Optimal Coordination of Directional Overcurrent Relay for Power Delivery System With A Hybrid Shuffled Frog Leaping Algorithm

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Abstract: This paper presents a new approach for optimal coordination of over current relay in a power delivery system (PDS). For this, the relay coordination problem is formulated as the optimization problem by minimizing the relays operation times. Also, an efficient hybrid algorithm based on Shuffled Frog Leaping (SFL) algorithm and linear programming (LP) is introduced for solving complex and non-convex optimization problem. To investigate the ability of the proposed method, a 30-bus IEEE test system is considered. Also, to validate the obtained result by SFL-LP, a GA-LP method is applied. Simulation results show the efficiency of proposed method.

Key words: Directional over current relay coordination, looped power delivery system (PDS), short-circuit analysis, shuffled frog leaping algorithm, linear programming.

INTRODUCTION

Directional over current relays (DOCRs) are good technical and economic alternative for the protection of interconnected sub transmission systems and back-up protection of transmission systems. These relays are coordinated to provide a reliable redundant protection scheme while minimizing load interruption. DOCRs have two types of settings: pickup current setting and time multiplier setting (TMS). Basically, to determine these settings, two different approaches are used; conventional approach, and optimization techniques. Several optimization techniques have been proposed to solve the over current relay coordination problem. For example in (Birla et al., 2006), genetic algorithm (GA), evolutionary algorithm (EA), and particle swarm optimization (PSO) algorithms are used to calculate the optimal solution for relay settings. In (Noghabi et al., 2009) a novel hybrid GA method is developed. The hybrid GA method is designed to improve the convergence of conventional GA using a local LP optimizer.

In this paper, solving of relay coordination problem for PDS is performed using the optimization framework suggested in (Noghabi et al., 2009). For this aim, the relay coordination problem is formulated as the optimization problem by minimizing the relays operation times. Also, an efficient hybrid algorithm based on Shuffled Frog Leaping (SFL) algorithm and linear programming (LP), which is called SFL-LP algorithm, is used for solving complex and non-convex optimization problem. SFLA is a population-based optimization algorithm inspired from the memetic evolution of a group of frogs when searching for food and proven its superior capabilities, such as faster convergence and better global minimum achievement (Eusuff et al., 2006). In the proposed hybrid approach, the SFLA and LP are used as global and local optimizers, respectively. These cause a decrease in the search space which results in time consuming and computational efficiency in finding the optimum solutions. To investigate the ability of the proposed method, the numerical results are presented on a 30-bus IEEE test system. Moreover, to validate the results obtained by SFL-LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from (Noghabi et al., 2009) and applied for comparison. Simulation results show the efficiency and superiority of the SFL-LP algorithm over the GA-LP algorithm.

The paper is organized as follows. In the next section an overview on the directional over current relay coordination problem is presented. The basic concept of SFLA briefly is explained in section 3. The normal coordination procedure and the hybrid method proposed to solve the relay coordination problem for a PDS are discussed in section 4. Section 5 provides the PDS under study. Simulation results to evaluate the proposed method are provided in section 6 and finally conclusion part is in section 7.

2. Relay Coordination Problem:

The coordination problem of DOCRs is one of the most important problems to be solved in the operation and protection of a power system. The primary objective of the relay coordination problem is to determine the time multiplier setting and pickup current setting of each relay which would minimize the time of operation of the primary relays, while satisfying certain coordination constraints (Barker and Mello, 2000; Kauhaniemi and Kumpulainen, 2004; Brahma and Girgis, 2004).
The optimal coordination problem of DOCRs, can be formulated as an optimization problem, where consists of minimizing an objective function (performance function) subject to limits on problem variables and certain coordination constraints. In this work, the total time objective function, for primary relay near-end-fault, is considered as (1) by including the constraints aiming to avoid the sympathy trips. These constraints are relay setting constraints and backup-primary relay constraints that presented in the next subsections.

\[
\min J = \sum_{i=1}^{n} w_i t_i
\]  

In (1), \( n \) is the number of relays. Also, \( t_i \) is the operation time of \( i^{th} \) relay for near-end fault and \( W_i \) is the correspondent weighting factor and depends upon the probability of a given fault occurring in each protection zone. Commonly these weighting factors set to one. Fig. 1 shows the concepts of near-end fault \( F_1 \) and far-end fault \( F_2 \).

![Diagram of relay system](image)

**Fig. 1:** The concepts of near-end and far-end faults for \( i^{th} \) relay (Noghabi et al., 2009).

**2.1. Relay Characteristics:**
There are various linear and nonlinear over current relay characteristics reported in the literature. In this work, relays were assumed identical and with characteristic functions approximated by:

\[
t_i = TDS_i \left\{ \frac{A}{M_i^2 - 1} + B \right\}, \quad M_i = \frac{I_{fi}}{I_{pi}}
\]

Where \( TDS_i \) stand for the time multiplier setting, and also, \( I_{pi} \) and \( I_{fi} \) are pickup current setting of the \( i^{th} \) relay the fault current passing through \( i^{th} \) relay, respectively.

**2.2. Primary-Backup Relay Constraints:**
In the relay coordination problem, to ensure the relay coordination, it is necessary that the operating time of the backup relay be greater than that of the primary relay for the same fault location by a coordination time interval \( CTI \). For this, the coordination constraints between the primary \( i^{th} \) relay and its/their backup relay(s) for the near-end and the far-end faults are considered as follows:

\[
\begin{align*}
t_j^{F1} - t_i^{F1} & \geq CTI \\
t_j^{F2} - t_i^{F2} & \geq CTI
\end{align*}
\]

Where \( t_i^{F1} \) is the operating time of \( i^{th} \) primary relay for the near-end fault. Also, \( t_j^{F1} \) is defined in the \( j^{th} \) backup relay. Moreover, CTI is the minimum interval that permits the backup relay to clear a fault in its operating zone. In the other words, the CTI is the time lag in operation between the primary and its backup
relay. It includes many factors, such as the breaker operating time and a safety margin. The value of CTI is usually chosen between 0.2 and 0.5 s.

2.3. Bounds on the Relay Settings: The limits on the relay parameters can be written as following inequalities:

\[ TDS_{\text{min}}^k < TDS^k < TDS_{\text{max}}^k \] (4)

\[ Ip_{\text{min}}^k < Ip^k < Ip_{\text{max}}^k \] (5)

3. SFLA Overview: Over the last decades there has been a growing concern in algorithms inspired by the observation of natural phenomenon. It has been shown by many researches that these algorithms are good alternative tools to solve complex computational problems.

The SFLA is a meta-heuristic optimization method inspired from the memetic evolution of a group of frogs when searching for food (Huynh, 2008). SFLA, originally developed (Eusuff and Lansey, 2003) in determining the optimal discrete pipe sizes for new pipe networks and for existing network expansions. Due to the advantages of the SFLA, it is being researched and utilized in different subjects by researchers around the world, since 2003 (Elbeltagi, 2007; El-Khattam and Sidhu, 2008; Bijami et al., 2010; Ebrahimi et al., 2011).

The SFL algorithm is a memetic meta-heuristic method that is derived from a virtual population of frogs in which individual frogs represent a set of possible solutions. Each frog is distributed to a different subset of the whole population described as memeplexes. The different memeplexes are considered as different culture of frogs that are located at different places in the solution space (i.e. global search). Each culture of frogs performs simultaneously an independent deep local search using a particle swarm optimization like method. To ensure global exploration, after a defined number of memeplex evolution steps (i.e. local search iterations), information is passed between memeplexes in a shuffling process. Shuffling improves frog ideas quality after being infected by the frogs from different memeplexes, ensure that the cultural evolution towards any particular interest is free from bias. In addition, to improved information, random virtual frogs are generated and substituted in the population if the local search cannot find better solutions. After this, local search and shuffling processes (global relocation) continue until defined convergence criteria are satisfied. The flowchart of the SFLA is illustrated in Fig. 2.

The SFLA begins with an initial population of “P” frogs \( F = \{X_1, X_2, ..., X_P\} \) created randomly within the feasible space \( \Omega \). For S-dimensional problems (S variables), the position of the \( i^{th} \) frog is represented as \( X_i = [x_{i1}, x_{i2}, ..., x_{is}]^T \). A fitness function is defined to evaluate the frog’s position. Afterward the performance of each frog is computed based on its position. The frogs are sorted in a descending order according to their fitness. Then, the entire population is divided into \( m \) memeplexes, each of which consisting of \( n \) frogs (i.e. \( P = n \times m \)). The division is done with the first frog goes to the first memeplex, the second frog goes to the second memeplex, frog \( m \) goes to the \( m^{th} \) memeplex, and the \( (m + 1)^{th} \) frog back to the first memeplex, and so on. The local search block of Fig. 2 is shown in Fig.3.

According to Fig.3, during memeplex evolution, the position of frog \( i^{th} \) \( (D_i) \) is adjusted according to the different between the frog with the worst fitness \( (X_w) \) and the frog with the best fitness \( (X_b) \) as shown in (6). Then, the worst frog \( X_w \) leaps toward the best frog \( X_b \) and the position of the worst frog is updated based on the leaping rule, as shown in (7).

\[ \text{Position change} (D_i) = \text{rand()} \times (X_b - X_w) \] (6)

\[ X_w(\text{new}) = X_w + D_i \left[ \frac{\text{new}}{D_{\text{max}}} \right] < D_{\text{max}} \] (7)

where \( \text{rand()} \) is a random number in the rang \([0,1]\) and \( D_{\text{max}} \) is the maximum allowed change of frog’s position in one jump. If this repositioning process produces a frog with better fitness, it replaces the worst frog, otherwise, the calculation in (6) and (7) are repeated with respect to the global best frog \( (X_g) \), (i.e. \( X_g \) replaces \( X_i \)). If no improvement becomes possible in this case, then a new frog within the feasible space is randomly generated to replace the worst frog. Based on Fig. 2, the evolution process is continued until the termination criterion is met. The termination criterion could be the number of iterations or when a frog of optimum fitness is found (Huynh, 2008).
4. Proposed Approach To Solve Relay Coordination Problem:

Here, the optimization framework suggested in (Noghabi et al., 2009) is adopted to develop a hybrid method based on SFL and LP algorithms for solving this complex and nonconvex optimization problem.

In the proposed hybrid approach, the SFLA and LP are used as global and local optimizers, respectively. For this, the LP algorithm is employed as a local optimizer to improve the convergence of SFL algorithm and the SFL algorithm is used to solve the first sub problem [i.e., the nonlinear part of optimization problem (1)] in order to determine the \( I_{pi} \) variables.

By extracting the frog information, the DOCRs coordination problem is converted to a Linear Programming problem. Therefore to evaluate the fitness value for each frog, the standard LP is solved to determine the corresponding TMS variables. The flowchart of the proposed hybrid method is shown in Fig. 4.

As can be seen from Fig. 4, the LP sub problem is the main part of fitness function evaluation which is called several times by the SFL algorithm. To compute the fitness value for each frog, firstly, the values of the \( I_{pi} \) variables are extracted by decoding the frog information. Based on the fixed values of the variables, the nonlinear DOCRS coordination problem is converted to a LP problem.

Then, by solving this LP problem the corresponding fitness value and the TMS variables are computed. This causes a decrease in the search space which results in time consuming and computational efficiency in finding the optimum solutions.

For some individuals according to the values of the variables, the LP sub problem is not converged. In these cases, some of the inequality coordination constraints are violated. To decrease the chance of these frogs in the next process, their fitness values are penalized. The amount of penalty is composed of a fixed value and a variable value in proportion to the number of violated constraints. Whole approach can be summarizing as following steps:
- Extracting of relays pickup current by decoding each frog.
- Determination of TMS variables by solving LP problem. The objective function in LP sub problem is defined based on (1).
- calculating fitness value for each frog.
Fig. 3: Local search block of Fig. 2 (Huynh, 2008).
5. Case Study:

5.1. PDS Under Study:

In order to show the effectiveness of the proposed method, some numerical results are presented on a 30-bus IEEE test system (http://www.ee.washington.edu/research). The considered PDS system is modeled with all of its detailed parameters (synchronous condensers with their generation limits, shunt reactors, distribution transformers taking into consideration their turn’s ratio, and aggregated loads represented by constant power models). This study system is illustrated in Fig. 5.

Table 1: The ratios of the current transformers (CTs)

<table>
<thead>
<tr>
<th>Relay Number</th>
<th>CT</th>
<th>Relay Number</th>
<th>CT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200/5</td>
<td>16</td>
<td>200/5</td>
</tr>
<tr>
<td>2</td>
<td>300/5</td>
<td>17</td>
<td>100/5</td>
</tr>
<tr>
<td>3</td>
<td>600/5</td>
<td>18</td>
<td>100/5</td>
</tr>
<tr>
<td>4</td>
<td>300/5</td>
<td>19</td>
<td>200/5</td>
</tr>
<tr>
<td>5</td>
<td>300/5</td>
<td>20</td>
<td>600/5</td>
</tr>
<tr>
<td>6</td>
<td>600/5</td>
<td>21</td>
<td>100/5</td>
</tr>
<tr>
<td>7</td>
<td>300/5</td>
<td>22</td>
<td>100/5</td>
</tr>
<tr>
<td>8</td>
<td>50/5</td>
<td>23</td>
<td>200/5</td>
</tr>
<tr>
<td>9</td>
<td>600/5</td>
<td>24</td>
<td>100/5</td>
</tr>
<tr>
<td>10</td>
<td>200/5</td>
<td>25</td>
<td>200/5</td>
</tr>
<tr>
<td>11</td>
<td>200/5</td>
<td>26</td>
<td>200/5</td>
</tr>
<tr>
<td>12</td>
<td>300/5</td>
<td>27</td>
<td>200/5</td>
</tr>
<tr>
<td>13</td>
<td>100/5</td>
<td>28</td>
<td>100/5</td>
</tr>
<tr>
<td>14</td>
<td>100/5</td>
<td>29</td>
<td>300/5</td>
</tr>
<tr>
<td>15</td>
<td>200/5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The considered PDS is fed from three primary distribution substations (132/33 kV) at buses 10, 12, and 27. Each primary distribution feeder is protected by two directional over current relays, one relay at each end. The PDS is assumed to have 29 existing directional over current relays and the system is originally well coordinated.
It is assumed that all relays are identical and have the standard IEEE moderately inverse relay curves with the following constants 0.0515, 0.114, and 0.02 for A, B, and C, respectively (Huynh, 2008).

Also, the TMS values can range continuously from 0.1 to 1.3, while seven available discrete pickup tap settings (0.5, 0.6, 0.8, 1.0, 1.5, 2.0 and 2.5) are considered (Huynh, 2008). The ratios of the current transformers (CTs) are indicated in Table 1 and the CTI is assumed to be 0.3 s for each backup-primary relay pair.

5.2. Scenarios Under Study:

In this paper, coordination of directional relays is done with explained optimal algorithm. Furthermore, in order to validate the results obtained by SFL-LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from (Noghabi et al., 2009) and applied for comparison.

6. Analysis And Results:

To evaluate the optimal tuned relay settings, the DOCRs coordination problem is solved using the proposed hybrid method.

The first step to implement the SFL is generating the initial population (N frogs) where N is considered to be 100. The number of memeplex is considered to be 10 and the number of evaluation for local search is set to 10. Also $D_{\text{max}}$ is chosen as inf.

Based on Fig. 2 the local search and shuffling processes (global relocation) continue until the last iteration is met. In this paper, the number of iteration is set to be 2000

To validate the obtained result by SFL-LP, a GA-LP method is applied. The number of chromosomes in the population is set to be 100. One point crossover is applied with the crossover probability $p_c = 0.9$ and the mutation probability is selected to be $p_m = 0.01$. Also, the number of iterations is considered to be 2000, which is the stopping criteria used in SFL.

To find the best value for the solution, the algorithms are run for 10 independent runs under different random seeds. The average best-so-far of each run are recorded and averaged over 10 independent runs. To have a better clarity, the convergence characteristics in finding the best values is given in Fig. 6, where shows SFL performs better than GA at early iterations.

The optimal values of the decision parameters (i.e., pickup tap settings and TMS variables) are shown in Table 2. Also, the final optimal total time obtained is 15.59s.
**Fig. 6:** Convergence characteristics of SFL and GA on the average best-so-far cost function.

**Table 2:** Pick up tap settings and TMS variables.

<table>
<thead>
<tr>
<th>Relay No.</th>
<th>SFL</th>
<th>TDS</th>
<th>SFL</th>
<th>TDS</th>
<th>Relay No.</th>
<th>SFL</th>
<th>TDS</th>
<th>GA</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2/5</td>
<td>0/9197</td>
<td>2/5</td>
<td>0/9507</td>
<td>16</td>
<td>2/5</td>
<td>0/2112</td>
<td>2/5</td>
</tr>
<tr>
<td>2</td>
<td>2/5</td>
<td>0/5989</td>
<td>2/5</td>
<td>0/6198</td>
<td>17</td>
<td>2</td>
<td>0/5288</td>
<td>2/5</td>
</tr>
<tr>
<td>3</td>
<td>2/5</td>
<td>0/4412</td>
<td>2/5</td>
<td>0/4667</td>
<td>18</td>
<td>1/5</td>
<td>0/8302</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>0/2367</td>
<td>2/5</td>
<td>0/1711</td>
<td>19</td>
<td>2/5</td>
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<td>2/5</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>0/1217</td>
<td>2/5</td>
<td>0/1</td>
<td>20</td>
<td>1/5</td>
<td>0/1</td>
<td>0/8</td>
</tr>
<tr>
<td>6</td>
<td>2/5</td>
<td>0/3267</td>
<td>2/5</td>
<td>0/4031</td>
<td>21</td>
<td>1/5</td>
<td>1/0201</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>2/5</td>
<td>0/7592</td>
<td>2/5</td>
<td>0/8881</td>
<td>22</td>
<td>2/5</td>
<td>0/6426</td>
<td>2/5</td>
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<td>8</td>
<td>2</td>
<td>0/5106</td>
<td>2/5</td>
<td>0/4174</td>
<td>23</td>
<td>2/5</td>
<td>0/2997</td>
<td>2/5</td>
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<td>9</td>
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<td>0/1</td>
<td>2</td>
<td>0/1</td>
<td>24</td>
<td>1</td>
<td>0/6968</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
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<td>2/5</td>
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<td>1</td>
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<td>2/5</td>
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<td>12</td>
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<td>0/1</td>
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<td>15</td>
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<td>0/3546</td>
<td>2/5</td>
<td>0/4238</td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Moreover, Table 3 shows a sample of backup-primary relay pair short circuit currents, operating times.

**Table 3:** Sample of backup-primary relay pair (for SFL results).

<table>
<thead>
<tr>
<th>Relay unit</th>
<th>Relay current (Amp.)</th>
<th>Operating Time (sec.)</th>
<th>CTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_1$</td>
<td>6180</td>
<td>1.0232</td>
<td>-</td>
</tr>
<tr>
<td>$R_{19,1}$</td>
<td>627</td>
<td>1.3506</td>
<td>0.3274</td>
</tr>
<tr>
<td>$R_{23,1}$</td>
<td>880</td>
<td>1.3916</td>
<td>0.3684</td>
</tr>
</tbody>
</table>

**7. Conclusion:**

This paper presents a new approach for optimal coordination of directional overcurrent relay for a power delivery system (PDS). In the proposed scheme, solving of relay coordination problem is done by minimizing the relays operation times. For this, the relay coordination problem is formulated as the optimization problem and solved by an efficient hybrid algorithm based on Shuffled Frog Leaping (SFL) algorithm and linear programming (LP). To investigate the ability of the proposed method, a 30-bus IEEE test system is considered with three scenarios. Moreover, to validate the results obtained by SFL-LP algorithm, the hybrid approach based on Genetic Algorithm (GA) and LP algorithm (GA-LP) is adopted from (Noghabi et al., 2009) and applied for comparison. Simulation results show the efficiency of the proposed algorithm.
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