

A new modified characteristic equation for optimal coordination of directional overcurrent relays

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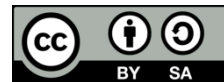
Relay characteristics

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ABSTRACT

The integration of distributed generation (DG) into power systems is increasing to meet the requirements of the utility system. Renewable energy sources are given priority due to their clean energy and high consistency advantages. Integration of DG into the system makes the bi-directional flow of current. Directional type overcurrent relays are usually used for protection of lines associated with bidirectional power flows. The installation of DGs, (especially, inverter-based) invites challenges to the existing protection schemes. A new modified characteristic equation-based approach is proposed in this paper to obtain the faster operational time of relays. The relay coordination scheme proposed in this paper is applied to an 8-bus test system integrated with the solar-based photovoltaic integrated distributed generator (PVIDG). The comparative analysis between the conventional and proposed approaches is done.

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1. INTRODUCTION

Protection plays a vital role in the healthy operation of any power system network. In fault conditions, the protection system takes responsibility for detecting and clearing faulty parts of the system, and it prevents the expansion of the fault current and its parameters to the rest part of the system. The system should be able to detect the smallest fault current presence in the system. The smaller the fault current that the system can detect, the more sensitive the system is [1]. The power system experiences havoc as long as the fault present in the system increases and it gradually loses its stability. Thus, the speed of the protection is crucial to decrease the effect caused by the fault and to run the system efficiently. In addition, it is, and to be mentioned that, the speed and the accuracy are in the inverse relationship. The system works less accurately with high-speed operation. This is because; the system operates at high speed with lesser information inverse to that of the slow-speed system. Therefore, the Protection Engineer must be able to balance between the two requirements [2].

A comprehensive review of various optimization methods used for the coordination of relays is discussed in [3]. The optimal coordination of relays using wild horse optimizer and non-linear programming is discussed in [4]. The optimal layout of protection equipment is been discussed in [5]. A relay protection scheme for islanded microgrids using harmonics generated in inverter-based DGs is proposed in [6]. Relay coordination using the Augmented Lagrangian Genetic Algorithm is proposed in [7]. Relay coordination in an islanded microgrid using a fault limiter is proposed in [8]. Directional overcurrent protection considering 'n-1' contingency is solved using mixed integer linear programming (MILP) in [9]. Relay coordination suitable for

both grid-connected mode and islanded modes of microgrid is been proposed in [10]. A hybrid dynamic relay coordination scheme is proposed in [11]. A centralized relay coordination scheme considering load variations, changes in topological structure and DG locations is discussed in [12]. Mathematical modeling for coordination between relays in distribution systems equipped with distributed generators is discussed in [13]. Relay coordination in an active distribution network consisting of synchronverters is proposed in [14]. Relay coordination in inverter-interfaced microgrids under islanded conditions is discussed in [15].

Optimal relay coordination in a test system integrated with a photovoltaic (PV) system is discussed in [16]. Optimal coordination is done using a general algebraic modelling system (GAMS) in [17]. Protection coordination in a DG-integrated system is done using the particle swarm optimization technique in [18]. Relay coordination in a radial distribution system considering on/off-grid is discussed in [19]. Optimal relay coordination in an inverter-based islanded Canadian system is proposed in [20]. A communication signal-independent protection coordination scheme for microgrids is proposed in [21]. The optimal coordination of relays in the meshed distribution system is discussed in [22]. Optimal coordination of relays for minimization of energy not supplied (ENS) is proposed in [23]. Relay coordination using the Moth-Flame optimization method is proposed in [24]. The over-current relay coordination problem is solved using the Opposition Jaya Algorithm in [25]. A communications-based relay setting scheme considering n-1 contingencies is proposed in [26]. Relay coordination in d.c.microgrid considering line faults is proposed in [27]. The optimal overcurrent relay coordination problem in an interconnected system is discussed in [28]. Data-driven optimal relay coordination for active distribution systems is proposed in [29]. Elite marine predators algorithm is used in [30] for optimal coordination of relays in complex networks.

In this paper, a new method is proposed to overcome the relay coordination problems associated with power systems integrated with DGs. Most of the literature cited above have used intermediate protective devices, while the proposed approach avoids the usage of intermediate devices. In this approach, a characteristic equation is framed that ensures the faster operation of relays during faults. The remaining part of this paper is categorized into the following sections. Section 2 discusses the formulation of the problem. Section 3 discusses the solution methodology. Section 4 discusses the results obtained in this work. Section 5 discusses the relay coordination studies and Section 6 concludes the work proposed in this paper.

2. PROBLEM FORMULATION

The prime objective of the optimum relay coordination scheme is to reduce the overall and individual operational/tripping time of relays along with optimum settings, namely, Time Multiplier Setting and Plug Setting by satisfying all the associated constraints. The objective/fitness of this problem is to minimize the total/sum of the operating times of primary relays of the system.

$$\text{Objective function: } \text{Min} \sum_{i=1}^{N_{\text{relay}}} T_i \quad (1)$$

Where N_{relay} is the total number of relays, T_i is the operating time of relay R_i . Subjected to the following constraints:

$$\geq T_i + CTI \quad (2)$$

where T_j is the backup relay tripping time, T_i is the primary relay tripping time and CTI is the coordination time interval.

$$TMS_{i,\min} < TMS_i < TMS_{i,\max} \quad (3)$$

where TMS_i is the time multiplier setting of relay R_i , $TMS_{i,\min}$ is the minimum TMS and $TMS_{i,\max}$ is the maximum TMS.

$$PS_{i,\min} < PS_i < PS_{i,\max} \quad (4)$$

where PS_i is the plug setting of the relay R_i , $PS_{i,\min}$ is the minimum PS and $PS_{i,\max}$ is the maximum PS. The boundaries of PS are calculated by the following equations,

$$PS_{\min} = \max \left(TS_{\min}, \frac{1.25 \times I_{L,\max}}{CT} \right) \quad (5)$$

$$PS_{\max} = \min \left(TS_{\max}, \frac{2 \times I_{L,\max}}{3 \times CT} \right) \quad (6)$$

where $I_{L,max}$ is maximum value of load current.

In protection system, Inverse Definite Minimum Time (IDMT) characteristic type of relays are popular and mostly used. In this paper, the IEC standard characteristic is considered. Conventional/standard characteristic as (7):

$$T = \left[\frac{0.14}{\left(\frac{I_f}{CT \times PS} \right)^{0.02} - 1} \right] \times TMS \quad (7)$$

The newly modified characteristic equation is given by (8),

$$T = \left[\frac{0.14}{\left(\frac{I_f}{CT \times PS} \right)^{0.02} - 1} \right] \times TMS \times \left(\frac{1}{e^{1-v}} \right)^k \quad (8)$$

Where T is operational time of relay, I_f is the short circuit current, TMS is the Time Multiplier Setting of relay, PS is the Plug setting of relay, V is the per unit value of voltage which is measured by relay, k is a constant which varies between 0 and 2.

3. METHOD

There are numerous algorithms in implementation for solving the relay coordination problem. The firefly algorithm (FFA) is used in the current project because of its advantageous ability to solve non-linear and multi-objective problems efficiently. FFA provides high-convergence-rate solutions. It does not require an initial value to start the iteration process. The FFA is a bio-inspired algorithm, which works on the flashing light of fireflies. In about two thousand varieties of Firefly species in nature, most of them exhibit short and rhythmic flashes, which are often unique patterns for some particular species. Fireflies produce flashes by the process of bioluminescence. The flashlight pattern function for signaling systems is still in debate. The flashing light guides Fireflies to discover the mates and attract potential prey [31]. Indeed, the flashing light intensity I at a distance from a particular source of light r obeys the inverse square law. The brightness of Firefly is associated with the quality of the fitness function used in optimization algorithms as (9) and (10):

$$I \propto \frac{1}{r^2} \quad (9)$$

$$I = \frac{I_s}{r^2} \quad (10)$$

where I is the intensity of light received from the light source, which is at distance r units, I_s is the intensity of original light source. The attributes of the FFA from the above discussion are formulated [32]:

A. Attractiveness

The relationship between actual and original light intensity is expressed as (11),

$$I_r = I_0 \times e^{-\gamma r^2} \quad (11)$$

the actual Attractiveness function formulation is given as (12),

$$\beta_r = \beta_0 \times e^{-\gamma r^m}, m \geq 1 \quad (12)$$

where r is the distance between two Fireflies, I_s is lightning intensity varies with r , I_0 is original light intensity, γ is light absorption constant (maintains light intensity reduction), β_0 is Initial attraction (at $r = 0$).

B. Distance

The distance between any two p and q fireflies at X_p and X_q are formulated as (13),

$$r_{p,q} = \|X_p - X_q\| = \sqrt{\sum_{i=1}^j (x_{p,i} - x_{q,i})^2} \quad (13)$$

where $r_{p,q}$ is the distance between p and q Fireflies, $X_{p,i}$ is the i^{th} section of spatial coordinate X_p and j is the dimension number.

C. Movement

The movement of p firefly towards the brighter q firefly is shown as (14).

$$X_p = X_p + (\beta_0 \times e^{-\gamma r^m})(X_q - X_p) + (X_p \times \varepsilon_p) \quad (14)$$

Where X_p is the solution of Firefly and ε_p is the random value generation by uniform distribution [0, 1]. In the above equation, the present position of p firefly is represented by the first term, the movement of a dull firefly towards a brighter q firefly is demonstrated by the middle term, and the third term showcases the random movements of a firefly in the range of [0, 1]. The flowchart describing this algorithm is shown in Figure 1.

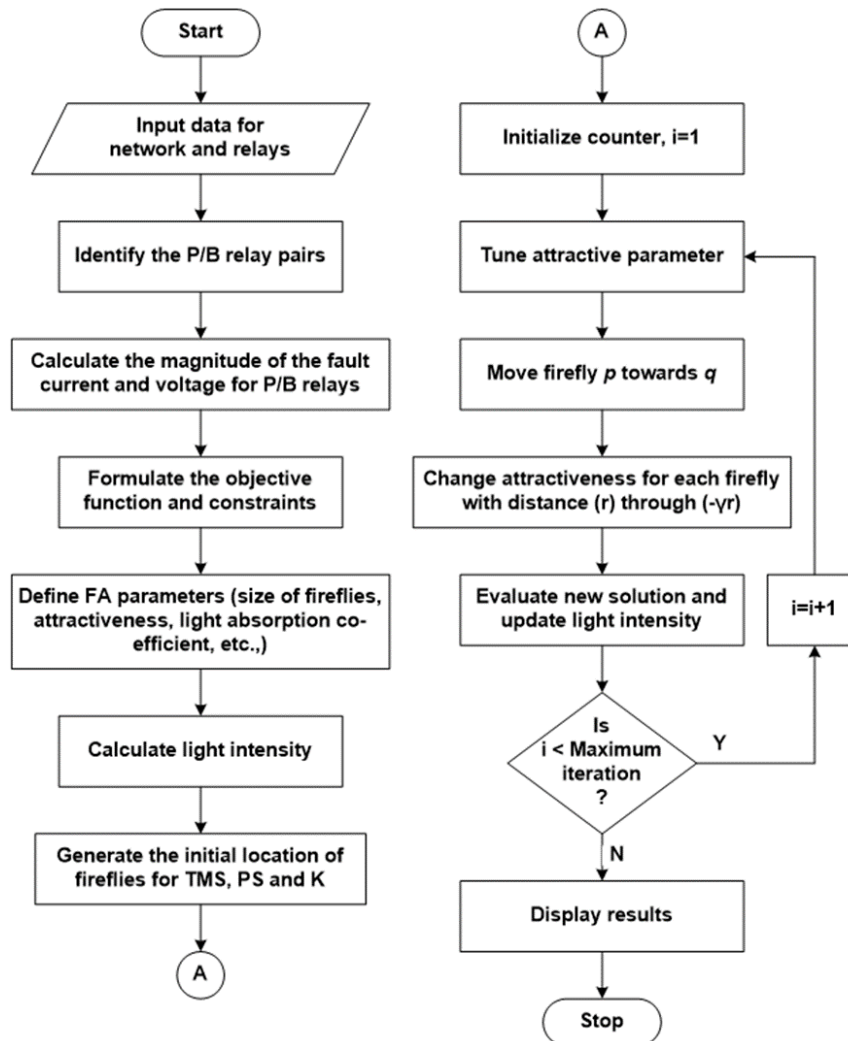


Figure 1. Flowchart of firefly algorithm

4. RESULTS AND DISCUSSION

A very commonly and popularly used 8-bus test system integrated with Inverter based solar PV distributed generation (DG) unit for solving and testing Relay coordination problems is used in the current project. The single line diagram of the photovoltaic integrated distributed generator (PVIDG) integrated 8-bus test system is shown in Figure 2. The system contains two generators, two transformers with 8 buses, and 7 branches. The Directional Overcurrent Relays are connected end-to-end of a branch. Therefore, the system requires fourteen relays R1 to R14. The proposed approach uses a new modified equation of protection coordination for optimal coordination of overcurrent relays.

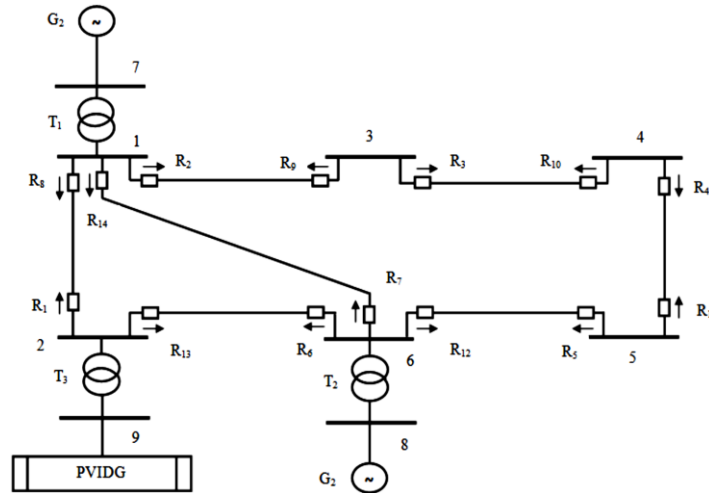


Figure 2. The single line diagram of PVIDG integrated 8-bus test system

5. RELAY COORDINATION STUDIES

There are fourteen CTs connected to fourteen relays in the main system of the current considered system [1]. The relay coordination problem is studied considering a 3-Ø fault.

5.1. Comparative analysis of conventional and modified characteristic approaches

The results of both approaches are merged into a comparative single table and analyzed. The Conventional/standard characteristic of relays has the only current parameter, and the variables to optimize are TMS and PS. In the newly modified characteristic of relays, voltage, and current are the two parameters that work on, and the variables to optimize are TMS, PS, and k. From the analysis of both results, the following points are observed. A comparison of relay settings TMS, PS & K using both approaches is presented in Table 1. Comparison of Tp, Tb & CTI of PVIDG integrated 8-bus test system using the new modified characteristic of relays approach are described in Table 2.

5.2. Review of analysis

The comparison of both approaches in tabular form is given in Table 3. From Table 3, the total operational time of primary relays in the conventional approach is 7.8373s, whereas, it is 3.6642s in the new modified approach. 53.246% reduction of operational time is noticed in the new modified approach to that of the Conventional approach. Furthermore, the sum of operational times of relays acting as Backup in the Conventional approach is 11.234s and in the new modified approach is 6.7648s. It is to be noted that, there is a 39.782% reduction of operational time of backup relays in the new modified approach to the Conventional approach. The obtained total CTI values are 4.8749s and 4.5566s in the Conventional and the new modified approaches, respectively. The new approach is 6.5293% reduced to that of the Conventional way.

Table 1. Comparison of relay settings TMS, PS & K using both approaches

Relay	Conventional/standard characteristic		Modified characteristic		
	TMS	PS	TMS	PS	K
1	0.1	1.9606	0.4419	1.716	1.9939
2	0.2647	1.5782	0.7661	1.9093	1.9996
3	0.252	1.329	0.7888	1.6035	1.8432
4	0.2229	0.9075	0.694	1.7087	2
5	0.101	2.0211	0.5365	1.5749	1.9999
6	0.2826	0.808	0.5268	2.2889	1.9625
7	0.2691	1.3683	0.5321	1.6554	1.5285
8	0.3403	0.6467	0.8139	1.1351	2
9	0.1498	2.1141	0.2703	1.7886	1.1786
10	0.2204	1.2576	0.8448	0.9098	1.876
11	0.2395	1.2262	0.6349	2.1867	1.9999
12	0.293	1.4664	0.7561	1.9662	2
13	0.1167	1.6944	0.3997	1.9213	1.9923
14	0.3084	1.2295	0.6073	2.087	1.8246
OF (s)	7.8373		3.6642		

Table 2. Comparison of T_p , T_b , and CTI of PVIDG integrated 8-bus test system using the new modified characteristic of relays approach

Relay pair		Conventional/standard characteristic			Modified characteristic		
PR	BR	T_{br}	T_{br}	$\Delta T = T_{br} - T_{br}$	T_{br}	T_{br}	$\Delta T = T_{br} - T_{br}$
1	6	0.3559	0.6839	0.328	0.2	0.4	0.2
2	1	0.6555	0.9204	0.2649	0.2766	0.5277	0.2511
2	7	0.6555	0.8556	0.2	0.2766	0.4766	0.2
3	2	0.6091	0.8091	0.2	0.324	0.524	0.2
4	3	0.5314	0.7314	0.2	0.2895	0.4895	0.2
5	4	0.435	0.635	0.2	0.2699	0.4699	0.2
6	5	0.5541	0.7754	0.2213	0.2101	0.494	0.2839
6	14	0.5541	0.9363	0.3823	0.2101	0.4765	0.2664
7	5	0.5754	0.7754	0.2	0.2629	0.494	0.231
7	13	0.5754	0.9077	0.3323	0.2629	0.5481	0.2851
8	7	0.6256	0.8556	0.23	0.2405	0.4766	0.2361
8	9	0.6256	0.8382	0.2126	0.2405	0.4429	0.2024
9	10	0.516	0.7166	0.2006	0.2638	0.4638	0.2
10	11	0.5887	0.7914	0.2027	0.3059	0.5059	0.2
11	12	0.645	0.8509	0.2059	0.3016	0.5016	0.2
12	13	0.7071	0.9077	0.2006	0.2765	0.5481	0.2716
12	14	0.7071	0.9363	0.2292	0.2765	0.4765	0.2
13	8	0.4006	0.7821	0.3815	0.2	0.4443	0.2443
14	1	0.6378	0.9204	0.2826	0.2429	0.5277	0.2847
14	9	0.6378	0.8382	0.2004	0.2429	0.4429	0.2
ΣT		7.8372	11.234	4.8749	3.6642	6.7648	4.5566

Table 3. Comparison of the sum of operational times of primary, Backup and CTI using both approaches

Relay type	Conventional/standard characteristic	Modified characteristic	Reduction % of operational time
Primary relay	7.8373s	3.6642s	53.246%
Backup relay	11.234s	6.7648s	39.782%
CTI	4.8749s	4.5566s	6.5293%

These results imply that the new approach of the modified characteristic of relays gives better results in the faster tripping time of relays and maintains appropriate coordination between P/B relay pairs. From observation, it is noticed that the factors of low fault current magnitude and the responsibility to serve as backup protection more than once effect the operational time of relays. In the considered system, the relays 1, 5, 7, 9, 13, and 14 act as backup protection more than once. Most of the relays experienced a low fault current magnitude in the system. Due to these, the conventional approach of relays took the longest time to respond which is overcome by the new approach. It can be clearly noticed from the results and analysis that, the new voltage-current-based characteristic of relays performs better than the Conventional characteristic of relays.

6. CONCLUSION

The implementation of DG meets the requirements of the utility system but brings some challenges to the protection system (especially, the inverter-based DG system). In this paper, a commonly used 8-bus test system with PV-based DG integration; the relay coordination studies are performed. Two cases of conventional and newly modified approaches are studied and compared. In the conventional/standard characteristic of the relays approach, the time of operation of primary as well as backup acting relays of IDG integrated 8-bus test system is extensive. The newly modified characteristic of the relay approach uses an additional parameter, an inverse voltage that gives fruitful results in terms of low operational time of both primary and backup relays, CTI. The comparative analysis exhibits better coordination in the implementation of the new approach compared to the other conventional approaches used in the literature.

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AUTHOR CONTRIBUTIONS STATEMENT

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Neelakanteshwar Rao Battu	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	
Surender Reddy Salkuti	✓	✓		✓	✓	✓		✓	✓	✓		✓	✓	✓

C : Conceptualization

M : Methodology

So : Software

Va : Validation

Fo : Formal analysis

I : Investigation

R : Resources

D : Data Curation

O : Writing - Original Draft

E : Writing - Review & Editing

Vi : Visualization

Su : Supervision

P : Project administration

Fu : Funding acquisition

CONFLICT OF INTEREST STATEMENT

The authors state no conflict of interest.

INFORMED CONSENT

We have obtained informed consent from all individuals included in this study.

ETHICAL APPROVAL

This article does not contain any studies with human participants or animal studies performed by any of the authors.

DATA AVAILABILITY

The datasets used and/or analyzed during the current study are available from the corresponding author [SRS], on reasonable requests.




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