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Application of Firefly Algorithm for Optimal Coordination of Directional Overcurrent Protection Relays in Presence of Series Compensation

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Abstract-This paper presents an optimal coordination of Inverse Definite Minimum Time (IDMT) direction overcurrent relays in power electrical networks to consider the impact of the transmission line series compensation (SC) on the relays settings and coordination. The coordination problem is formulated as a non-linear constrained mono-objective optimization problem. The objective function of this optimization problem is the minimization of the operation time (T) of the associated relays in the systems, and the decision variables are: the time dial setting (TDS) and the pickup current setting (I_P) of each relay. To solve this complex non linear optimization problem, a variant of evolutionary optimization techniques named Firefly Algorithm (FA) is used. The proposed method is validated on 8-bus transmission network test system considering various scenarios. The obtained results show a high efficiency of the proposed method to solve such complex optimization problem, in such a way the relays coordination is guaranteed for all simulation scenarios with minimum operating time.

Keywords: Series Compensation, Directional Overcurrent Protection, Fault Current, Optimal Coordination, Coordination Time Interval, Settings, Firefly Algorithm.

1. INTRODUCTION

SYSTEM protection is an important part in the power network systems. The most important part in designing the protection needs to consider such as the type of relays, the size of circuit breaker and fuse, the type and size of current transformer, the coordination of relays, and them component to maintain the stability of the system. Then to maintain the stability each relay in the power network must setting in proper technique in term of current and time operation. During the operation of modern interconnected power systems, abnormal conditions can frequently occur. Such conditions cause interruption of the supply, and may damage the equipments connected to the system, arising the importance of designing a reliable protective system. In order to achieve such reliability, a back-up protective scheme is provided to act as a second line of defense in case of any failure in the primary protection (the first line of defense). To insure reliability of the protective system, the back-up scheme shouldn’t come in to action unless the primary fails to take the appropriate action. In other words, it should operate after a certain time delay known as coordination time interval (CTI), giving the chance for the primary protection to operate. The fore mentioned situation leads to the formulation of the well-known protective relay setting coordination, that consists of the selection of a suitable setting of each relay such that their fundamental protective function is met under the desirable qualities of protective relaying, namely sensitivity, selectivity, reliability, and speed [1].

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Overcurrent relaying, which is simple and economic, is commonly used for providing primary protection (principal) in transmission, distribution and sub-transmission systems and as secondary (backup) protection in transmission systems [2]. To reduce the power outages, mal-operation of the backup relays should be avoided, and therefore, DOCR coordination in power transmission and distribution networks is a major concern of protection engineer. A relay must get sufficient chance to protect the zone under its primary protection. Only if the primary protection does not clear the fault, the back-up protection should initiate tripping. Each protection relay in the power system needs to be coordinated with the relays protecting the adjacent equipment [3], the overall protection coordination is thus very complicated. Overcurrent relay have two types of settings: pickup current setting and time multiplier setting.

In recent years, many research efforts have been made to achieve optimum protection coordination (optimum solution for relay settings) without SC using different techniques and methodologies, including Linear Programming (LP) technique in [4], Interval Linear Programming (ILP) considering different network topologies in [5], Nonlinear Programming (NLP) techniques environment by Sequential Quadratic Programming (SQP) method in [6], and as well as the Simplex Method (SM) in [7] and Two Phase Simplex Method (TPSM) in [8]. Application of non-linear Random Search (RS) technique in DOCR coordination is reported in [9] while implementation of Full Adaptive Technique (FAT) is study in [10]. However a new objective function approach is presented in [11, 12] to solve the optimization problem of coordination with the Genetic Algorithm (GA) and with Continuous Genetic Algorithm (CGA) in [13], Hybrid Genetic Algorithm corresponding to each network topology in [14], and Hybrid Genetic Algorithm (GA) - Nonlinear Programming (NLP) approach for determination of optimum values of TMS and PS of DOCR in [15]. A new method to coordinate the DOCR using Evolutionary Algorithms (EA) is presented in [16, 17] while Differential Evolution Algorithm (DEA) in [18], Modified Differential Evolution Algorithm (MDEA) in [19], and Self-Adaptive Differential Evolutionary (SADE) algorithm in [20]. Application Particle Swarm Optimization (PSO) in [21], Modified Particle Swarm Optimizer in [22, 23], Evolutionary Particle Swarm Optimization (EPSO) Algorithm in [24], Box-Muller Harmony Search (BMHS) in [25], Zero-one Integer Programming (ZOIP) approach in [26], Covariance Matrix Adaptation Evolution Strategy (CMA-ES) in [27], Teaching Learning-Based Optimization (TLBO) in [28], and Seeker Algorithm (SA) is presented in [29].

Application for Firefly Algorithm (FA) for solving the economic dispatch (ED) problem by minimizing the fuel cost and considering the generator limits and transmission losses in [30, 31], for ED and considers highly realistic constraints, such as transmission losses, ramp rate limits, and valve-point effects over a short-term time span in [32], for solving non-convex ED with valve loading effect in [33], for combined heat and power ED for these plants to optimize the fuel cost in [34]. Application for optimal allocation and sizing of Distributed Generation (DG) in distribution networks to minimize the total power losses in [35, 36], optimal placement of wind turbines in power system considering the fuel cost and emission of thermal units in [37], optimally place the Distribution Static Synchronous Compensator (D-STATCOM) for enhancing power quality [38]. Application for automatic generation control of a Combined Cycle Gas Turbine (CCGT) plant with classical controllers in [39] and for designing Power System Stabilizers (PSS) under different operating conditions to improve damping of power system low frequency oscillations under dynamic disturbances in [40], and for power demand forecasting in a deregulated electricity market and smart grid environments in [41].

This research paper presents the solution of the coordination problem of IDMT directional overcurrent protection relays using Firefly Algorithm approach. The original FA algorithm is enhanced in order to handle the constraint violation problem using penalty function. The problem is formulated as a non linear constrained mono-objective optimization problem. Our goal behind this optimization is to find an optimal setting of Time Dial Setting (*TDS*) and Pickup current (I_p) of each relay that minimizes the operating time of overall relays. The new idea presented in this paper, is taking into account the variation of the effective impedance of the line caused by the action of series compensation devices of the line. Two simulation scenarios with and without SC are considered in this paper.

2. IMPACTS OF FIXED SERIES COMPENSATION ON POWER SYSTEMS

Series compensation (SC) of transmission line is defined as the insertion of reactive power elements to ensure the following benefits [42]: reduces line voltage drops, limits load-dependent voltage drops, influences load flow in parallel transmission lines, increases transfer capability, reduces transmission angle, and increases system stability. Let consider the circuit in figure 1, that represents a typical SC installed in midline between bus *A* and *B*, where R_L, X_L and X_{SC} are respectively the line resistance, the line reactance and the reactance of the series capacitor.

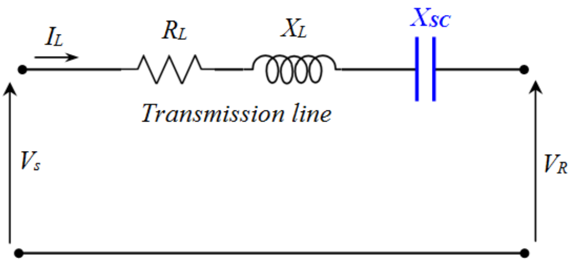


Figure 1. Single transmission line with SC.

The approximated voltage drop per phase from source to load obtained from phasor diagram is given by:

$$\Delta V = R_L.I_L\cos(\varphi_R) + (X_L - X_{SC}).I_L\sin(\varphi_R) \tag{1}$$

$$\Delta V = \frac{P_R.R_L + Q_R.(X_L - X_{SC})}{V_R} \tag{2}$$

The second equation represented the voltage regulation provided by the series capacitor is continuous and instantaneous. In case of voltage fluctuations due to large variations of the load, a series capacitor will improve the quality at the loads downstream from the series capacitor [43]. Figure 2 shows the influence of the series capacitor on the voltage profile for a radial power transmission line with inductive loads.

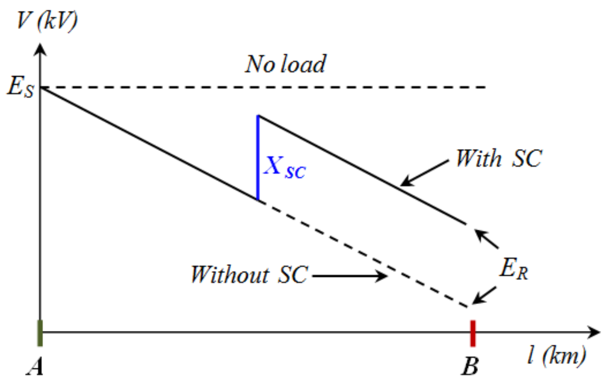


Figure 2. Voltage profile on transmission line with SC.

Transmission lines utilize SC to reduce the net series inductive reactance of the line in order to enhance the power transfer capability of the line. The power transfer along a transmission line is often explained in terms of the simple two busbar power system. If a series capacitor having reactance X_{SC} is inserted, the net series reactance becomes $(X_L - X_{SC})$ and the active power ($P_{L\text{-}SC}$) and reactive power ($Q_{L\text{-}SC}$) transfer with SC over a transmission line is given by:

$$P_{L-SC} = \frac{V_S.V_R}{X_T - X_{SC}}.\sin(\delta) \tag{3}$$

$$Q_{L-SC} = \frac{V_S.V_R}{X_T - X_{SC}}.\cos(\delta) \tag{4}$$

Where, X_T is the total uncompensated reactance (with source and load reactance) and δ is the transmission angle between the sending and receiving end voltages. The merits of SC can be illustrated by computing power transfer (P_L) where transmission angle δ is a variable and calculating load bus voltage (V_B) where the load is a variable.

This gives a graphical visualization in figure 3. To illustrate further the benefits of SC, consider a given power transfer P_o. The P_o in the compensated line is further away from steady state maximum power transfer capacity, which indicates increased angular and voltage stability margins for the same power transfer level [44], [45].

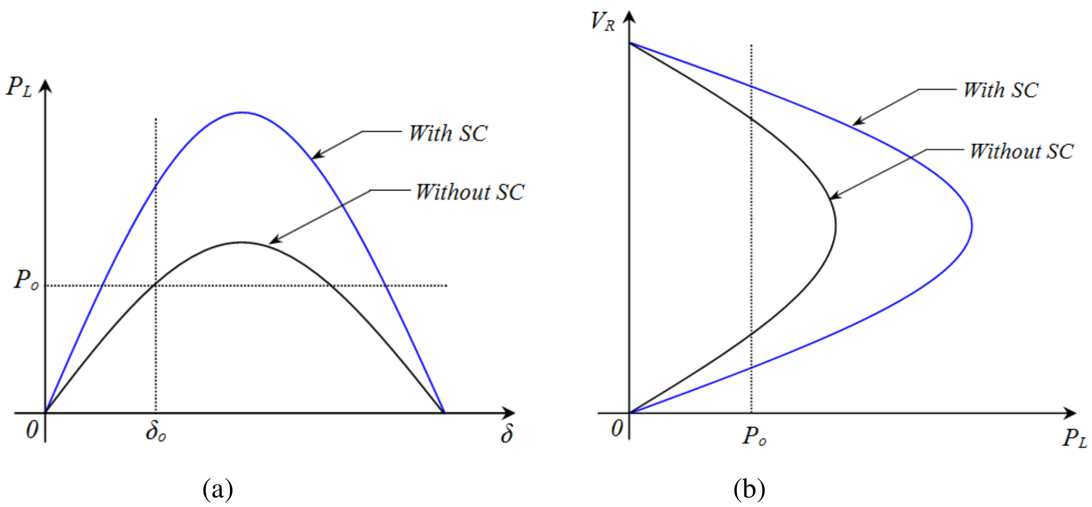


Figure 3. Power-angle and voltage-power curves:
a). $P_L = f(\delta)$, b). $V_R = f(P_L)$.

The use of series capacitors also allows increased power transfer for the same transmission angles δ_o and enhances the voltage profile of the line. Since, series capacitors compensate the inductive reactance of the line, reactive transmission line losses are significantly reduced. On the other hand, the insertion of reactive power elements in the line will modify its impedance as well as the short circuit currents.

Therefore, in this case the overcurrent relay setting must be modified considering the new effective impedance of the line. To overcome this technical problem, we propose following an intelligent overcurrent relays coordination in the presence of SC using FA method, where the relays coordination problem is formulated as a constrained non linear mono-objective optimization problem.

3. OPTIMAL OVERCURRENT RELAY COORDINATION

The coordination of IDMT directional overcurrent relays in a multi-loop system is formulated as an optimization problem. The coordination problem, including objective function and constraints, should satisfy all three aforementioned requirements.

3.1. Objective Function

The aim of this function (*f*) is to minimize the total operating time of all overcurrent protection relays in the system with respect to the coordination time constraint between the backup and primary relays.

$$f = Min\left\{\sum_{i=1}^{N} T_i\right\} \tag{5}$$

Where, T_i is represents the operating time of the i^{th} relay, N is represents the number of relays in the power system. For each protective relay the operating time T is defined as follows [12-15]:

$$T_i = TDS \times \frac{K}{\left(I_M / I_P \right)^S + L} \tag{6}$$

Where, T is relay operating time (*sec*), TDS is time dial setting (*sec*), I_M is the fault current measure by relay (A), I_P is pickup current (A), K_{CT} is ratio of the current transformer. The constant K, L, and S that depends of characteristic curve for IDMT directional overcurrent relay, the current I_M is defined by:

$$I_M = \frac{I_F}{K_{CT}} \tag{7}$$

3.2. Constraints

The coordination problem has two types of constraints, including the constraints of the relay characteristic and coordination constraints. Relay constraints include limits of relay operating time and settings. Coordination constraints are related to the coordination of primary and backup relays.

3.2.1. Relay Operating Time

The operating time of a relay is a function of the pickup current setting and the fault current seen by the relay. Based on the type of relay, the operating time is determined via standard characteristic curves or analytic formula. The bounds on operating time are expressed by:

$$T_i^{\min} \le T_i \le T_i^{\max} \tag{8}$$

Where, $T_i^{\min}$ and $T_i^{\max}$ are the minimum and maximum operating times of the i^{th} overcurrent relay.

3.2.2. Coordination Time Interval

During the optimization procedure, the coordination between the primary and the backup relays must be verified. In this paper, the chronometric coordination between the primary and the backup relays is used as follows equation:

$$T_{backup} - T_{primary} \ge CTI \tag{9}$$

Where, T_{backup} and $T_{primary}$ are the operating time of the backup relay and the primary relay respectively, *CTI* is the minimum coordination time interval. For the electromechanical relays, the *CTI* is varied between 0.30 to 0.40 sec, while for the numerical relays it's varied between 0.10 to 0.20 sec [28].

3.2.3. Time Dial and Pickup Current Settings

The time dial setting adjusts the time delay before the relay operates when the fault current reaches a value equal to, or greater than, the pickup current setting.

$$TDS_i^{\min} \le TDS_i \le TDS_i^{\max} \tag{10}$$

$$I_{Pi}^{\min} \le I_{Pi} \le I_{Pi}^{\max} \tag{11}$$

Where, $TDS_i^{\min}$ and $TDS_i^{\max}$ are the minimum and the maximum limits of TDS for the i^{th} relay. $I_{Pi}^{\min}$ and $I_{Pi}^{\max}$ are the minimum and the maximum limits of I_P for the i^{th} relay.

Figure 4, represented the time-current of all IDMT overccurent relaying characteristics for o IEC 60255-3 standard.

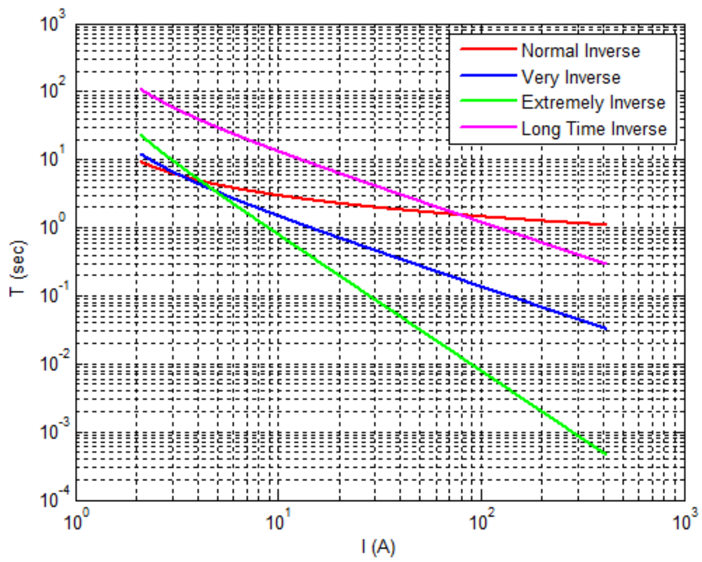


Figure 4. Time-current of IDMT overccurent relaying characteristics.

4. METHODOLOGY OF FIREFLY ALGORITHM

Nature-inspired methodologies are among the most powerful algorithms for optimization problems. The Firefly Algorithm (FA) is a novel nature-inspired algorithm inspired by the social behavior of fireflies, was induced by Yang in 2008 [46, 47]. The algorithm was based on the idealized behavior of the flashing characteristics of fireflies. Although FA has many similarities with other algorithms which are based on the so-called swarm intelligence; it is indeed much simpler both in concept and implementation [46-48].

Furthermore, this proposed technique is very efficient and can outperform other conventional algorithms, for solving many optimization problems; where the statistical performance of the firefly algorithm was measured against other well-known optimization algorithms using various standard stochastic test functions [46].

The pseudo code of the firefly-inspired algorithm was developed using these three idealized rules [46-48]:

a). all fireflies are unisex and are attracted to other fireflies regardless of their sex,

b). the degree of the attractiveness of a firefly is proportional to its brightness, and thus for any two flashing fireflies, the one that is less bright will move towards the brighter one,

c). finally, the brightness of a firefly is determined by the value of the objective function. For a maximization problem, the brightness of each firefly is proportional to the value of the objective function and vice versa.

As light intensity and thus attractiveness decreases as the distance from the source increases, the variations of light intensity and attractiveness should be monotonically decreasing functions. In most applications, the combined effect of both the inverse square law and absorption can be approximated using the following Gaussian form:

$$I(r) = I_0 e^{-\gamma . r^2} \tag{12}$$

Where, r is the distance between any two fireflies, I_0 is the original light intensity and γ is the light absorption coefficient which controls the decrease of light intensity and can be taken as a constant. As a firefly's attractiveness is proportional to the light intensity seen by adjacent fireflies.

4.1. Degree of the attractiveness of a firefly

In the FA, the main form of attractiveness function β can be any of the monotonically decreasing functions as given in:

$$\beta(r) = \beta_0 e^{-\gamma . r_{pq}^n} \quad n \geq 1 \tag{13}$$

Where, β_0 is the attractiveness at $r = 0$ [49] and also the movement of a firefly (i) is attracted to another more attractive (brighter) firefly (j).

4.2. Distance

The attractiveness can be achieved by tuning the parameters β_0 and γ. The distance r_{ij} between two fireflies is given in [47]:

$$r_{ij} = \left\| x_i - x_j \right\| = \sqrt{\sum_{k=1}^{d} \left(x_{i,k} - x_{j,k} \right)^2} \tag{14}$$

Where, $x_{i,k}$ is the k^{th} component of the spatial coordinate of the j^{th} firefly and d is the number of dimensions. The $j \in \{1, 2, ... , m\}$ is a randomly chosen index. Although j is determined randomly, it has to be different from i. Here, m is the number of fireflies. For other applications such as scheduling, the distance can be any of the suitable forms, and not necessarily the Cartesian distance (equation 14). In general, $\beta_0 \in [0, 1]$, and this when $\beta_0 = 0$, only a non-cooperative distributed random search is applied. When $\beta_0 = 1$, the scheme of a cooperative local search is performed such that the brightest firefly strongly determines the other fireflies' position, especially in its neighborhood [46, 47]. When $\gamma = 0$, there is no variation or the fireflies have constant attractiveness. When $\gamma = \infty$, it results in attractiveness being close to zero, which again is equivalent to the complete random search. In general, the value of γ is between 0 and 10 [46, 47].

4.3. Movement

The movement of a firefly i, when attracted to another more attractive (brighter) firefly j, is determined by [46, 47]:

$$x_i^{'} = x_i + \beta(r) \times \left(x_i - x_j \right) + \alpha \left(rand - \frac{1}{2} \right) \tag{15}$$

Where, x'_i is the firefly position of the next generation. x_i and x_j are the current position of the fireflies and x'_i is the i^{th} firefly position of the next generation. The second term in equation (4) is due to attraction. The third term introduces randomization, with α being the randomization parameter and "rand" is a random number generated uniformly but distributed between 0 and 1. The convergence of the algorithm is obtained when $m \geq n$ for any large number of fireflies (m), where n is the number of local optima of an optimization problem [46].

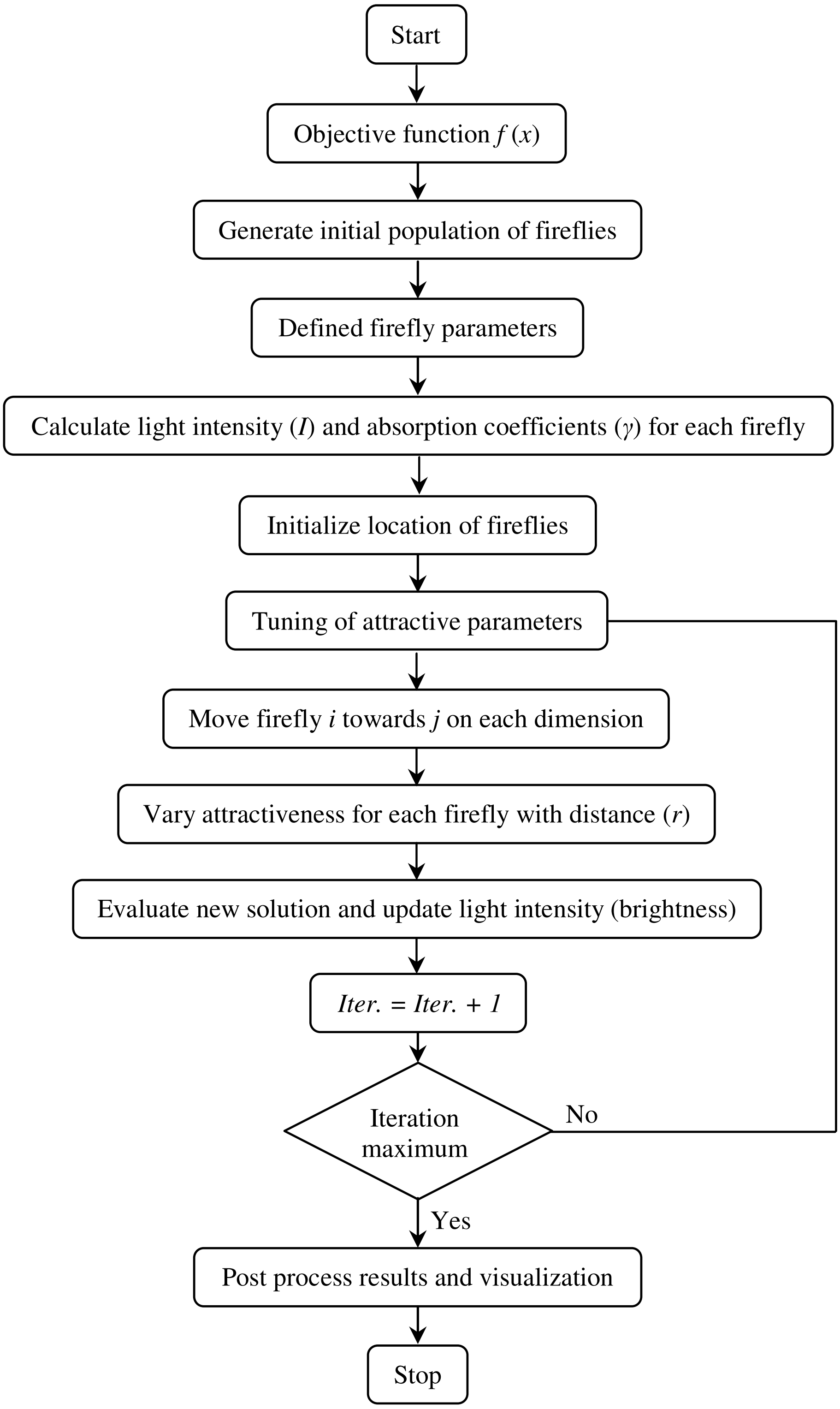


Figure 6. Schematic Flowchart of the FA.

5. CASE STUDY, SIMULATION RESULTS AND INTERPRETATIONS

The impact of SC on relays coordination is performed on the following two scenarios: SCA: without compensation, and SCB: with compensation. As we mentioned above, the relays coordination problem is formulated as constrained mono-objective problem and solve it using the FA considering 28 decision variables (14 variables represent the *TDS* and 14 variables represent the I_P).

Figure 7, represents the case study of a network fed by two generators and with six bus, seventh transmission lines and fourth load [22]. The power system study is compensated with SC located at middle of the transmission line 1-6, where compensation degree K_C=40%. The 8-bus system has a link to another network, modeled by a short circuit power of 400 MVA. The transmission network consists of 14 directional overcurrent relays. The values of CT ratio are given in Appendix.

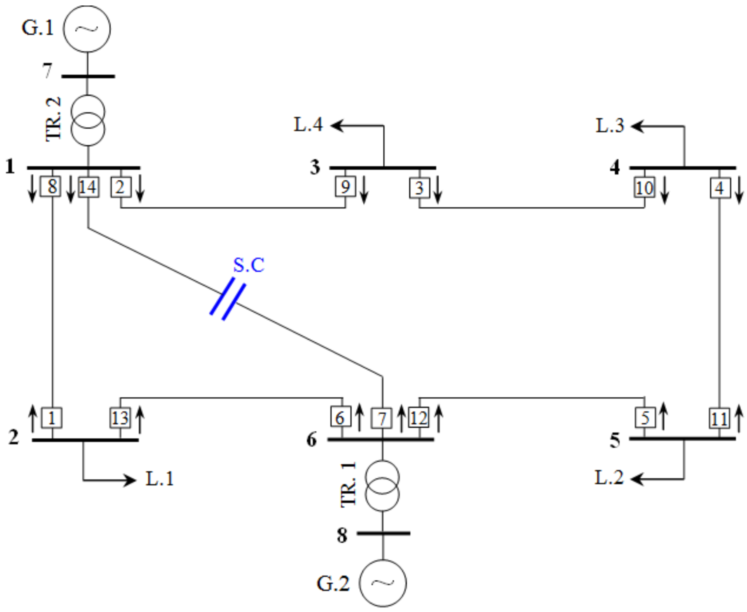
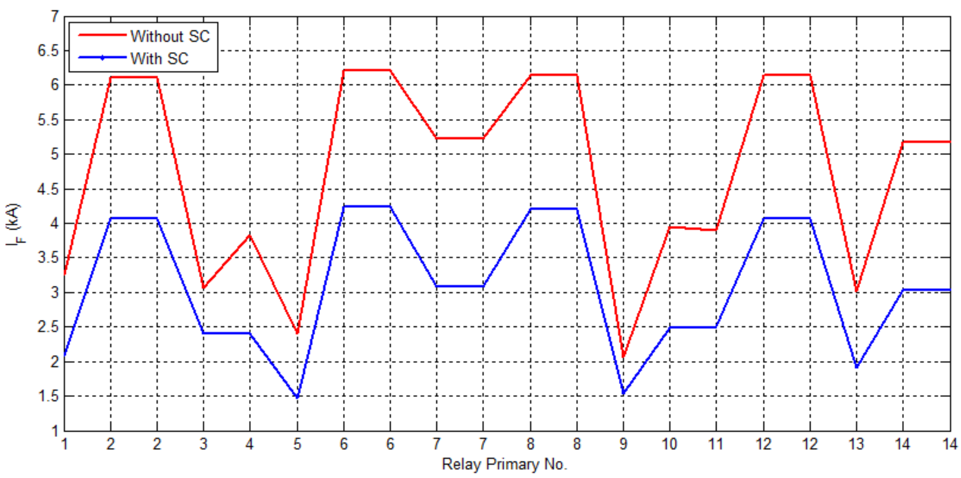


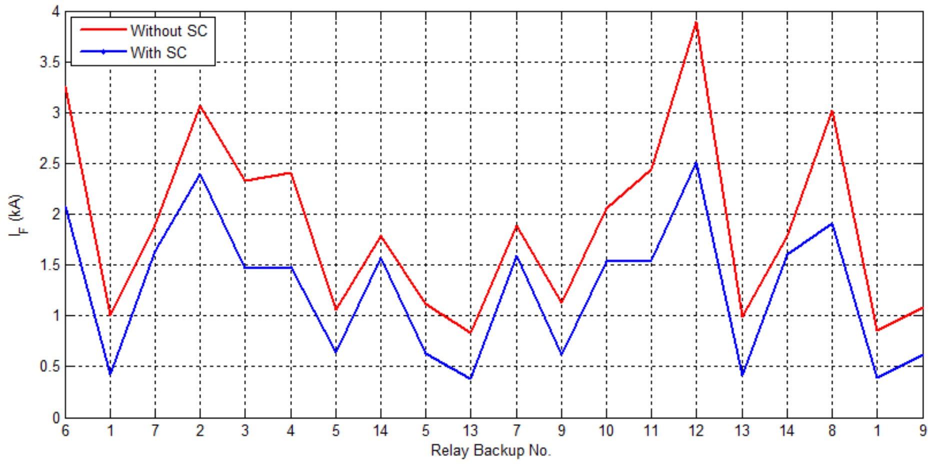
Figure 7. Single line diagram of the 8-bus network with SC.

5.1. Impacts SC on fault current

Figure 8, depicts the impact of SC on fault current seen by the primary and backup relays. From this figure, it is clear that the fault current values are reduced when the SC is installed in power system. This is due to the decrease of the transmission impedance.



(a)



(b)

Figure 8. Fault current on directional overcurrent relays with/without SC.
a). Primary, b). Backup.

5.2. Impacts of SC on coordination time

Firstly, the optimal relays coordination without considering SC is computed using FA. The convergence characteristic of the FA, without compensation, is depicted in figure 9.

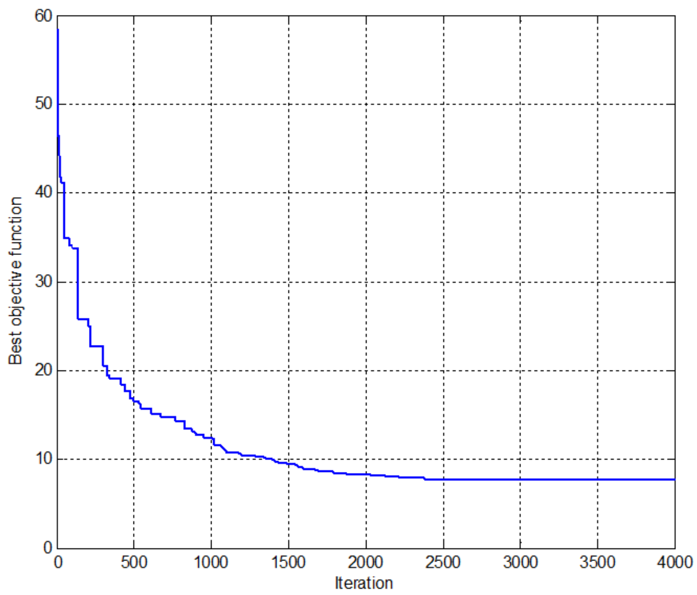


Figure 9. Convergence characteristic of FA for SCA.

From this figure, we can see that the optimization algorithm is convergence within 2500 iterations. The optimal relays settings are presented in table 1. From this table, we can remark that the overall operating time of the relays is reduced to 7.7207 sec.

Table 1. Optimal relays coordination solution for SCA.

IDMT Relay	Control variables	
	TDS	I_P
1	0.1000	1.8307
2	0.2455	1.7843
3	0.2247	1.8407
4	0.2282	0.9286
5	0.1000	2.2071

6	0.1542	1.9299
7	0.2220	1.9113
8	0.3393	0.6784
9	0.2139	1.2261
10	0.1533	2.3653
11	0.2344	1.1702
12	0.3789	0.7010
13	0.1075	1.8142
14	0.3630	0.7889
f (sec)	7.7207	

Table 2 presents, the CTI values of the relays with and without SC.

Table 2. Impact of SC on relay coordination time.

Primary Relay	Backup Relay	CTI (sec)	
		SCA	SCB
1	6	0.2001	0.2643
2	1	0.2138	**-16.2846**
2	7	0.2060	**0.1641**
3	2	0.2005	0.2462
4	3	0.2000	0.3072
5	4	0.2000	**0.1526**
6	5	0.5971	3.3775
6	14	0.5300	0.5070
7	5	0.4049	3.3358
7	13	0.6187	**-6.5362**
8	7	0.2068	0.2200
8	9	0.2109	0.5887
9	10	0.2001	0.3557
10	11	0.2004	0.2299
11	12	0.2101	0.2221
12	13	0.2001	**-14.4425**
12	14	0.2239	**0.1667**
13	8	0.4085	0.4392
14	1	0.3815	**-7.0582**
14	9	0.2002	0.5249

From this table, it is clear that all relays are coordinated in SCA, but among of them are not coordinated in SCB (CTI value written in bold). Thus, we can conclude that SC causes a loss of coordination between the relays. In this situation, we must compute the new settings of the relays to ensure the coordination.

5.3. New setting and coordination in the presence of SC

To overcome the miss of the relays coordination caused by the SC of the power system; we calculate the new settings of relays using FA. The convergence characteristic of the method is depicted in figure 10.

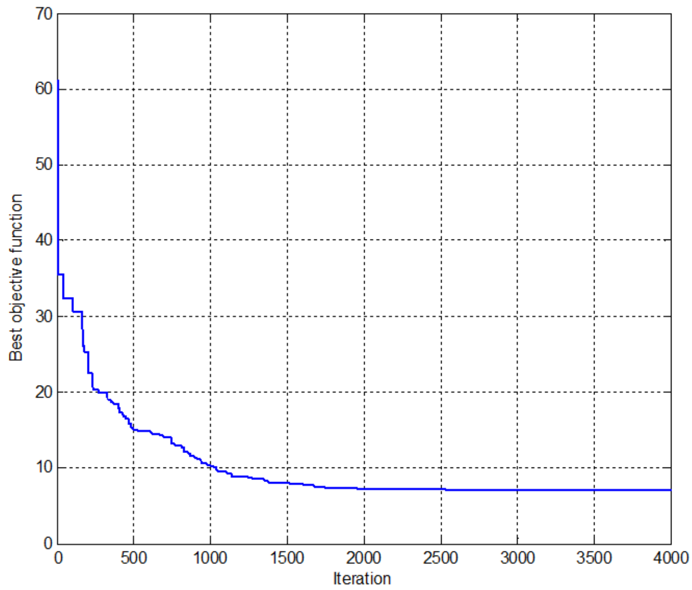


Figure 10. Convergence characteristic of FA for SCB.

The new relay settings are presented in table 3. As shown in table 3, the new relay settings allow a time decrease to 6.9834 sec. furthermore, we can see in table 4 that all relays are well coordinated after optimization.

Table 3. Optimal relays coordination solution for SCB.

IDMT Relay	Control variables	
	TDS	I_P
1	0.1002	0.9592
2	0.2522	1.0232
3	0.1532	2.2665
4	0.1488	1.5919
5	0.1000	1.7908
6	0.1604	1.4416
7	0.2507	1.2329
8	0.1452	1.3944
9	0.1246	1.2543
10	0.1164	1.7466
11	0.1991	0.8299
12	0.2027	1.5810
13	0.1000	1.2616
14	0.1995	1.7488
f (sec)	6.9834	

Table 4. CTI value of SCB after optimization

Primary Relay	Backup Relay	CTI (sec)
		SCB
1	6	0.3030
2	1	0.5474
2	7	0.2001
3	2	0.2002
4	3	0.2001
5	4	0.2000
6	5	1.3497

6	14	0.3597
7	5	1.1946
7	13	2.3516
8	7	0.4316
8	9	0.3787
9	10	0.2000
10	11	0.2166
11	12	0.2010
12	13	1.6822
12	14	0.2001
13	8	0.2003
14	1	0.7320
14	9	0.2002

5.4. Comparison with published results

For comparison purpose table 5, presents a comparison of the best obtained value of the objective function for SCA with other published results. From this table, we can see that the proposed method provides the best solution compared with the other results.

Table 5. Comparison of published results

Method	LP [50]	GA [14]	GA-LP [14]	PSO-LP [51]	SOA [29]	**Proposed method**
f(SCA)	11.1443	11.0010	10.9499	10.4267	8.4270	**7.7207**

6. CONCLUSION

This paper presents the optimal setting and coordination of the overcurrent relays in the series compensation of power system. The obtained results show that the SC of power system contributes to the current fault decreasing.

Furthermore, we conclude that the SC of power system engenders a miss of coordination of the relays. To overcome this technical problem, we propose the formulation of this problem as a constrained mono-objective problem and solve it using the FA. The new obtained settings provide a well relays coordination in the presence of SC.

The continuity of this work will be the coordination of the directional overcurrent relays considering several conflicting objective functions in the presence of FACTS devices and renewable dispersed generation.

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APPENDIX

Appendix A: Ratio of Current Transformer

IDMT Relay No.	I_{n1} / I_{n2}	K_{CT}
1, 2, 4, 5, 6, 8, 10, 11, 12, 13	1200 / 5	240
3, 7, 9, 14	800 / 5	160

Appendix B: Series Compensation

$K_C = 40$ %, $Q_{SC} = 15$ MVar, $X_{SC} = 0.20$ Ω.

Appendix C: IDMT Overcurrent Relay

Standard: IEC 60255-3, *Curve*: Normal inverse, $K = 0.14$, $S = 0.02$, $L = -1.0$

Appendix D: FA Parameters

$\alpha = 0.5$, $\gamma = 1.0$, $\beta_0 = 0.2$, $n = 100$, $Iter_{\max} = 4000$.