with system with high frequency switch and in parallel there is a current limiting reactor connected. SFCL has superconducting module connected in series with system with high frequency switch and in parallel there is a current limiting reactor connected. For the control logic of the SFCL two quantities to be measured current flowing throw the SFCL and voltage across the switch element. In this case magnitude current should not exceed the pre define value and voltage across the should not drop below the pre define value [1]. Here high frequency switch is acted as the sensing element and high impedance reactor acts as the FCL for triggering of the high frequency switch pulse-width modulation (PWM) technique can be used in gate driver circuit [2].

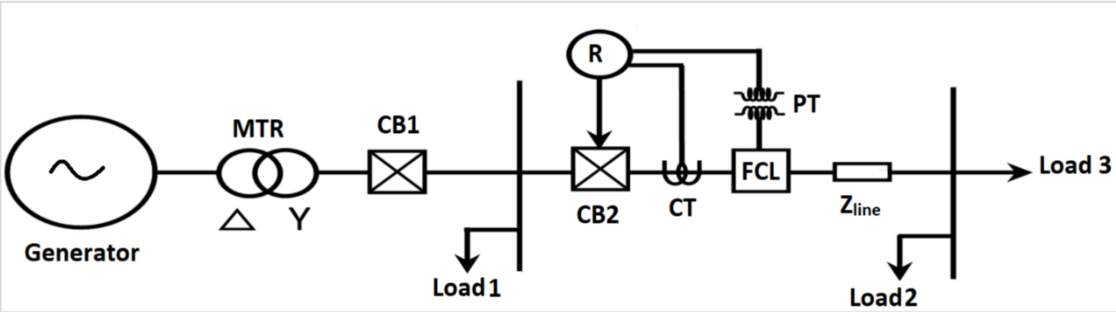

Figure 2 Radial distribution system with OCR using voltage component of FCL

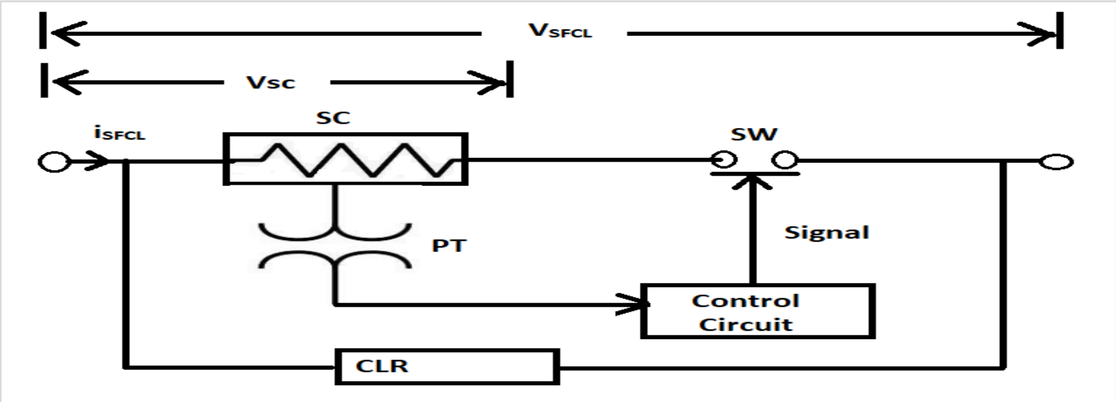

Figure 3 Block diagram of overall Structure of trigger type SFCL[1]

Two comparators can be used for generating control signal output of both the comparator is given to and gate, so when both the comparator generates high output then and then only and gate generates high output. The predefine value(i) is taken as the 1.3 times of the normal rated current as the current exceeds the 1.3 times of the rated current comparator generates the output. Here the value less the 1.3 times of current may operate for the transient condition and value greater than the 1.3 times of the rated current may cause the delay in operation. Same can be done for the voltage component the predefine value of the voltage component (V_t) is 0.95 pu of normal condition voltage. When both of the comparator gives high output than the and gate generates the high output and insulated-gate bipolar transistor (IGBT) gate driver circuit generates the gate signal according to it [2].

To evaluate the effectiveness of the reported characteristic and POF, distribution systems have been taken. Further, a hardware setup has been designed in such a way that the model can be configured as ring mains distribution. The said distribution system is scaled down at 230 V and 1.5 kVA level and accordingly the actual reactance has been calculated for the laboratory model. The operating time as per relay characteristics defined in Equation (2) has been compared with conventional OCR characteristic. For the satisfactory operation with the new relay characteristic, the operating times obtained with both the methods should be approximately same or with the least error. *Figure (3b)* depicts the hardware setup of ring main distribution system. In prototype setup, all the parameters of ring mains distribution network have been scaled down.

4.Experimental setup

Ring mains distribution network

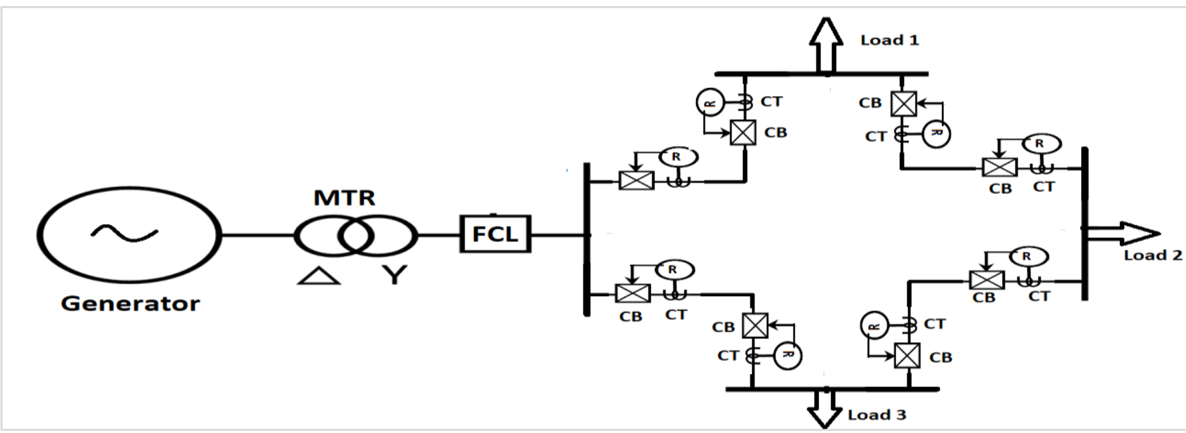

Figure 3(a) Ring mains distribution network with implementation of FCL [8]

Figure 3(b) Hardware setup for protective scheme of ring main distribution system

4.1Simulation results

The performance of proposed objective function and reported characteristic have been evaluated on ring mains distribution network and prototype system. *Table 2* depicts the primary and backup relay's fault current and CT ratio of ring mains system and further four cases are discussed to evaluate the performance of proposed objective function. These cases are as follows:

1. Conventional Relay Characteristic with Actual Fault Current and Conventional Objective Function (CCAFOF)
2. Conventional Relay Characteristic with FCL and Conventional Objective Function (CCFCLOF)
3. Conventional Relay Characteristic FCL with Actual Fault Current and Proposed Objective Function (CCAFPOF)
4. Reported relay characteristic with and proposed objective function (RCFCLPOF)

Prototype ring main distribution system

Table 2 depicts fault current data and primary & backup relay pairs for prototype ring mains distribution system. *Table 3* presents the PS and TMS of prototype ring main system. It can be seen from *Table 3* that the sum of operating time of primary relays using only conventional approach CCAFOF for prototype ring mains distribution system is 12.34 s whereas the sum of operating time for CCAFPOF scheme, it is 11.94s. It shows the effectiveness of POF over conventional objective function. However, when FCL is installed for the reduction in fault level, the operating time of the relays CCFCLOF scheme increases significantly as compared to CCAFOF and CCAFOF is compared with CCFCLPOF scheme, POF plays better in all aspects. It can be concluded that the proposed objective function reduces the operating time to a great extent. When the conventional objective function with FCL is compared with the proposed objective function and the reported characteristics, the operating time is reduced. The same pattern of operating time is found for back up relays. *Figure 4* shows the comparative analysis of operating time of primary relays for all four cases. It is observed that operating time considering POF are in prescribed limit. Similarly, *Figure 5* and *Figure 6* show the comparative analysis of operating time of backup relays for all four cases. It is observed from *Figure 5* that except one case (relay pair 5) the operating time of backup relay is large as compared to other cases. Figure depicts the comparative analysis of CTI or all four cases. Two major miscoordination were found in case of CCFCLOF case whereas no miscoordination found in case CCAFPOF and RCFCLPOF

Table 2 Fault current and CT ratio for prototype ring mains distribution system

Sr. No.	Primary relay (PR)	CT ratio	PR Fault current	Voltage at FCL at the instant of fault for PR	Backup relay	CT ratio	BR fault current
		(BR)	Amp.	Volt	(BR)	(BR)	Ampere
1	R1	2	17.5	24	--	--	--
2	R2	2	17.5	--	--	--	--
3	R3	2	2.5	--	R7	2	2.5
4	R4	2	9.3	--	R1	2	9.3
5	R5	2	2.5	--	R8	2	2.5
6	R6	2	9.3	--	R2	2	9.3
7	R7	2	5.7	--	R6	2	5.7
8	R8	2	5.7	24	R4	2	5.7

Table 3 PS and time settings for prototype ring main distribution system

RELAY	Conventional characteristic with actual fault level & OF (CCAFOF)		Conventional Characteristic with FCL & OF CCFCLOF)		Conventional Characteristic With actual fault current & POF (CCAFPOF)		Reported Characteristic With FCL & POF (RCFCLPOF)	
	PS	**TMS**	**PS**	**TMS**	**PS**	**TMS**	**PS**	**TMS**
R_1	0.56	0.34	1.34	0.36	0.74	0.29	1.24	0.68
R_2	1.23	0.37	2.42	0.25	1.27	0.41	1.08	0.56
R_3	1.78	0.27	1.45	0.29	2.32	0.19	1.39	0.25
R_4	1.43	0.42	0.78	0.1	1.5	0.38	0.98	0.51
R_5	2.12	0.31	2.19	0.34	1.28	0.2	0.86	0.32
R_6	2.26	0.41	2.27	0.1	2.19	0.47	1	0.45
R_7	1.89	0.32	1.68	0.2	2.1	0.32	1.25	0.28

R_8	1.28	0.23	1.26	0.2	0.84	0.2	1.53	0.59
$\sum t_p$	**12.34s**		**15.13s**		**11.97s**		**15.08s**	
$\sum t_b$	**11.44s**		**14.30s**		**35.95s**		**13.98s**	

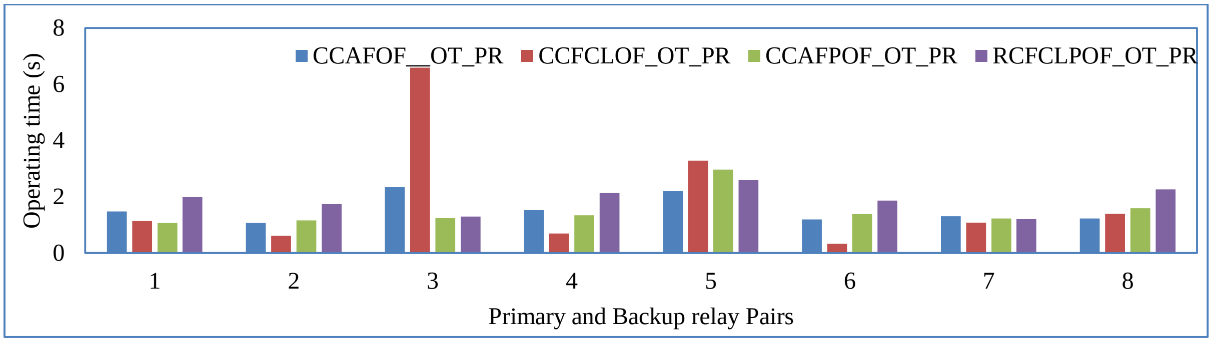

Figure 4 Comparative analysis of operating time of primary relay for various cases in prototype model

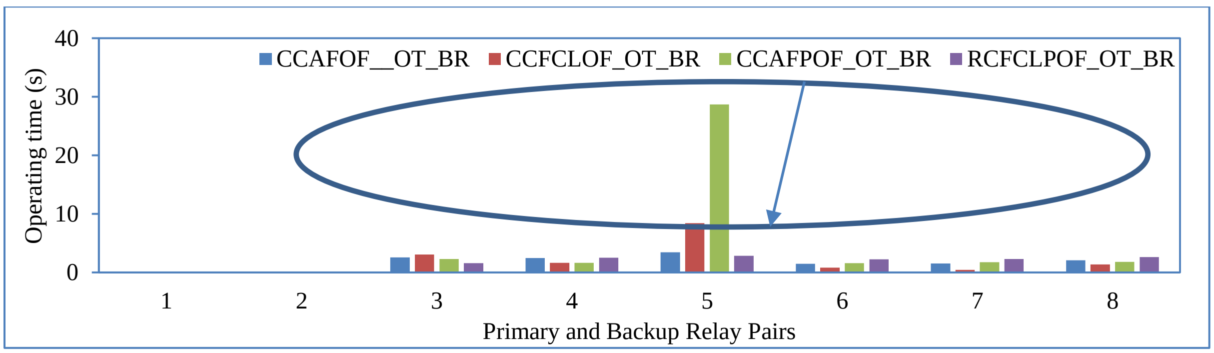

Figure 5 Comparative analysis of operating time of backup relays for various cases in prototype ring main system

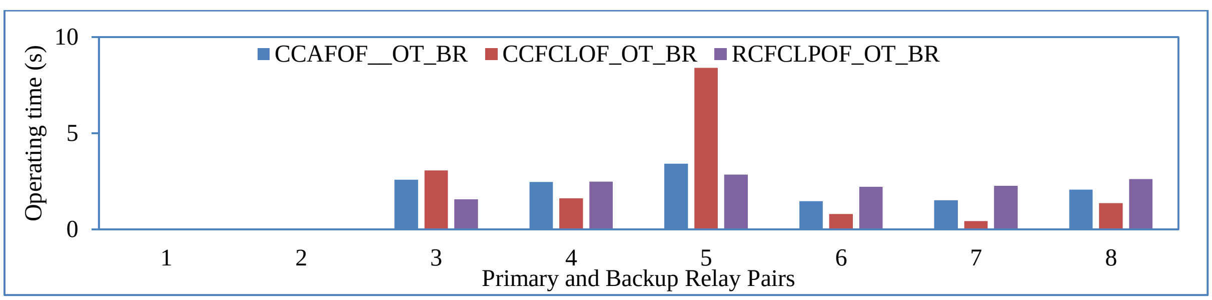

Figure 6 Comparative analysis of operating time of backup relays for various cases in prototype ring main system

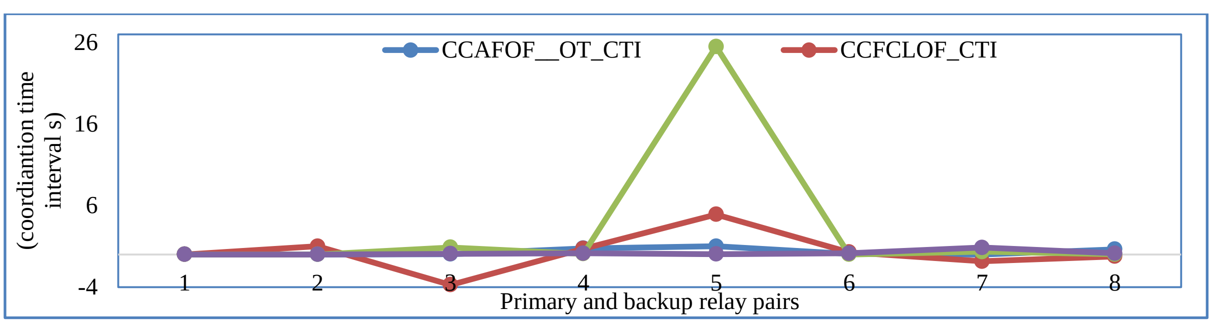

Figure 7 Comparative analysis of CTI for various cases for prototype ring main system

Ring main distribution system

Table 4 depicts fault current data and primary & backup relay data for prototype ring mains distribution system [12]. *Table 5* presents the of ring main system. It can be seen from *Table 5* that the sum of operating time of primary relays using only conventional approach CCAFOF for ring mains distribution system is 8.13s whereas the sum of operating time for CCAFPOF scheme, it is 8.90s. For this case, POF does not perform better as compared to conventional objective function. However, when FCL is installed for the reduction in fault level, the operating time of the relays (CCFCLOF scheme) increases significantly as compared to CCAFOF and if CCAFOF is compared with CCFCLPOF scheme, POF plays better in all aspects. It can be concluded that the proposed objective function reduces the operating time to a great extent. When the conventional objective function with FCL is compared with the proposed objective function and the reported characteristics, the operating time is reduced. The same pattern of operating time is found for back up relays. *Figure 8* shows the comparative analysis of operating time of primary relays for all four cases. It is observed that operating time considering POF are in prescribed limit but operating time of primary relays 3 & 5 for case CCFCLOF was found higher as compared to rest of the cases. Similarly, *Figure 9* shows the comparative analysis of operating time of backup relays for all four cases. The operating time of backup relays are in prescribed limits for all other cases. *Figure 10* depicts the comparative analysis of CTI or all four cases. It can be observed from *Figure 10* due to CCAFOF, two major miscoordinations were found between primary and backup relays. Similarly, three major miscoordination were found in case of CCFCLOF whereas, no miscoordination have been observed for the cases CCACPOF and RCFCLPOF.

Table 4 Fault current and CT ratio for ring mains distribution system

Sr. No.	Relay	CT PR	PR_I_f Amp	BR	BR fault current Amp
1	R1	500	7653	--	--
2	R2	500	7653	--	--
3	R3	500	1093	R7	1093
4	R4	200	4100	R1	4100
5	R5	500	1093	R8	1093
6	R6	200	4100	R2	4100
7	R7	200	2460	R6	2460

Table 5 Comparative analysis of operating time for various methods

RELAY	**Conventional characteristic with actual fault level & OF** (CCAFOF)		**Conventional Characteristic with FCL & OF** CCFCLOF)		**Conventional Characteristic With actual fault current & POF** (CCAFPOF)		**Reported Characteristic With FCL & POF** (RCFCLPOF)	
	PS	**TS**	**PS**	**Time sharing (TS)**	**PS**	**TS**	**PS**	**TS**
R_1	1	0.5	1.23	0.56	1.12	0.49	2.32	0.57
R_2	1	0.5	1.29	0.5	1	0.44	1.9	0.52
R_3	0.75	0.1	0.89	0.23	0.79	0.1	1.09	0.18
R_4	1.25	0.35	0.81	0.27	1.23	0.49	1.29	0.51
R_5	0.75	0.1	0.85	0.24	0.79	0.1	1.02	0.2
R_6	1.25	0.35	1.36	0.27	1.25	0.5	1	0.5
R_7	1	0.25	1.12	0.29	1	0.37	1.18	0.43
R_8	1	0.25	1.14	0.29	1	0.37	1.1	0.41
$\sum t_p$	**8.13s**		**15.02s**		**8.90s**		**7.07s**	
$\sum t_b$	**6.15s**		**6.89s**		**7.19s**		**6.83s**	

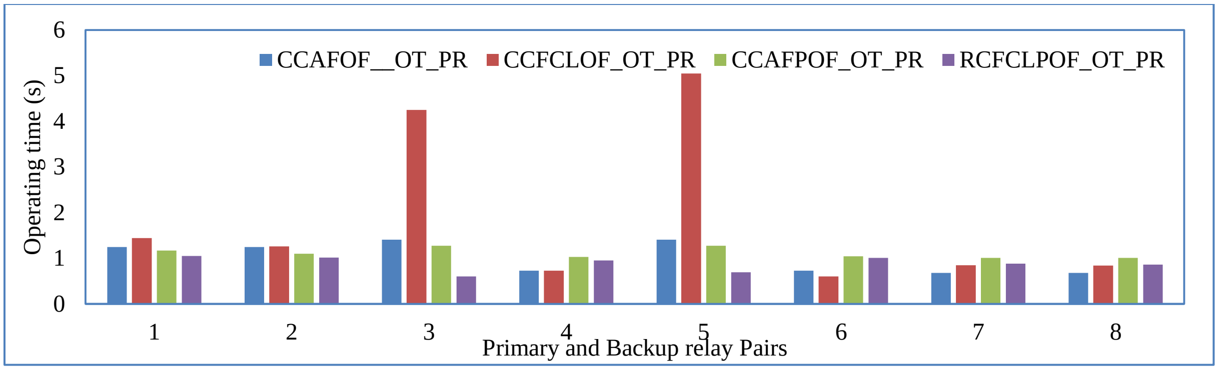

Figure 8 Comparative analysis of operating time of primary relay for various cases

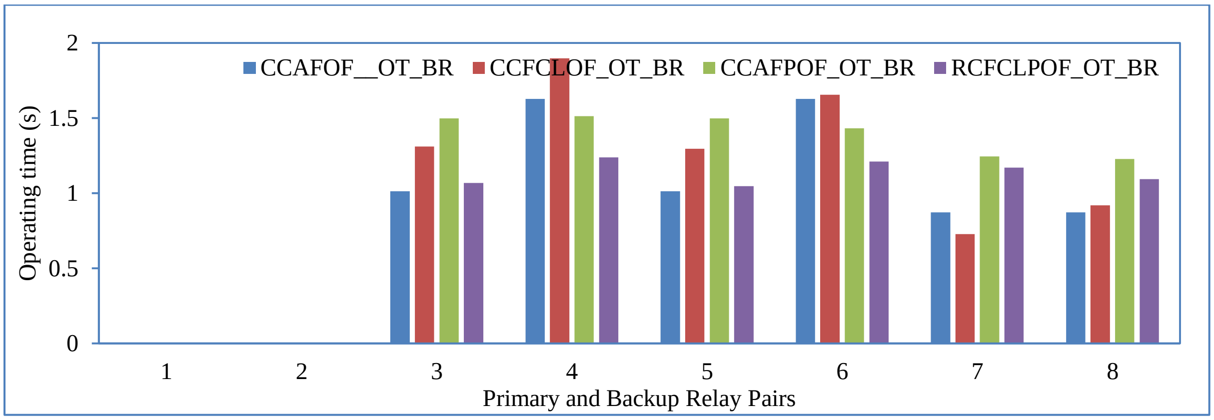

Figure 9 Comparative analysis of operating time of backup relays for various cases

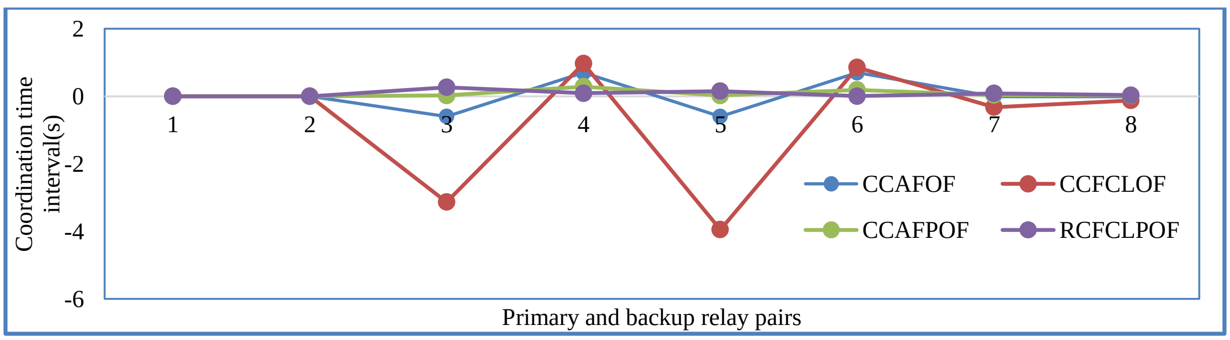

Figure10 Comparative analysis of CTI for various cases

9 Bus distribution system

To evaluate the effectiveness of the said objective function along with voltage component-based relay characteristic, it is further tested on 9 bus distribution system. *Figure 11* depicts the single line diagram of 9 bus distribution system. There are 24 DORCs . The fault current data, primary and backup relay pairs are given in [12]. As there is only one source in this system, a FCL is located at bus 1. The relays 17, 19, 21 and 23 are voltage component based normal inverse OCR and these relays operate based on two input signals connected at bus 1. First signal is received from the current transformer and second signal is obtained from PT. Rest of the relays are normal inverse relays. *Table 6* depicts the PS and TMS of all relays for various cases. It can be seen from *Table 6* that sum of operating time of primary relays for various cases varies significantly. It is concluded that reported relay characteristic play very important role to maintain the coordination between primary and backup relays. As it can be seen from *Table 6* that the operating time for case CCAFOF is 18.01s whereas in case of CCAFPOF the operating time of all primary relay is 11.27s which indicate that

POF optimize the operating time at great extent. Similarly, for other cases, POF effectiveness scan be examined. Further, *Figure 12* depicts the comparative analysis of operating time of primary relays for all four cases. It is observed that for case CCFCLOF the operating time of primary relay increase significantly due to presence of FCL and conventional relay characteristic and conventional objective function. *Figure 13* presents comparative analysis of operating time of backup relays. It is found that for case CCFCLOF operating time of backup relay for few cases increases as per expectation whereas the operating time for other cases remain in prescribed limit. *Figure 14* shows the comparative analysis of CTI for various cases. It is seen from *Figure 14* that many miscoordinations have been found in case of CCAFOF and CCFCLOF whereas no miscoordination have been observed for the cases CCAFPOF and RCFCLPOF. In this way, it can be concluded that proposed objective function and reported OCR characteristic may improve relay coordination to a great extent in presence of FCL.

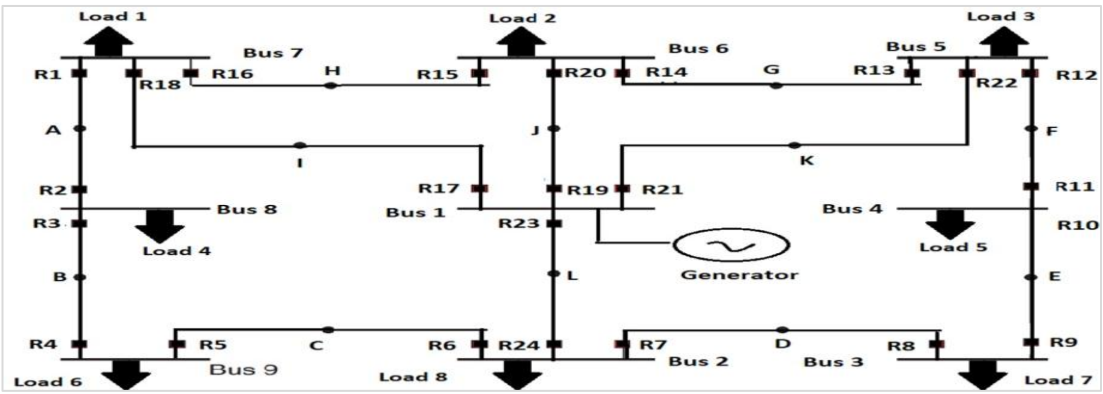

Figure 11 9 Bus distribution system

Table 6 Relay setting obtained by OF and POF using FCL and without FCL & voltage component-based relay characteristic for 9 bus distribution system

Relay	Conventional characteristic with actual fault level & OF (CCAFOF)		Conventional Characteristic with FCL & OF CCFCLOF)		Conventional Characteristic With actual fault current & POF (CCAFPOF)		Reported Characteristic With FCL & POF (RCFCLPOF)	
	PS	**TMS**	**PS**	**TMS**	**PS**	**TMS**	**PS**	**TMS**
1	302.34	0.1	298.45	0.12	234.23	0.23	298.45	0.238
2	321	0.14	309.24	0.113	212.34	0.1	234.56	0.134
3	653.65	0.21	451.23	0.191	542.45	0.164	184.94	0.198
4	56.49	0.112	34.49	0.1	217.45	0.25	309.32	0.27
5	398.32	0.209	72.34	0.102	198.24	0.14	210.29	0.193
6	296.12	0.11	298.34	0.1	209.78	0.1	209.78	0.134
7	393.49	0.341	212.67	0.2	373.97	0.2	138.82	0.234
8	312.33	0.218	132.4	0.2	156.7	0.17	292.3	0.22
9	535.38	0.102	186.93	0.23	152.52	0.141	234.24	0.2
10	434.42	0.23	456.67	0.12	273.56	0.1	245.35	0.21
11	324.2	0.256	129.84	0.1	289.57	0.121	243.34	0.2
12	432.4	0.2	112.98	0.16	234	0.1	328.52	0.183
13	80.34	0.1	72.35	0.19	398.24	0.2	193.29	0.26
14	563.5	0.1	159.78	0.32	162.66	0.13	183.45	0.183
15	543.2	0.24	421.4	0.25	521.72	0.387	247.59	0.43
16	432.4	0.1	239.3	0.15	357.3	0.2	226.67	0.267
17	543.5	0.32	451.67	0.24	385.67	0.17	352	0.25
18	459.3	0.372	210.52	0.3	337.3	0.1	231.3	0.17
19	532.5	0.25	198.46	0.173	418	0.23	640.52	0.29

Relay	Conventional characteristic with actual fault level & OF (CCAFOF)		Conventional Characteristic with FCL & OF CCFCLOF)		Conventional Characteristic With actual fault current & POF (CCAFPOF)		Reported Characteristic With FCL & POF (RCFCLPOF)	
	PS	**TMS**	**PS**	**TMS**	**PS**	**TMS**	**PS**	**TMS**
20	502.4	0.25	239.49	0.2	378.56	0.2	248.3	0.28
21	427.9	0.104	219.22	0.1	673.56	0.123	310.42	0.19
22	705.8	0.224	683.42	0.2	345.45	0.1	294.99	0.203
23	579.7	0.273	229.86	0.14	468.2	0.1	236.73	0.192
24	346.3	0.4	215.99	0.26	129.88	0.1	234.34	0.178
$\sum t_p$	**18.01s**		**12.50s**		**11.27s**		**16.42s**	
$\sum t_b$	**28.18s**		**17.44s**		**20.37s**		**33.49s**	

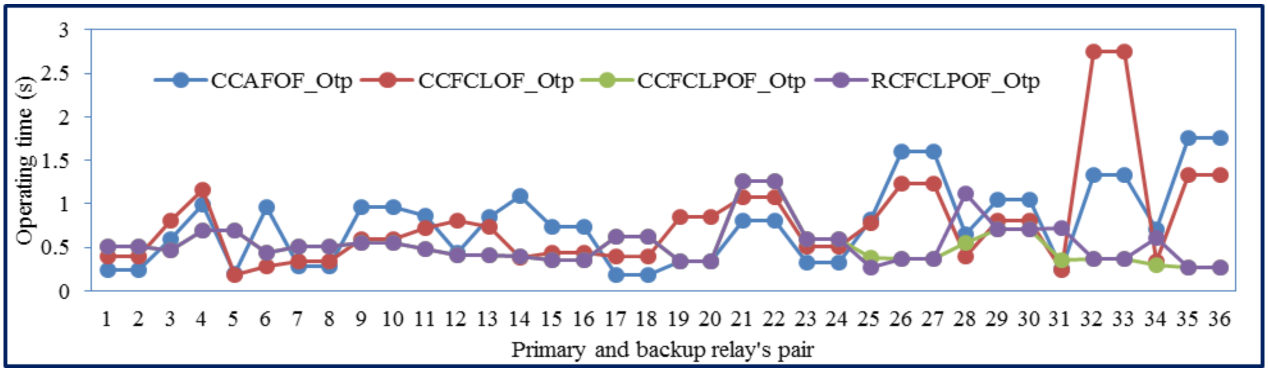

Figure12 Comparative analysis of primary relay's operating time for various cases

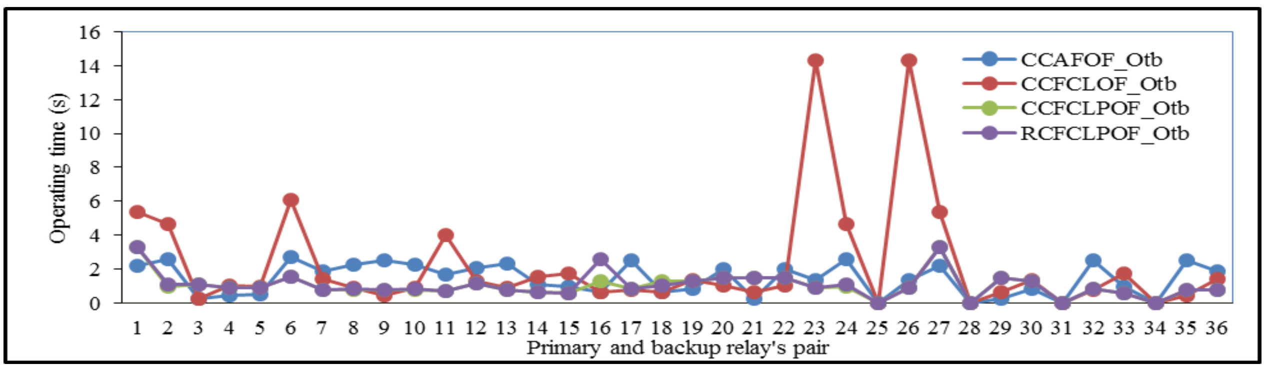

Figure 13 Comparative analysis of backup relay's operating time for various cases

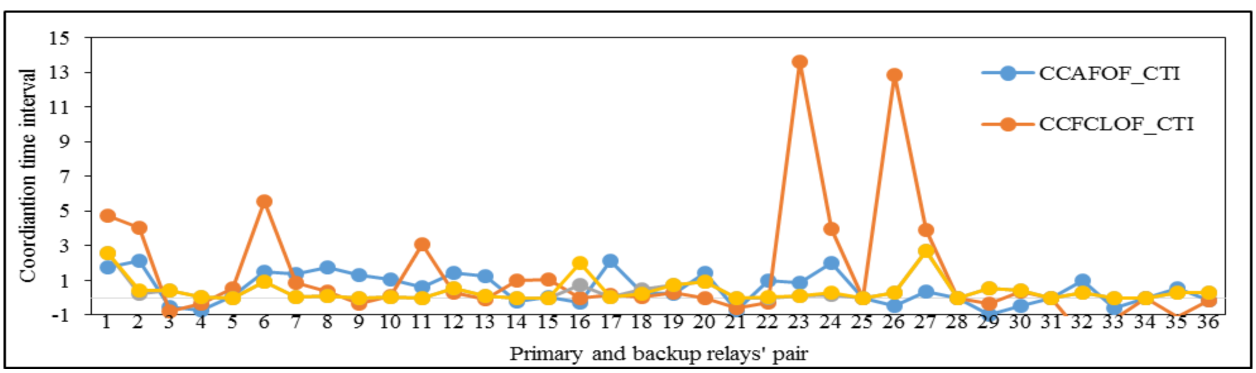

Figure 14 Comparative analysis of CTI for various cases

Table 7 depict the comparative analysis of Comparative analysis of trip time for primary and backup relays considering various cases i.e. for 9 bus test system, ring main distribution system and prototype ring main distribution system. It can be seen from *Table 7* that average trip time for PR has been reduced while considering RCCFCLPOF case as compared CCAFOF case except prototype ring main distribution system. Similarly it can be observed that POF and reported characteristic significantly reduced the average trip time of individual relays 9 bus test system. It can be further noted that average tripping time in case of CCAFOF is 0.75s whereases in case CCAFPOF the average tripping time is 0.46s. It means POF reduce the tripping time at significantly and further the percentage average tripping time in case of RCCFCLPOF has reduced by 9.33% for individual relay with comparison to CCAFOF in 9 bus test system. Similarly, the average tripping time for rest of the two systems convey that the POF work efficiently with and without reported characteristic.

Table 7 Comparative analysis of trip time for primary and backup relays considering various cases

		CCAFOF	CCFCLOF	CCAFPOF	RCCFCLPOF
9 Bus Distribution System	Average trip time for PR	0.75s	0.52s	0.46s	0.68s
	Average trip time for BR	1.17s	0.72s	0.84s	1.39s
Ring Mains Distribution System	Average trip time for PR	1.01s	1.87s	1.11s	0.88s
	Average trip time for BR	0.76s	0.86s	0.89s	0.85s
Prototype Ring Main System	Average trip time for PR	1.54s	1.89s	1.49s	1.88s
	Average trip time for BR	1.43s	1.78s	4.49s	1.74s

5. Discussion

In this research paper, three systems have been evaluated based on reported OCR Characteristic and proposed objective function. It can be observed from prototype ring main distribution system that conventional characteristic with FCL & OF (CCFCLOF) suffers from miscoordination between primary and backup relays and having high operating time of primary relays. The higher operating time cannot be appreciated protection point of view. The presence of FCL in ring main distribution system will increase around 22.60% operating time of primary relays whereas the operating time of backup relays will increase 25%. Further, it can be seen that operating time in case of CCAFPOF have reduced by 3% with reference to operating time of primary relays for case CCAFOF. It indicates the effectiveness of propose objective function. But, for case of reported relay characteristic with FCL & POF, there is very small improvement have been observed which can be further improve by using recent soft computing techniques. It can be also observed that there is no miscoordination have been observed when POF is adopted forver current relays coordination. In similar manner, the result can be analyzed for ring main distribution system. The presence of FCL in ring main distribution system will increase around 84.74% operating time of primary relays whereas the operating time of backup relays will increase 16.9%. Also there are miscoordination between primary and backup relays. Further, it can be seen that operating time of primary relays in case of CCAFPOF have reduced by 59% with reference to operating time of primary relays for case CCAFOF. This show the robustness of propose objective function. Further, for case of reported relay characteristic with FCL & POF, there is 20.5% reduction of operating time of primary relays with comparison to CCAFPOF. It can be also notice that there is no miscoordination have been observed when POF is adopted for OCR coordination.

In case of 9 bus test system, again the effectiveness of POF and reported relay characteristic can be seen. The operating time of primary relays in case of CCAFPOF is reduced significantly by 37.42% CCAFOF scheme. Similarly, it can be seen that there is no miscoordination have been noted in case of proposed objective function. In this way the effectiveness of proposed objective function can be observed with reported relay characteristic. It is found in all three test systems that POF with reported characteristic work efficiently as compared to other schemes. It is also found that miscoordinations may occurs in case of conventional objective function and in presence of FCL. Results reveals that in ring main distribution systems two major miscoordination have been observed. In case of primary and backup relay pair no 3 and 5, backup relay operates earlier to primary relay which cannot be appreciated in any protective scheme.

The major limitation of proposed work is that the proposed objective function and reported characteristic is not implemented on higher test systems i.e. IEEE-15 bus IEEE-30 bus systems and due to this actual performance of reported characteristic and proposed objective function cannot be judge. Another limitation is location of FCL. The location of limiters will decide the actual fault current magnitude and further it will lead to decide the operating time of each relay. In present study, only at one location FCL is placed even though there are many relays in system. The trip time of individual relay in case of CCAFPOF and RCFCLPOF has reduced.

A complete list of abbreviations is shown in *Appendix I.*

6. Conclusion and future work

In this paper, the efficacy of nonstandard relay characteristics based on voltage component is verified. The effectiveness and robustness of said characteristic is evaluated on hardware setup of ring main distribution system and IEEE-9 bus distribution system. It has been observed that operating time of OCR increase significantly due to presence of FCL action. The said relay characteristic and proposed objective function not only reduce the operating time of OCR but also help to achieve optimum relay setting of each OCR. Further it can be concluded that with the incorporation of POF with reported relay characteristic may lead to optimum OCR coordination without any miscoordination between primary and backup relays. The proposed idea can be implemented in the complex power system network. The optimum time can be reduced using recent soft computing techniques for adoptive relaying systems.

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Conflicts of interest

The authors have no conflicts of interest to declare.

Author's contribution statement

Shanker D. Godwal: Conceptualization, investigation, hardware setup, data collection, interpretation of the result, and writing the original draft. **Kartik S. Pandya**: Conceptualization, writing review, and supervision. **Akhilesh A. Nimje:** Hardware setup, writing review, and supervision. **Vipul N Rajput:** Conceptualization, review, and supervision.

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Shanker D. Godwal is currently pursing his Ph.D the From M V Patel Dept. of Electrical Engineering, Charotar University of Science & Technology (CHARUSAT) Changa, India. He pursued his Bachelor's of Engineering from Swami Keshavanand Institute of Technology Jaipur Rajasthan, India, and his Master's of Engineering from Veermataja Jijabai technological Institute Mumbai India. His research interests include Power System Protection ,Optimization, and power system stability.
Email: shanker.godwal@nirmauni.ac.in

Kartik S. Pandya (Senior Member, IEEE) received the Ph.D in Electrical Engineering from the M.S. University of Baroda, India in 2013. His research interests include Power System Optimization, Computational Intelligence Methods, Restructured Power Systems, Smart Grid and Power System Protection Optimization.
Email: kartikpandya75@gmail.com

Akhilesh A. Nimje. Nimje is working as Associate Professor at the Department of Electrical Engineering, Institute of Technology, Nirma University. Dr Nimje obtained BE degree in Electrical Engineering from Nagpur University in the year 1997. He received MTech degree in power systems engineering from Indian Institute of Technology, Kharagpur in the year 2002 and PhD degree in power systems engineering from KIIT university, Bhubaneswar in the year 2012. His areas of interests include rural electrification, facts, power system analysis, distributed generations and renewable energy sources.
Email: akhilesh.nimje@nirmauni.ac.in

Vipul N Rajput received his PhD degree in Electrical Engineering at Charotar University of Science and Technology, Changa, Gujarat, India. He pursued his Bachelor's of Engineering from Government Engineering College, Dahod, Gujarat, India, and his Master's of Engineering from Birla Vishwakarma Mahavidyalaya, Anand, Gujarat, India. His research interests include power system protection, distributed generation and artificial intelligence.
Email: vipulrajput16986@gmail.com

Appendix I

S. No.	Abbreviation	Description
1	BR	Backup Relay
2	CCAFOF	Conventional Relay Characteristic with Actual Fault Current and Conventional Objective Function
3	CCFCLOF	Conventional Relay Characteristic with FCL and Conventional Objective Function
4	CCAFPOF	Conventional Relay Characteristic FCL with Actual Fault Current and Proposed Objective Function
5	CT	Clearing Time
6	CTI	Coordination Time Interval
7	DGs	Distributed Generation
8	DOCR	Directional Overcurrent Relay
9	EMTP	Electromagnetic Transients Program
10	ETAP	Electrical Transient And Analysis Program
11	FCL	Fault Current Limiter
12	FCT	Fault Clearing Time
13	FIS	Fuzzy Interface System
14	GA	Genetic Algorithm
15	GAMS	General Algebraic Modeling System
16	IDMT	Inverse Definite Minimum Time
17	IEC	International Electrotechnical Commission
18	IGBT	Insulated-Gate Bipolar Transistor
19	MVA	Mega Volts Amperes
20	PR	Primary relay
21	PS	Plug Setting
22	PSO	Particle Swam Optimization
23	POF	Proposed Objective Function
24	PT	Potential Transformer
25	PWMS	Pulse-Width Modulation
26	RCFCLPOF	Reported Relay Characteristic With and Proposed Objective Function
27	RV	Reliability Verification
28	TMS	Time Setting Multiplier
29	TS	Time Sharing