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Protection Coordination Optimization for FREEDM (Future Renewable Electric Energy Delivery and Management) System

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Abstract: The FREEDM (future renewable electric energy delivery and management) system is a smart distribution system that facilitates seamless integration of high-penetration DRER (distributed renewable energy resources) and DESD (distributed energy storage devices) with the existing distribution system. Protection schemes have been proposed to detect the overcurrent faults throughout the FREEDM system, according to its requirements. In this paper the time inverse directional over current protection coordination scheme is developed as a backup protection when the primary protection communication failed. The proposed scheme is applied to FREEDM network using conventional mathematical model. To speed up the fault clearing time without coordination loss, the settings of the proposed relays in the two directions are minimized using genetic algorithm. The developed methods are validated using ETAP software. The results ensure that the faults throughout the FREEDM system sections are detected and the relays tripping time are minimized.

Key words: FREEDM, protection coordination, genetic algorithm, ETAP software.

Nomenclature

FREEDM	Future Renewable Electric Energy Delivery and Management
DRER	Distributed Renewable Energy Resources
NSF	National Science Foundation
SST	Solid-state transformer
FID	Fault Isolation Device
IFD	Intelligent Fault Detection
IEM	Intelligent Energy Management
PC	Protection coordination
PCS	Pickup current setting
OCRs	Overcurrent relays
PCO	Protection-coordination optimization
TDS	Time dial setting
CTM	Coordination time margin
T_i	The ith Relay operating time
K_1, K_2	The curve set-related parameters (inverse, very inverse, extremely inverse, etc.)
I_f	Fault current value
I_{pickup}	Pickup (set start) current value
I_{pi}	Pickup current for relay i
$I_{pi\,min}$	Minimum pickup current of relay i
$I_{pi\,max}$	Maximum pickup current of relay i
$TDS_{i\,min}$	Minimum Time Multiplier Setting for relay i
$TDS_{i\,max}$	Maximum Time Multiplier Setting for relay i

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1. Introduction

FREEDM (future renewable electric energy delivery and management) concept created by NSF is a smart grid system with novel features used to improve the integration between green DRERs (distributed renewable energy resources) and DESDs (distributed energy storage devices) with the existing conventional power networks. This integration can be utilized to provide a reliable source to the loads in addition to storing energy [1-3]. Three key components are introduced by FREEDM system to increase the effectiveness of the protection system and consequently improve service quality to customers. These devices are SST, FID and IFD. SST is a digitally controlled converter used instead of the standard transformer. This device guarantees controlling the flow of power in two directions, voltage magnitude and various phase relationships of current and voltage. It allows active controlling of DRER and loads. Other than the conventional transformer, the SST is capable to limit the fault current inherently to 2.0 pu significantly by reducing the voltage for the whole network [3-5]. FID is a new power electronic equipment used in FREEDM system, which is capable to break asymmetrical current with large capacity within microseconds [2, 5]. IFD, IFM and IEM are incorporated to quickly detect and manage the faults, and to achieve operative power flow control respectively [4]. The FREEDM system topology and its major components are shown in Fig. 1 [2]. FREEDM networks are mesh systems causing two major problems, higher short circuit level leading to voltage dip and bi-directional flow of power [2]. So, the pilot-differential protection using communication is used as primary protection capable to detect the faults in cycles. The overcurrent protection is used as a backup protection in case of communication problems/failures [1, 2]. The directional inverse time overcurrent relays are applied to detect the fault in the system as in Ref. [2].

The PC is a very important subject in power systems as it stops extending of the fault and prevent electric equipment from damage. OCRs are specifically applied to attain precise PC to evade electrical equipment strain and miss operation of the primary and backup protection elements [6]. Many studies previously exerted to properly set PCO and can be classified as conventional and analytical methodologies and computerized methods [7].

The conventional methods can be characterized as trial and error, topological analysis and optimization methods. Linear programming methodologies [8-10], nonlinear programming [11-13], mixed integer programing [11], sequential quadratic programming [14], simplex and dual simplex [15, 16], and analytical technique [17] require large number of iterations to solve the PC settings. The over-all optimal solution cannot be obtained when the conventional methods are

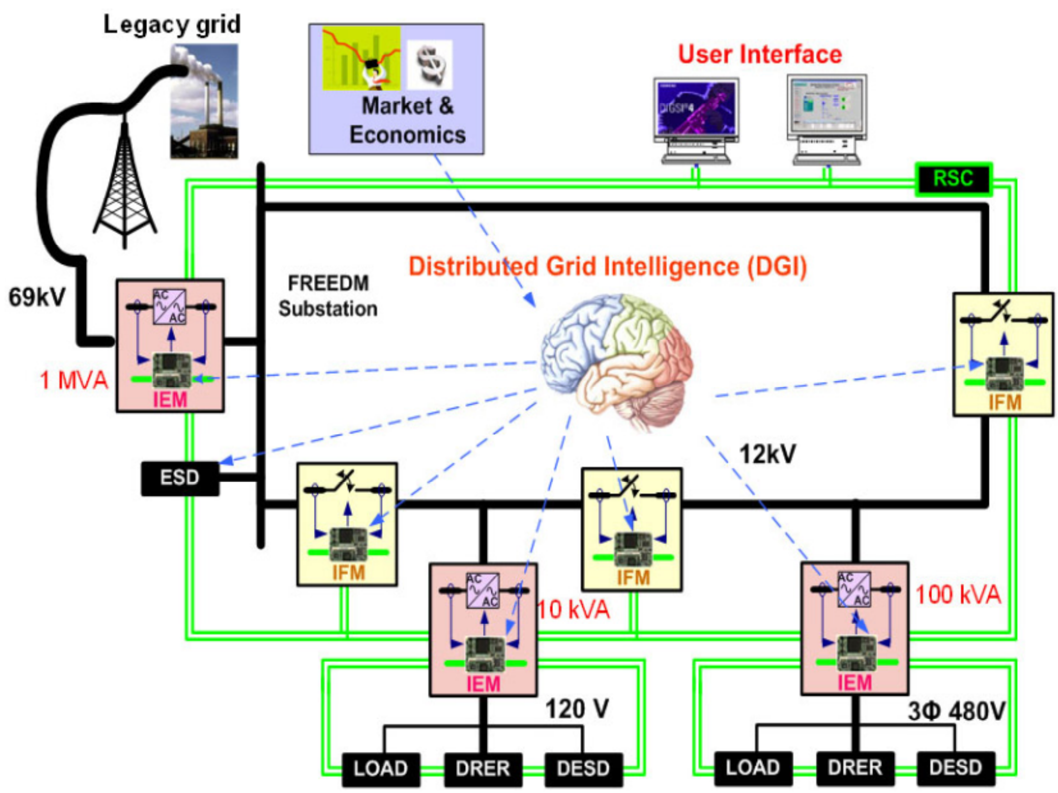

Fig. 1 FREEDM system topology and components [2].

used [7]. In addition, its convergence is another problem when applied to large systems. To expedite the convergence time, the topological analysis approaches are used [18, 19]. The artificial intelligence-based techniques prove good solution for these inadequacies [7]. Genetic algorithm [20-25] and modified firefly algorithm [6], were appropriately applied in resolving the PCO problem.

In this paper the time inverse directional over current protection coordination is designed/modeled and the relays settings are optimized using GA for FREEDM system. The proposed method can speed up the fault detection and isolation, so it can improve the reliability by reducing the outages time of faulty zones.

2. Problem Statement

The main aim of PCO between OCRs is to find out the optimal TDS and PCS of relays under system constraints [26]. The time margin between the primary and backup OCRs is critical decision to sustain the accuracy of the discrimination practice [27]. Interference between the main and backup relays is not permitted. CTM between the relays are generally taken between 0.2 to 0.5 S depending on the relay type and manufacturer [28]. The PCS can be adjusted between 50% and 200% with 25% step [9]. PCS has upper and lower limits based on the minimum and maximum fault current successively [6].

In this paper the PC is designed for the FREEDM system using the conventional technique and simulating the system in ETAP software for validation. The time dial setting and plug setting of the selected over current relays are designed according to the coordination procedures and constraints. To speed up the tripping times and to isolate the faulty section as soon as possible, GA is applied to minimize the relays TDS using the same rules and constraints. The minimum values are also reapplied to ETAP simulator to validate and proof the results.

3. Proposed Conventional Protection Coordination Algorithm

To only identify, detect and isolate the faulty section in the FREEDM system, which is a loop system, two sets of directional over current relays are selected and installed for each zone in two opposite directions as indicated in Fig. 2.

When a fault occurs at any zone, the direction of fault current is detected by both the two zone relays with opposite directions. Each relay has a backup relay as its direction to support the detection process. Relays R_1-R_2-R_3 can detect the fault in anticlockwise direction while relays R_4-R_5-R_6 can detect faults clockwise direction indicted in Fig. 2. For any fault at any section, the closet two relays in the faulty zone should be activated due to the clockwise and anticlockwise currents fed from both sides. For example, if a fault exists at zone 3, the fault currents passes through all relays but R_5 acts in clockwise direction, while R_2 detect the fault current in anticlockwise direction to isolate zone 3. Relays R_4 and R_X will be back up for R_5 respectively while relays R_1, R_X are back up for R_2 respectively. Both the relay operating time, pickup current setting and time multiplier setting are calculated as following:

A- Relay Operating Time

The over current relays setting can be expressed in Eq. (1) according to IEC 60255-151 [29].

$$T_i = \frac{TDS_i \cdot K_1}{M_i^{K_2} - 1} \text{ where } M_i = \frac{I_f}{I_{pickup}} \tag{1}$$

B- Relay Pickup Current Setting

$$I_{pi\,min} \leq I_{pi} \leq I_{pi\,max} \tag{2}$$

C- Relay Time Multiplier Setting

$$TDS_{i\,min} \leq TDS_i \leq TDS_{i\,max} \tag{3}$$

4. Proposed GA-based Optimal Protection Coordination

The model of the OCR coordination presented in the

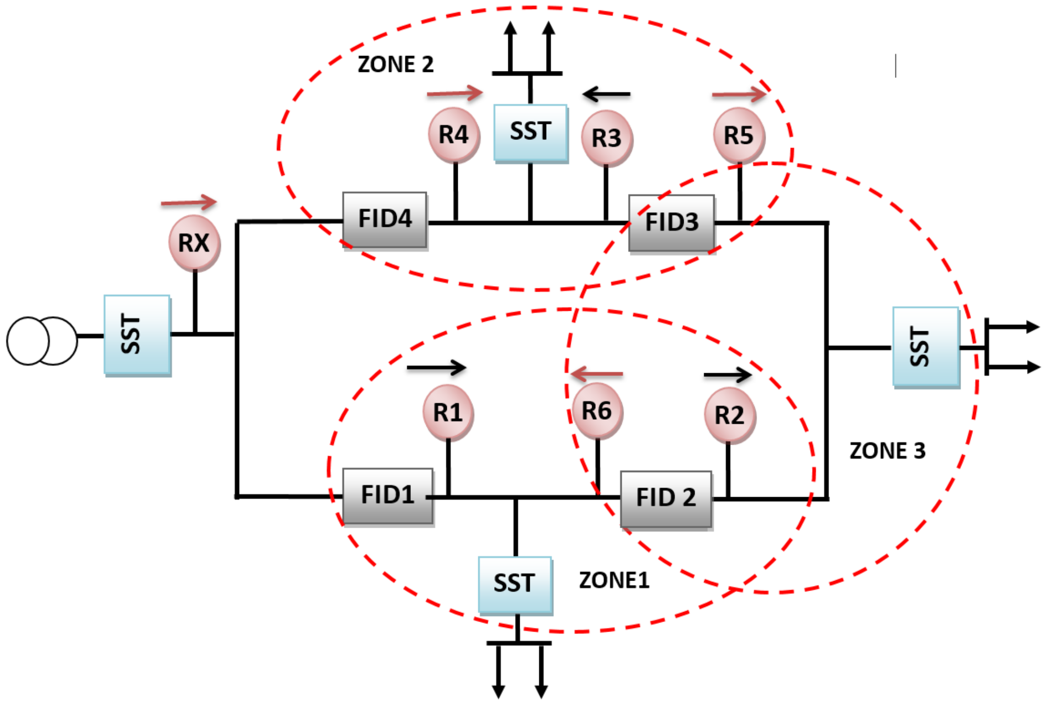

Fig. 2 Proposed locations and directions of overcurrent relays in FREEDM system.

previous section, requires a special optimization tool to handle the linearity of such highly-constrained model. Most of the deterministic optimization methods are not suitable to calculate and solve the presented optimization problem due to many mathematical difficulties. The search algorithm is a probabilistic intelligent method, which searches a population of points in parallel. GA gives correct effective and practical solutions to define the optimal decisions for any processes and tasks. GA can be applied with discrete, discontinuous and linear functions.

4.1 Problem Formulation

In this paper, GA is applied to minimize the relays time dial setting using the same rules and constraints. The main objective of the proposed method is to minimize the relays tripping time of the previously planned arrangement to isolate the faulty zone as soon as possible using GA. The proposed methodology procedure is explained by Fig. 3. The results of this method are proved using ETAP software. The objective function is formulated as in Eq. (1) under the same constraints mentioned in Eqs. (1), (2) and (3).

Objective Function

$$\text{Minimize: } T = \sum_{i=1}^{N} T_i \qquad (4)$$

where: T_i is relay (i) time delay for the nearest downstream maximum fault and N is the number of relays.

4.2 Genetic Algorithm

The GA is a probabilistic intelligent search algorithm, which searches a population of points in parallel. GA differs from other traditional optimization methods in three significant points [31]. It searches a population of points in parallel, it uses probabilistic rules rather than deterministic ones, and it can process an encoding set of parameters. The real coding is used in this research since it provides better performance and faster conversion compared to other coding methods. With other coding, it is required to alternate to the real coding in the phase of calculating the total daily cost, which results in additional processing time. It is required to examine the capability of the GA to solve the coordination problem compared to the traditional

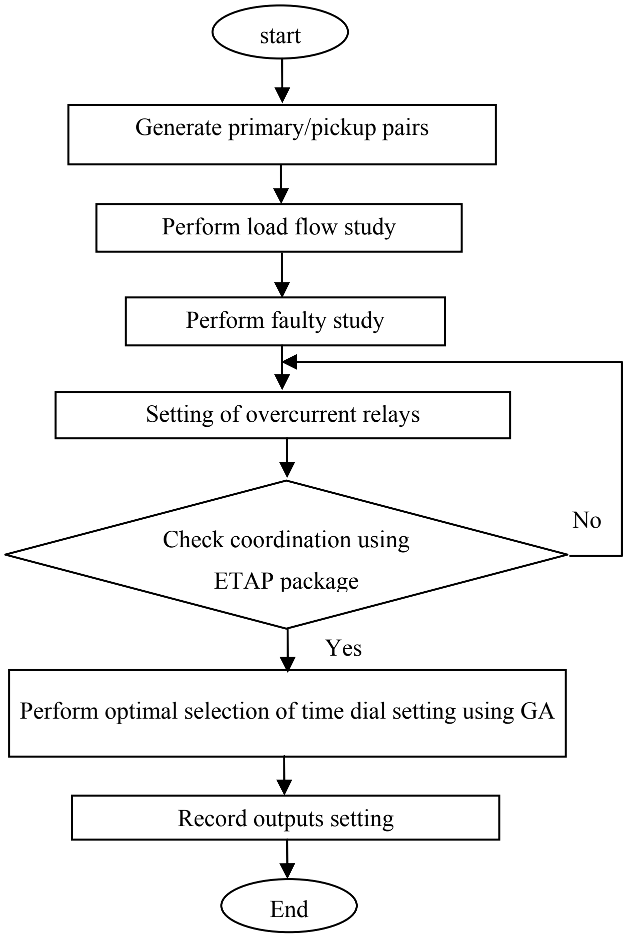

Fig. 3 A flow chart of the proposed methodology procedure.

technique. The success of the GA means that it will be possible to implement GA for other problems, where the traditional methods are not valid [23].

To employ GA with a tightly-constrained problem, such as the coordination problem, it is possible to generate only feasible solutions by avoiding individuals which violate the given constraints. Since the infeasible solutions mostly cover the search space at the initial generation, the complete avoidance of the infeasible solutions gives a high possibility for missing the area of global minimum. Another approach is achieved by moving the infeasible individuals to the nearest feasible area. For the highly-constrained problem, this approach would be too complex and a very time-consuming process. The penalty function approach is another alternative that converts the constrained problem to an unconstrained one by augmenting additional cost terms with the main objective function. The additional terms assign nonlinear costs for solutions that violate the constraints depending on their relative locations with respect to the feasibility boundaries [24, 25]. The flowchart indicated in Fig.4 shows the GA evolution process [32].

5. Implementation of Protection Coordination for FREEDM System

The FREEDM system indicated in Fig. 1 is used to apply and verify the proposed methodology [30]. Conventional circuit breakers are used instead of FIDs. The FREEDM system is represented in ETAP software as in Fig. 5 to perform load flow, short circuit and protection coordination studies without and with minimization.

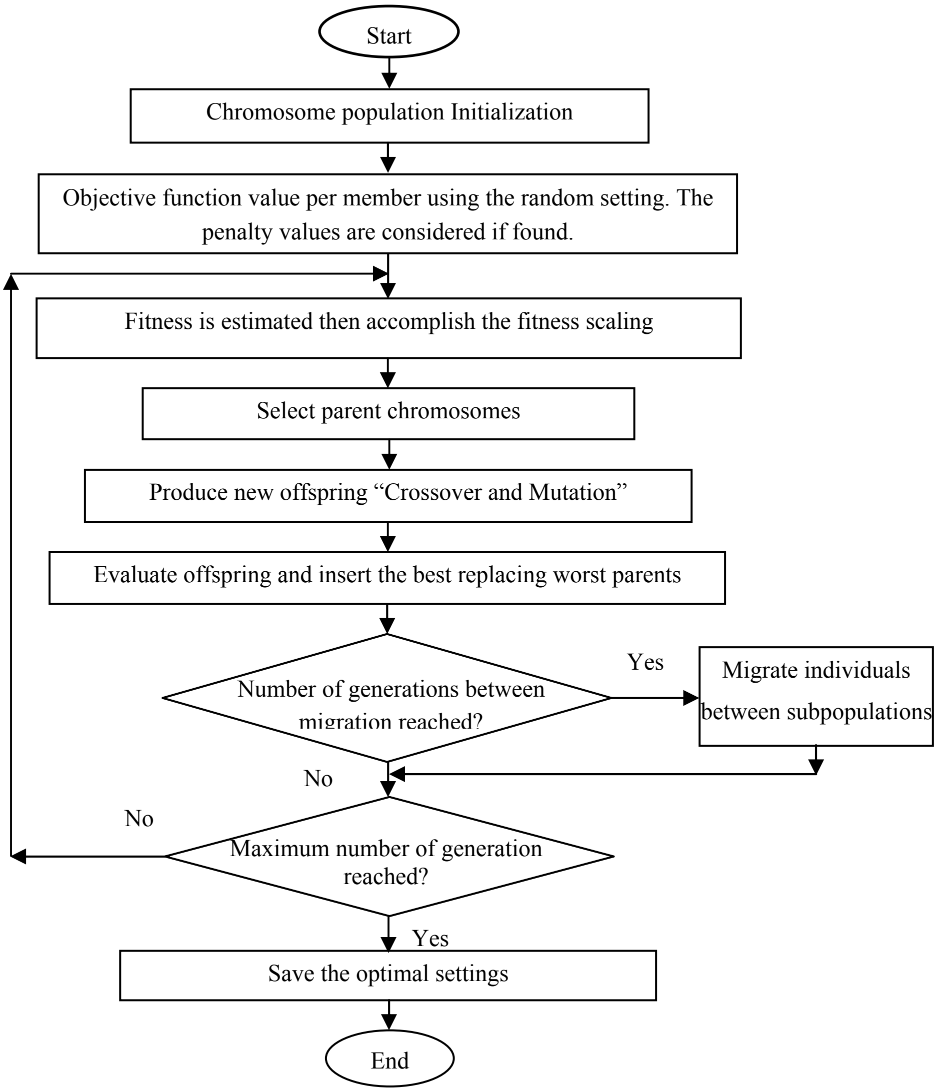

Fig. 4 Flowchart of the GA evolution process.

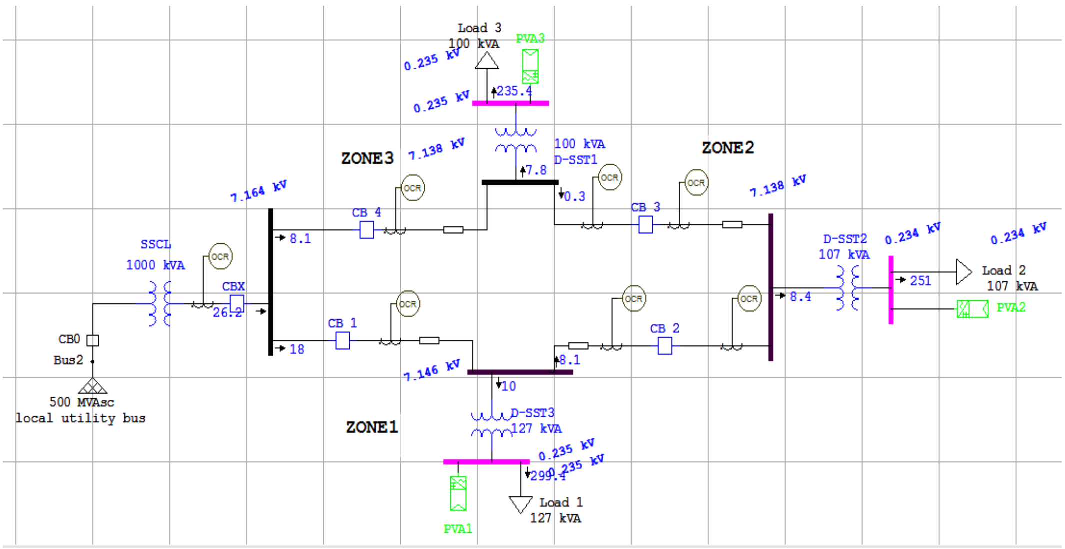

Fig. 5 FREEDM system load flow current represented in ETAP.

5.1 Description of System under Study

The system is composed of 12.47 kV/2 MVA distribution loop network, three main sections, four circuit breakers, local generation and energy storage devices capable to supply AC and DC currents with data as in Table 1 [1].

5.2 Conventional Protection Coordination

The proposed conventional protection coordination algorithm is applied to the tested FREEDM network modeled in ETAP program. The load flow and short circuit for the three zones are performed. The load flow currents in the FREEDM system represented in ETAP are expressed in Fig. 5. The load flow currents through different relays are given in Table 2.

The short circuit currents passing by certain circuit breakers at the three zones are recorded in Table 3. Whereas, Fig. 6 shows the short circuit current flow due to a fault at zone 1 conducted by ETAP.

The maximum and minimum fault currents obtained after performing the three lines to ground and line to ground faults using ETAP simulation are shown in Table 4.

5.2.1 Selection of Relay Current Pick up Values

The current pick up and time dial values are important characteristics of any rely. The results obtained in Table 4 are used to obtain the relays pickup currents (I_{pi}) and time dial (TDS) by applying Eqs. (1), (2) and (3). The minimum pickup current $I_{pi\,min}$ of any relay is considered as 125 to 150% of the full load current while the maximum pickup current $I_{pi\,max}$ of any relay is considered as 50% of the minimum fault current.

In order to determine time dial settings, maximum fault current seen by relays is used for calculation to ensure quick operation of relays for all type of faults. Table 6 shows the maximum currents seen by the relays during fault at different zones. Normal inverse over current relay is selected taking K_1, K_2 as 0.14 and 0.02 respectively [29]. TDS is considered as 0.5 for the primary relays while the time margin between primary and backup relay is considered as 0.2 sec. The relays operating time and the adjustable time multiplier settings for all relays can be calculated as indicated in Table 7.

Table 1 FREEDM network data [1].

Feeder lines data					
line	R1(ohm)	R0 (ohm)	L1(mh)	L0 (mh)	Length (km)
1	3.971	3.971	6.894	9.842	7.141
2	1.257	1.257	2.183	3.116	2.261
3	1.634	1.634	2.837	4.051	2.939
4	1.634	1.634	2.837	4.051	2.939
Feeder SST's data					
Distribution SST	Phase A	Phase B	Phase C	Loads at 0.24 kV	
D-SST1	0.116 MVA	0.194 MVA	0.102 MVA	0.100 MVA	
D-SST2	0.12 MVA	0.031 MVA	0.019 MVA	0.107 MVA	
D-SST3	0.138 MVA	0.185 MVA	0.166 MVA	0.127 MVA	

Table 2 Load flow current through relays using ETAP.

Relays	R1	R2	R3	R4	R5	R6	Rx
Current Ampere	18	8.1	0.3	8.1	0.3	8.1	26.2

Table 3 Short circuit current at the three zones passing by circuit breakers.

Zone	SC current at CB1 (A)	SC current at CB2 (A)	SC current at CB3 (A)	SC current at CB4 (A)	SC current at CBx (A)
1	0.751	0.151	0.141	0.136	0.886
2	0.555	0.563	0.257	0.248	0.803
3	0.374	0.38	0.388	0.398	0.771

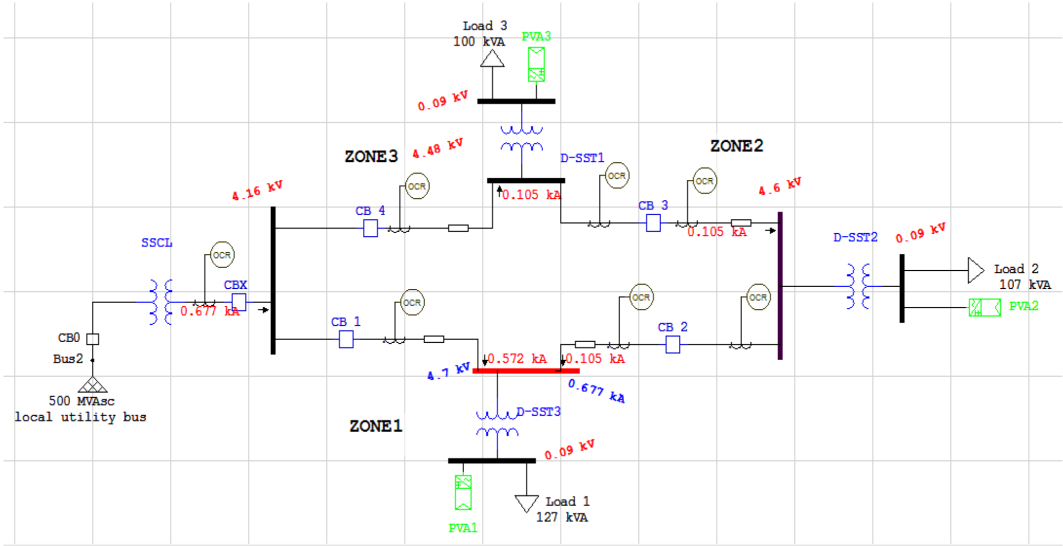

Fig. 6 FREEDM system short circuit current flow due to a fault at zone 1.

Table 4 Fault current magnitudes for faults at different zones.

	Fault current sensed by R1 at CB1 (kA)		Fault current sensed by R2 and R6 at CB2 (kA)		Fault current sensed by R3 and R5 at CB3 (kA)		Fault current sensed by R4 at CB4 (kA)	
Fault	LLL-G	SLG	LLL-G	SLG	LLL-G	SLG	LLL-G	SLG
Zone 1	0.572	0.657	0.105	0.12	0.105	0.12	0.105	0.12
Zone 2	0.555	0.457	0.563	0.457	0.257	0.205	0.248	0.205
Zone 3	0.374	0.303	0.38	0.303	0.388	0.303	0.388	0.317

Table 5 Relay pick up settings.

	R1	R2 and R6	R3 and R5	R4
$I_{pi\,max}$ (A)	1.25	1.487	1.4	1.4
$I_{pi\,min}$ (A)	0.225	0.304	0.0113	0.304
CT ratio	600/5	200/5	200/5	200/5
I_{pi} (A)	1	1.2	1.3	1.4

Table 6 Clockwise and anti- clockwise relays SC currents.

Zones	Relays acting as primary protection					Relays acting as backup protection				
	Clockwise		Anti-clockwise		Tripped CB	Clockwise		Anti-clockwise		Tripped CB
	Relay	I_{SC} (A)	Relay	I_{SC} (A)		Relay	I_{SC} (A)	Relay	I_{SC} (A)	
1	R6	105	R1	572	2 and 1	R5	105	RX	569	3 and X
2	R5	257	R2	257	3 and 2	R4	248	R1	248	4 and 1
3	R4	388	R3	388	3 and 4	RX	252	R2	380	X and 2

Table 7 Coordination settings obtained by conventional method.

I_{pi}	Clock wise coordination settings		Anti-clock wise coordination settings	
	T_i	TDS_i	T_i	TDS_i
1.4	T_4 =1.0	TDS_4 = 0.7	T_1 = 1.0	TDS_1 = 0.8
1.3	T_5 = 0.9	TDS_5 = 0.6	T_2 = 0.8	TDS_2 = 0.62
1	T_6 = 0.7	TDS_6 = 0.5	T_3 = 0.63	TDS_3 = 0.5
1.4	T_X =1.2	TDS_X= 1.15	T_X = 1.2	TDS_X = 1.15

The coordination study is verified using ETAP package. The Star View Coordination TCC curves for the relays operating in anti-clockwise and clockwise directions are shown in Figs. 7 and 8 respectively. The Coordination TCC curves before optimization for zone 2 and 3 are indicated in Figs. 9 and 10. The obtained results indicated in Table 7 and Figs. 7 to 10 ensure that the proposed method is capable to fully protect the FREEDM network and coordinate its relays tripping and enable to be backup protection for its primary protection when the communications failed.

5.3 GA-based Optimum Protection Coordination

Optimization coordination problem is solved as per the following arrangements:

- The development of primary and back up relays pairs are accomplished according to the previous explained arrangement for clockwise and anti-clockwise.
- Full load current is chosen according to load flow report (maximum current for normal scenario).
- Maximum value of short circuit current is taken from Table 6.
- Operating time of relay is calculated according to Eqs. (1), (2) and (3).

5.3.1 Optimization Criteria

The following assumptions are taken when applying the proposed GA-based method:

- Coordination time delay interval between backup and primary relay is 0.2 s.
- The TDS_i is maintained between 0.1 and 1.1 according to IEC 60255-151 [29].
- The minimum pickup current $I_{pi\,min}$ of a relay is considered as 125 to 150 % of the full load current. while the maximum pickup current $I_{pi\,max}$ of relay considered 50% of the minimum fault current
- K_1 and K_2 are taken as 0.14 and 0.02 respectively, according to IEC 60255-151 [29].

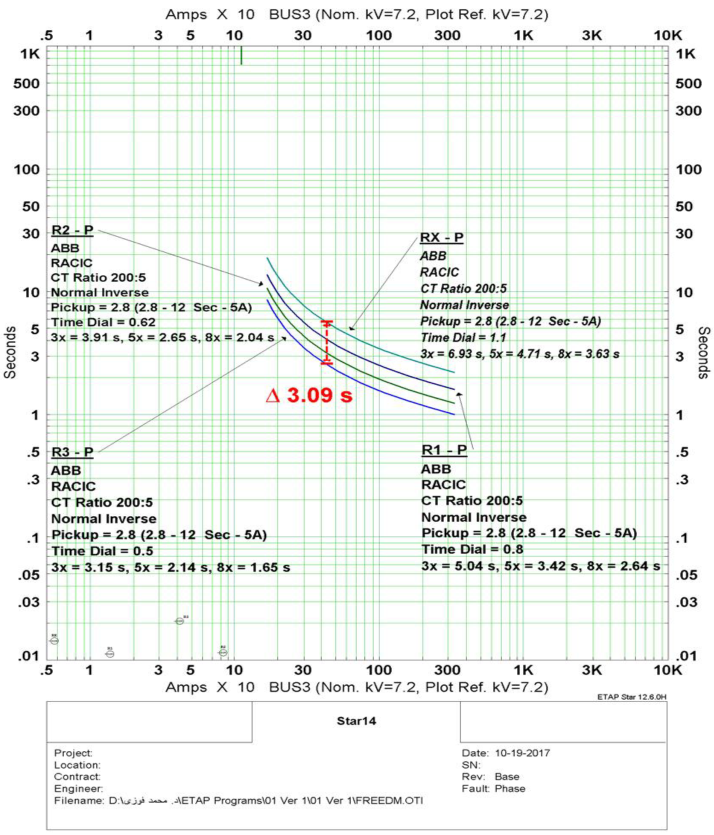

Fig. 7 Star view coordination TCC curves for the relays operating in anti-clockwise direction.

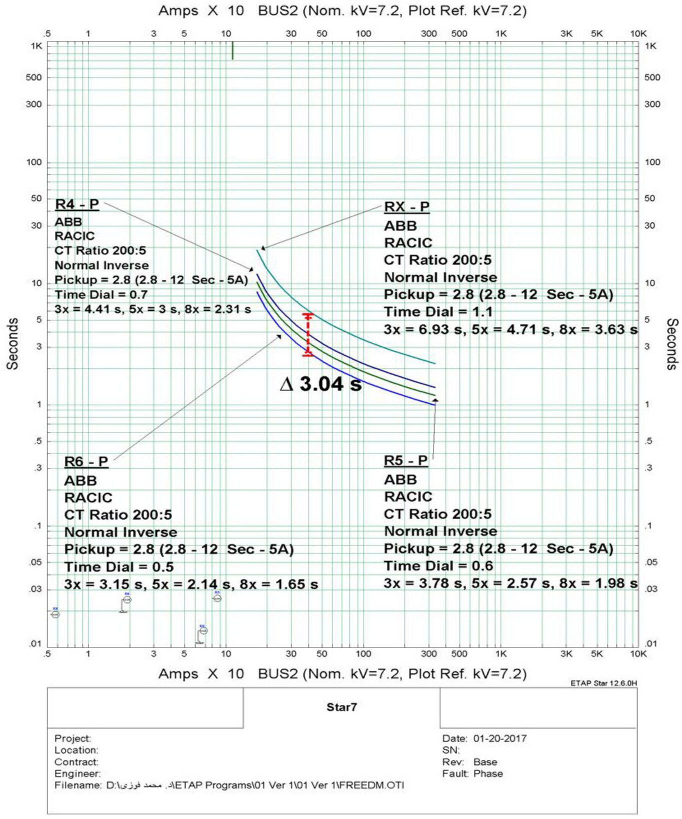

Fig. 8 Star view coordination TCC curves for the relays operating in clockwise direction.

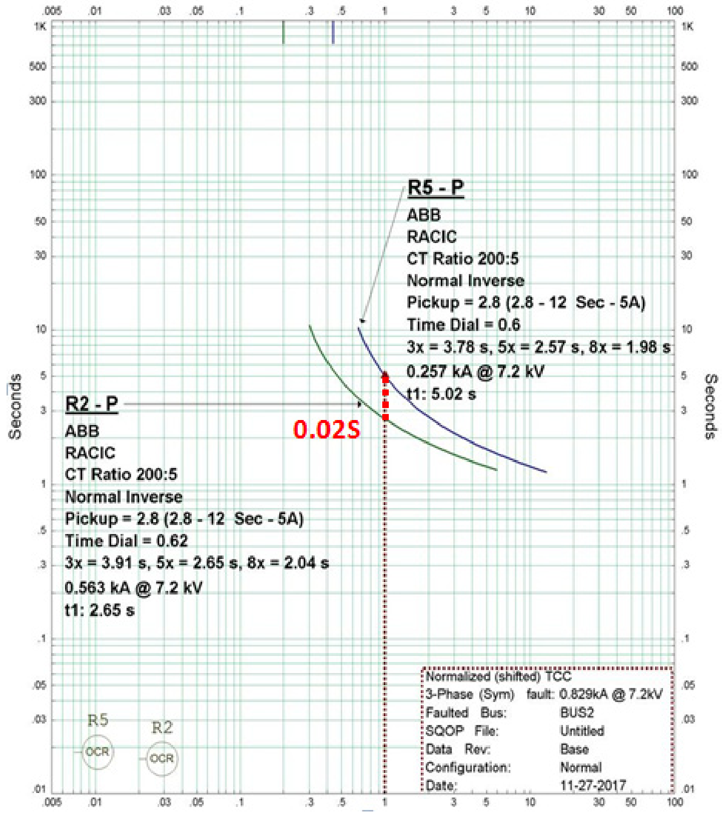

Fig. 9 Coordination TCC curves for R2, R5 at zone 2 before optimization.

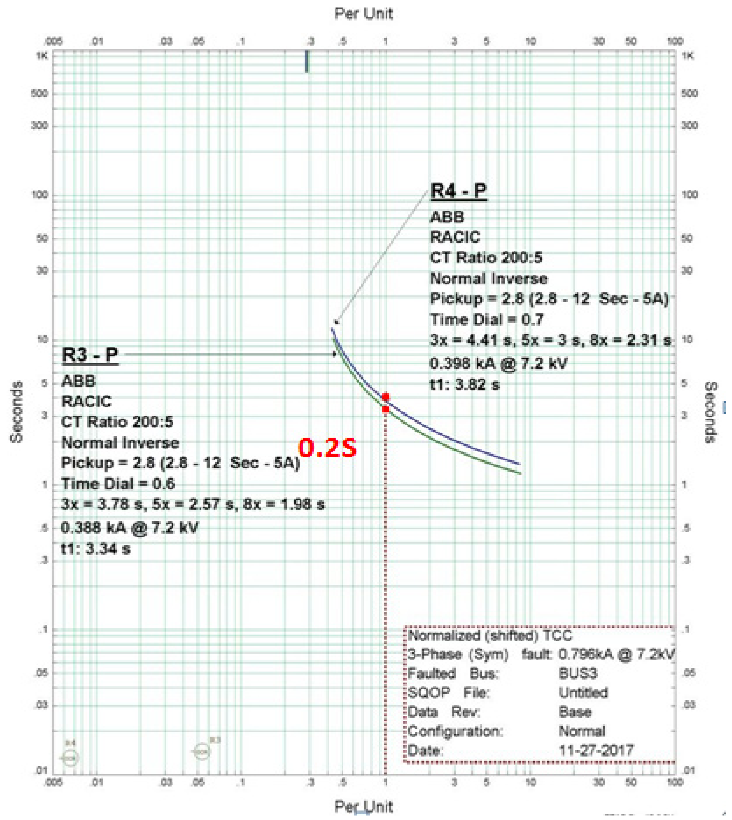

Fig. 10 Coordination TCC curves for R3 R4 at zone 3 before optimization.

The GA-based optimum protection coordination is applied to the FREEDM network test system. The results are applied to the FREEDM network system modeled in ETAP software for verification purposes. Table 8 summarizes the parameters of the GA-based optimization process applied to the coordination optimization.

5.3.2 Simulation Results

The developed GA program is implemented to the same FREEDM network with data indicated in Table 1 to minimize the relays tripping time and to isolate the faulty zone as soon as possible. The coordination settings results are tabulated in Table 9 indicating the optimum pickup currents with the minimum time dial setting and tripping time. To verify the effectiveness of the proposed GA, its coordination setting results are applied and simulated using ETAP software. The coordination is satisfied for all cases. Figs. 11 and 12 indicate the TCC coordination curves for the anti-clockwise relays, R_1-R_2- R_3-R_X and the clockwise relays, R_4-R_5-R_6-R_X respectively due to optimization. The TCC if a fault occurred at zone 2 and zone 3 are indicated in Figs.13 and 14.

A comparison between T_i and TDS_i for both clockwise coordination settings and anti-clock wise coordination settings is shown in Tables 10 and 11. From these tables the total tripping time in clockwise and counter-clockwise for conventional coordination and GA optimization coordination can be concluded in Table 12.

It can be observed that the anticlockwise relays total tripping time is reduced by 47.2% and 44.7% in clockwise direction. The proposed optimized protection method is capable to fully protect the FREEDM network and coordinate its relays tripping. The method is able to be backup protection for its primary protection when the communications failed within minimum time. The minimization of tripping time guarantees reducing faults consequences on the FREEDM system while achieving the protection requirements and protection coordination.

Table 8 GA-optimization parameters [32].

Total population size	200
Number of individuals per subpopulation	20
Maximum generations	1,000
Number of subpopulations	10
Generation gap	0.8
Migration rate between subpopulations	0.2
Insertion rate	0.9
Probability of crossover	0.9
Probability of mutation	0.01
Number of generations between migration	20

Table 9 Coordination settings after optimization using GA.

I_{pi}	Clock wise coordination settings		Anti-clock wise coordination settings	
	T_i	TDS_i	T_i	TDS_i
1.4	T_4 = 0.62	TDS_4 = 0.4848	T_1 = 0.53	TDS_1= 0.4279
1.3	T_5= 0.4	TDS_5 = 0.3001	T_2 = 0.31	TDS_2= 0.2584
1	T_6= 0.35	TDS_6 = 0.2405	T_3 = 0.36	TDS_3= 0.3046
1.4	T_X= 0.7	TDS_X= 0.673	T_X = 0.7	TDS_X= 0.673

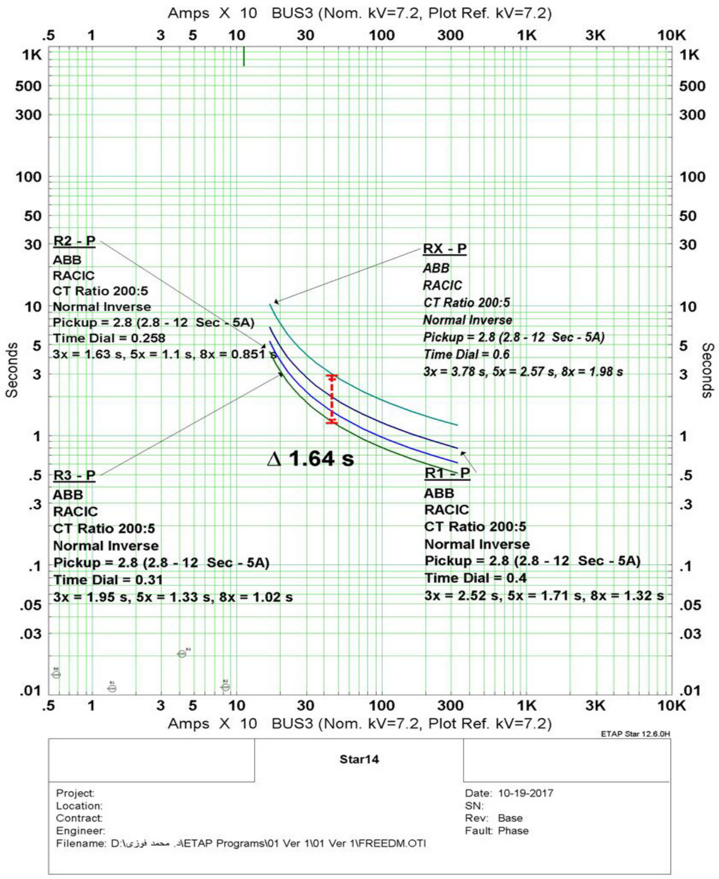

Fig. 11 Coordination TCC curves for R_1-R_2-R_3 R_X using GA optimization.

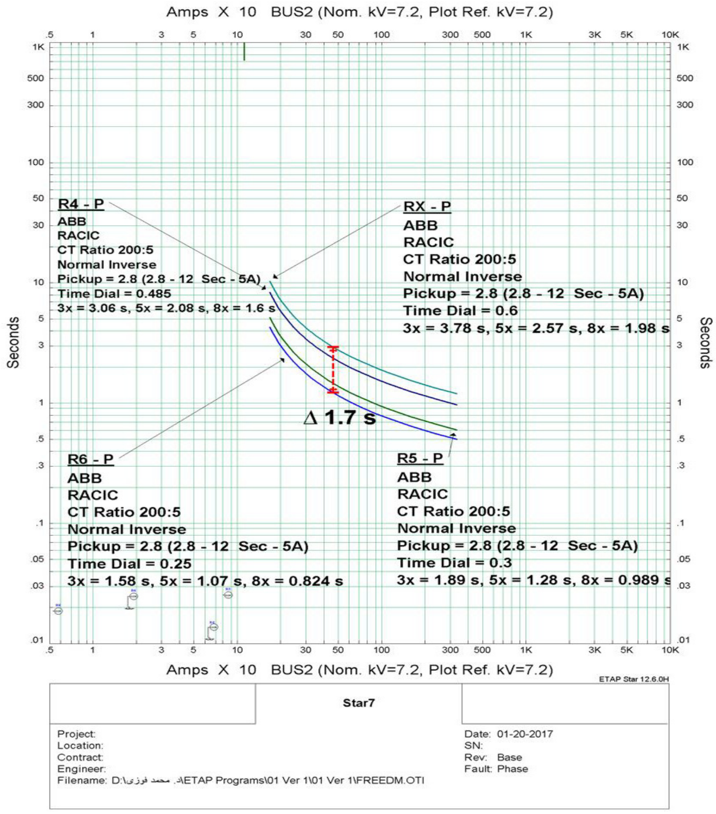

Fig. 12 **Coordination TCC curves for R_4-R_5-R_6 and R_X using GA optimization.**

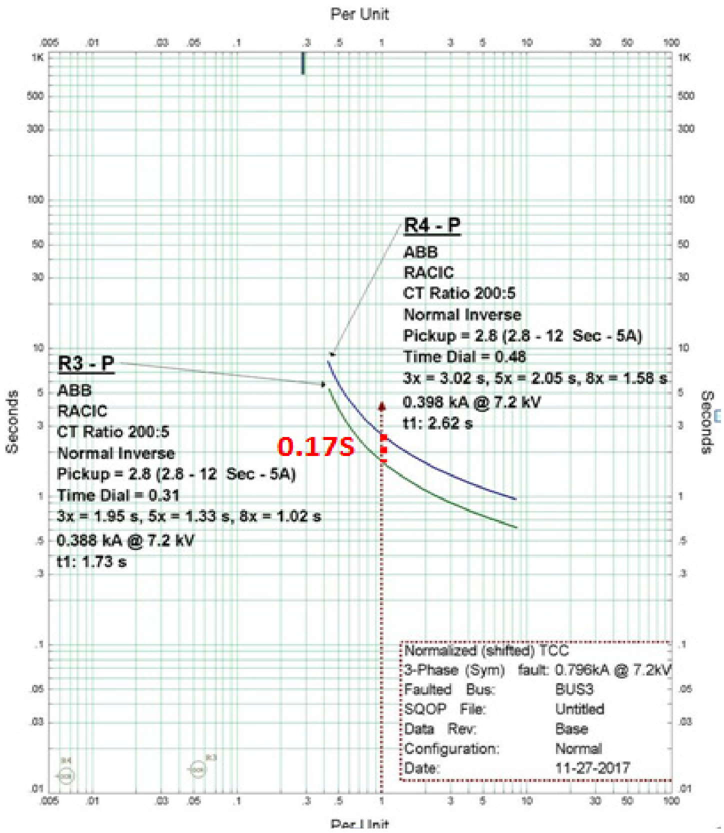

Fig. 13 **Coordination TCC curves for R3-R4 at zone 3 using GA optimization.**

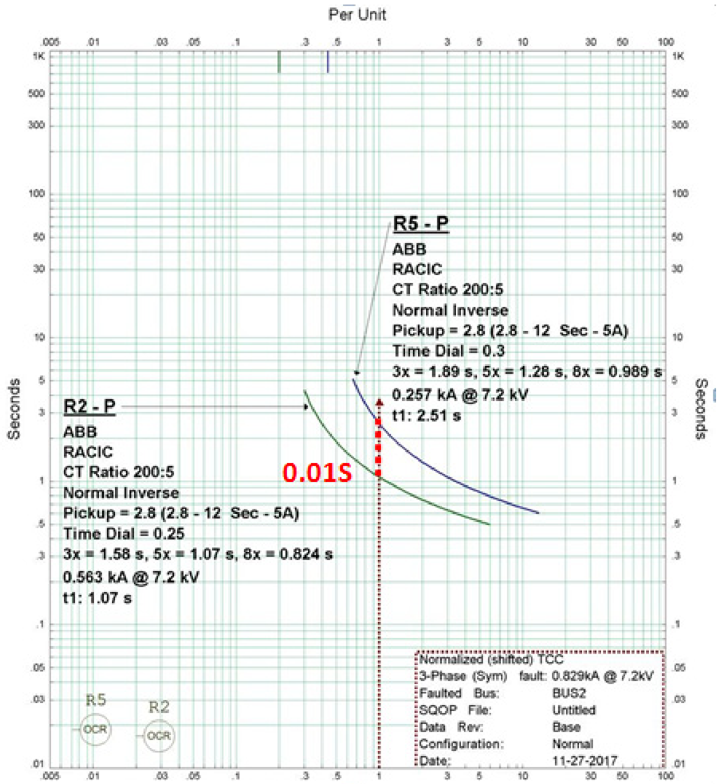

Fig. 14 Coordination TCC curves for R2 R5 at zone 2 using GA optimization.

Table 10 Clock wise coordination settings.

I_{pi}	T_i		TDS_i	
	Conventional	GA	Conventional	GA
1.4	$T_4 = 1.0$	$T_4 = 0.62$	$TDS_4 = 0.7$	$TDS_4 = 0.4848$
1.3	$T_5 = 0.9$	$T_5 = 0.4$	$TDS_5 = 0.6$	$TDS_5 = 0.3001$
1	$T_6 = 0.7$	$T_6 = 0.35$	$TDS_6 = 0.5$	$TDS_6 = 0.2405$
1.4	$T_X = 1.2$	$T_X = 0.7$	$TDS_X = 1.15$	$TDS_X = 0.673$

Table 11 Anti-clock wise coordination settings.

I_{pi}	T_i		TDS_i	
	Conventional	GA	Conventional	GA
1.4	$T_1 = 1.0$	$T_1 = 0.53$	$TDS_1 = 0.8$	$TDS_1 = 0.4279$
1.3	$T_2 = 0.8$	$T_2 = 0.31$	$TDS_2 = 0.62$	$TDS_2 = 0.2584$
1	$T_3 = 0.63$	$T_3 = 0.36$	$TDS_3 = 0.5$	$TDS_3 = 0.3046$
1.4	$T_X = 1.2$	$T_X = 0.7$	$TDS_X = 1.15$	$TDS_X = 0.673$

Table 12 Time between primary and backup relays (Sec).

Primary and backup relays	Conventional Coordination	GA Optimization
(Anti-clockwise) R_1 R_2 R_3 R_X	3.6	1.9
(Clockwise) R_4 R_5 R_6 R_X	3.8	2.1

6. Conclusion

Directional over current protection scheme is proposed for the FREEDM system using the conventional mathematical model as backup protection when the primary protection failed due to communication fail. The coordination of the proposed scheme is achieved for clockwise and anti-clockwise directions. The total time to isolate the FREEDM system is minimized using GA. The total tripping time in both anticlockwise and clockwise directions reduced by 47.2% and 44.7% respectively. The protection coordination is validated using ETAP software for both conventional and optimized methods.

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