Optimal Coordination of Directional Overcurrent Relays Using Bacteria Foraging Algorithm

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Received 25 August 2015; revised 24 February 2016; accepted 01 July 2016

Optimal setting in relay coordination of Directional overcurrent relay (DOCR) is a major challenge for protection engineers. This paper throws light on the application of Bacteria Foraging Algorithm (BFA) in solving problems related to coordination of directional overcurrent relays. The Time Dial Setting (TDS) and pick up current setting or plug setting (Ip) act as decision variables of each relay. The objective function for optimal coordination of the relays is to minimize the summation of operating times of all the primary relays, responding to clear the faults of their corresponding zones. In this study three models are considered namely IEEE 3-bus model, IEEE 4-bus model and IEEE 6-bus model. The results show that the proposed algorithm is competent and efficient to solve such non-linear problems.

Keywords: Power System Protection, Directional Overcurrent Relay, Bacteria Foraging Algorithm (BFA)

Introduction

In power system protective relay performs the crucial role of sensing fault and giving tripping command to the circuit breaker. If circuit breaker fails to operate or relay malfunction fault will persist in the system. In such cases a second line of defense is provided by the backup relay. Proper coordination between the primary and back up relay require selection of optimal values of Time Dial Setting (TDS) and pick up current setting or plug setting (Ip). C. W. So et al.¹², Razavi F. et al.³, Dipti⁴, Thakur M⁵ have successfully applied Genetic Algorithm for solving this problem. Other artificial intelligence algorithms like differential evolution (Mallipeddi R. et al.⁶, Thangaraj R et al.⁷, Joymala M et al.⁸), particle swarm optimization (Ming Ta Yang et al.⁹, M. M. Mansour et al.¹⁰, M. Bashir et al.¹¹, M. R. Asadi et al.¹², M. Zellagui et al.¹³), neural network (Abyane H.A. et al.¹⁴), fuzzy logic¹⁴ have also been applied. Deep K et al.¹⁵ used population based heuristic algorithm to solve the problem. M. Singh et al.¹⁶ have employed Teaching Learning-Based Optimization (TLBO) Algorithm to work out this problem.

The main objectives of this work is to investigate the performance of the bacteria foraging algorithm to optimize TDS and Ip of DOCR and compare their performance with respect to recently reported meta-heuristic algorithms. From the results obtained it can be concluded that algorithm is competent to solve such highly non linear problem.

Problem Formulation

A fault close to relay is known as the close-in fault for the relay and a fault at the other end of the line is known as a far-bus fault for the relay. In relay coordination problem, TDS and Ip are optimized. The objective function for optimal coordination of the relay is to minimize the summation of operating times of all the primary relays, responding to clear all the close-in and far-bus faults. The objective function can be stated:

\[
\text{Minimize OBJ} = \sum_{i=1}^{N_{cl}} T_{pri,cl_in}^{i} + \sum_{i=2}^{N_{far}} T_{pri, far, bus}^{i}
\]  

where \(N_{cl}\) is the number of relays responding for close-in fault. \(N_{far}\) is the number of relays responding for far-bus fault. \(T_{pri, cl, in}\) is the primary relay operating time for close-in fault. \(T_{pri, far, bus}\) is primary relay operating time for far bus fault.

Relay Characteristics

The operating time of DOCR is a multivariate non-linear function of pickup current value setting (Ip), TDS and the fault current seen by the relay. Therefore, the equation of operating time for DOCR is given by
is the \( \frac{T_{\text{backup}}}{I_{\text{p}}} \), where \( T_{\text{backup}} \) is the upper limit of \( I_{\text{p}} \), where \( \alpha \) and \( \epsilon \) number of relays \( \epsilon \)

\[
T_{\text{backup}} = \frac{\alpha \times T_{\text{DS}}}{I_{\text{p}}} - 1 \quad i=1, 2, 3 \epsilon \text{ number of relays } \epsilon \quad (2)
\]

\[
T_{\text{primary}} = \frac{\alpha \times T_{\text{DS}}}{I_{\text{p}}} - 1 \quad i=1, 2, 3 \epsilon \text{ number of relays } \epsilon \quad (3)
\]

In the above equation \( T_{\text{DS}} \) is the time dial setting of relay \( R_i \), \( I_{\text{p}(i)} \) is the pickup current of relay \( R_i \). The pickup current is the minimum value of current passing through relay coil above which the relay sends trip signal to the circuit breaker. \( I_{\text{p}(i)} \) represent the fault current flowing through the relay \( R_i \). The \( T_{\text{DS}} \) value is obtained through short-circuit analysis of the network considered. TDS and PS are unknown and they are the decision variables of the problem. The constants \( \bar{n} \) and \( n \) are used as 0.14 and 0.02 respectively as per [IEEE std. (1997)].

**Bounds on the Relay Settings**

Protective relay coordination requires proper setting of TDS and \( I_{\text{p}} \). Every relay has lower and upper limit values of TDS and \( I_{\text{p}}, \)

\[
T_{\text{DS}i}^{\text{min}} \leq T_{\text{DS}i} \leq T_{\text{DS}i}^{\text{max}}, \quad \text{where } T_{\text{DS}i}^{\text{min}} \text{ is the lower limit and } T_{\text{DS}i}^{\text{max}} \text{ is the upper limit value of TDS. In this study these limits are 0.05 to 1.1.}\n\]

\[
I_{\text{p}i}^{\text{min}} \leq I_{\text{p}i} \leq I_{\text{p}i}^{\text{max}}, \quad \text{where } I_{\text{p}i}^{\text{min}} \text{ is the lower limit and } I_{\text{p}i}^{\text{max}} \text{ is the upper limit of } I_{\text{p}i} \text{ and values range from 1.25 to 1.50.}
\]

**Coordination criteria**

To ensure relay coordination, the backup relay operating time should be greater than the corresponding primary relay for all kind of faults considered by a coordination time interval (CTI). The typical value of CTI ranges from 0.2 to 0.5 s. A CTI of 0.3s was selected in this study. The coordination constraints between the primary and the backup relays is

\[
T_{\text{backup}} - T_{\text{primary}} \geq \text{CTI}
\]

where \( T_{\text{backup}} \) represent the operating time of the backup relay. The \( T_{\text{primary}} \) denote operating time of the primary relay. CTI is the least coordination time interval between backup and primary relay.

**Bacteria Foraging Algorithm (BFA)**

Bacteria foraging algorithm is based on the natural selection survival of the fittest i.e. favor those bacteria with successful foraging strategies and eliminate bacteria with poor foraging strategies. BFA mimics the E. coli bacteria present in our intestines and possess a foraging strategy governed by four processes, namely, chemotaxis, swarming, reproduction, and elimination and dispersal\(^{17,18}\). After number of generation bacteria with poor foraging strategies are either eliminated or reshaped.

**Chemotaxis**

This process consists of swimming and tumbling. According to the movement of the flagella, the bacterium decides the direction (tumbling) and if the new location of bacterium after movement is better, the bacterium will continue to swim in the same previous direction (swimming) for a particular number of steps. This swim is continued as long as it continues to reduce the operating times, but only up to a maximum number of steps, \( N_s \). This represents that the cell will tend to keep moving if it is headed in the direction of increasingly favorable environments.

**Swarming**

The bacterium that has found the optimum path for food attracts other bacteria so that they can also reach the desired place more rapidly. This step makes the bacteria assemble into groups and hence move as concentric patterns of groups with high bacterial density.

**Reproduction**

Half of the total bacteria i.e. \( S_i = S/2 \) with least health will die out, and each of the left over better bacteria will split into two bacteria, which is placed in the same location. This makes the population of bacteria stable and follows the nature law of survival of the fittest.

**Elimination and Dispersal**

For some reason it is possible that the population of the bacteria changes. Some events can kill or disperse all the bacteria in a region and possibly destroy the chemotactic progress, at the same time it is also possible they may also assist in chemotaxis, since dispersal may result into bacteria being placed at better locations i.e. solutions. This step prevents bacteria from getting trap in local optima. For each elimination-dispersal event each bacterium in the population is subjected to elimination-dispersal with probability \( p_{\text{ed}} \). To keep the number of bacteria constant, if we eliminate a bacterium, simply disperse one to a random location in the optimization domain.

**Experimentation Results and Discussion**

The performance of the proposed algorithm is experimented on three test systems, with its own set
of decision variables. The programs are developed in Matlab command line and results are obtained on a Intel Core i5-2430 processor, 2.4 GHz 4GB RAM. Each model executed 30 trial runs and the best result is reported in the paper.

Parameters for BFA:
Population Size = 20
$N_c = 20$
$N_{re} = 12$
$N_s = 6$
$p_{ed} = 0.09$
$N_{ed} = 1$

The proposed methodology is applied on IEEE 3-bus, IEEE 4-bus and IEEE 6-bus system. The objective is to determine the optimal value of TDS and $I_p$ under certain constraints so that primary relay respond to the fault in its zone and back up relay operates if primary relays fails to respond. Table 1 shows the details of the systems optimized using BFA.

**IEEE 3-bus systems**
In this system there are 6 directional overcurrent relays accordingly the number of decision variables is 12 (two for each relay) i.e. TDS$_1$-TDS$_6$ and $I_p$.$I_p$. To optimize the problem all the 6 directional overcurrent relays should coordinate. The system data is provided in reference 9. The transient situation of the system is neglected in the study. The proposed method is tested on the system and optimal solution is tabulated in Table 1. Fig. 1 shows convergence characteristics for finding the optimal values. It is observed that the proposed algorithm converges in approximately $17^{th}$ generation ,1.3421s and 26539 numbers of function evaluations (NFE). Since result obtained is better and employed lesser number of NFE, it may be considered that the algorithm is efficient. Table 2 reports the comparison of the proposed algorithm with different algorithms. The compared algorithms are Genetic Algorithm(GA), self

<table>
<thead>
<tr>
<th>IEEE 3-bus model</th>
<th>IEEE 4-bus model</th>
<th>IEEE 6-bus model</th>
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<tbody>
<tr>
<td>TDS</td>
<td>$I_p$</td>
<td>TDS</td>
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<tr>
<td>1</td>
<td>0.1730</td>
<td>1.4793</td>
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<td>2</td>
<td>0.3720</td>
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<td>5</td>
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<td>1.2876</td>
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<td>6</td>
<td>0.1039</td>
<td>1.2500</td>
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<td>F</td>
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<td>2.9543</td>
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<tr>
<td>NFE</td>
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<td>28257</td>
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</table>

**Fig.1** Convergence characteristics of BFA of IEEE 3-bus system

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>IEEE 3-bus model</th>
<th>IEEE 4-bus model</th>
<th>IEEE 6-bus model</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLBO[16]</td>
<td>-</td>
<td>5.5890</td>
<td>23.7878</td>
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<tr>
<td>BFA(proposed)</td>
<td>1.3421</td>
<td>2.9543</td>
<td>5.9112</td>
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</tbody>
</table>
organizing migrating algorithms (SOMA), self-organizing migrating GA (SOMGA), GA with Laplace crossover and polynomial mutation (LX-POL), GA with Laplace crossover and power mutation (LX-PM), random search technique 2 (RST2), differential evolution (DE) and adaptive differential evolution (ADE). The result shows that the algorithm converges rapidly to a feasible and optimal solution.

IEEE 4-bus system

This system contains 2 generators, 4 lines and 8 directional overcurrent relays. Therefore number of decision variables is 16 (two for each relay) i.e. TDS1-TDS8 and I_p1-I_p8. Proper settings of all 8 directional relay are necessary for optimal solution. The required system data is referred from reference 9. The proposed algorithm is applied on the system and best result is reported on Table 1. Fig 2 shows convergence characteristics of the problem. The proposed algorithm converges in approximately 2nd generation, 2.9543s and 28257 NFE. Table 2 presented the comparison of the proposed algorithm with different algorithms.

IEEE 6-bus systems

This system contained 3 generators, 7 lines and 14 directional relays. Accordingly there are 28 decision variables i.e. TDS1-TDS14 and I_p1-I_p14. An effective coordination of 14 directional overcurrent relays can be achieved by ensuring proper settings of all the relays. The necessary system data is referred from reference 9. The optimal solutions of the system are presented on Table 1. Convergence characteristics of the problem are shown in Fig 3. The proposed algorithm converges to the optimal solution in approximately 2nd generation, 5.911s and 3347 NFE. Table 2 reported the comparison of proposed algorithm with some of the previously quoted results available in the literature in terms of objective function.

Conclusion

The co-ordination of the directional overcurrent relay is highly non linear and complex problem subject to various constraints. In this paper an efficient method is proposed to solve the coordination problem using BFA. Experimental results reveal that the algorithm is competent to provide better quality solutions with lesser number of NFE. BFA exhibits the higher capability of converging to better quality solutions with higher convergence rate. Hence, BFA is efficient and recommended for solution of highly nonlinear OPF problems in power system. There is lot more scope for further works in improvement of BFA algorithm like adaptive tuning of chemotactic steps, step size, swarming effect etc. Also the algorithm can be hybridized with particle swarm and optimization (PSO) and differential evolution (DE) for further improvement in finding better quality solutions and better convergence.

References


