Budgetary and Redundancy Optimization of Heterogeneous Series-Parallel Power Systems under Availability Constraints

Khaled Guerraiche\textsuperscript{a,*}, Mostefa Rahli\textsuperscript{a}, Abdelkader Zeblah\textsuperscript{b}, Latifa Dekhici\textsuperscript{a}

\textsuperscript{a}University of Oran USTO, Engineering Faculty, Electrical Department, B.P. 1505 El Mnaouar, Oran, Algeria
\textsuperscript{b}University of Sidi bel abbes, Engineering Faculty, Electrical Department, B.P. 89, sidi jilali,Sidi Bel abbes, Algeria

Abstract

This paper intends to resolve a redundancy optimization problem (ROP) using a recent bio-inspired metaheuristic which is Bat Algorithm (BA). The problem consists on selecting the appropriate components from a power system so to minimize investment cost. The selection must also satisfy a required reliability constraint. The optimization of multi-state series–parallel power system subject to this kind of common cause failures can be formulated into a nonlinear mathematic model. The series-parallel electrical availability system measurement leads into extensive computational process, which can slows down the optimization algorithm. That why, a commonly employed Universal Generation Function (UGF) is implemented. Experimental results on illustrative example show how Bat algorithm can yields to the optimal design and gives good results in an insignificant processing time.

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Peer-review under responsibility of the Euro-Mediterranean Institute for Sustainable Development (EUMISD)

Keywords: Bat algorithm (BA); Series-Parallel Power System; Reliability; Power System design; Universal Moment Generating Function (UMGF).

* Corresponding author. Tel.: +213-561-980-887.
E-mail address: khguerraiche@yahoo.fr
1. Introduction

Optimization is a field of sciences in which the best values of problem parameters are explored under specified conditions i.e. basically it targets to find those particular parameter values which enable an objective function to generate the minimum or maximum value under constraints [1,2,3]. Nowadays, many well-know optimization methods are nature-inspired. They have been developed by imitating the successful characteristics of natural systems and. Among these nature-inspired algorithms, most are bio inspired. Their fundamental principles are based on the evolutionary characteristics or on behaviors of biological systems. A popular subset of bio-inspired algorithms can be called swarm intelligence-based algorithms because they have been developed by drawing inspiration from the so-called swarm intelligence (SI) [4].

The bat algorithm (BA) is a very interesting approach recently proposed by Yang [5]. It is based on the nature behavior of micro-bats when looking for food. Micro bats use echolocation to guide their search. They generate sound waves with some given frequencies and pulse rates when they tend to get close to their prey. The pulse rate increases, while the loudness decreases. A bat algorithm idealizes these features for solving combinatorial and continuous optimization problems, i.e., the bats design parameters are bat positions and the prey is the objective [6].

This paper intend to adapt bat algorithm to the redundancy optimization problem and specifically to series-parallel power systems cost minimization under availability constraint. An Universal moment Generation Function (UMGF) is also implemented to evaluate solution reliabilities.

For that, after introducing the problem nomenclature, power system redundancy problem is described with mathematic formulation in the second section. In the third section, the reliability measurement choice is directed to the UMGF (or u-transform) approach. The fourth section details bat algorithm, their principles and pseudo code. Finally, computational results are illustrated in an example.

Nomenclature

\begin{align*}
  i,j,l &: \text{ Respectively indices of series, versions and demand period interval} \\
  N &: \text{ Number of series } i \\
  C_{ij} &: \text{ Cost of electrical component } j \text{ of type } i \\
  V_i &: \text{ Number of Available electrical components technologies of type } i \\
  k_{ij} &: \text{ Number of occurrence of component } j \text{ in series } i \\
  \Xi_{ij} &: \text{ Performance of power component } j \text{ of type } i \\
  A_{ij} &: \text{ Reliability of power component } j \text{ of type } i \\
  A_0 &: \text{ Minimum availability required} \\
  M &: \text{ Number of demand period interval} \\
  K_{max} &: \text{ Maximum number that can be taken from each component } j \\
  P_i &: \text{ Performance probability of } i^{th} \text{ device} \\
  Q_j &: \text{ Performance probability of } j^{th} \text{ device} \\
  W &: \text{ Demand levels} \\
  \gamma &: \text{ Operator for parallel device} \\
  \delta &: \text{ Operator for series device}
\end{align*}
2. Power System Problem

Let us consider a power system containing \( N \) electrical power components connected in series-parallel. Each component \( i \) in turn contains a number of different components connected in parallel. All components of any given subsystem belong to different versions. Components are characterized by their reliability \( (A_{ij}) \), cost \( (C_{ij}) \) and performance \( (\Xi_{ij}) \). The structure of subsystem \( i \) can be defined by the numbers of parallel components \( k_{ij} \) for \( 1 \leq j \leq V_i \), where \( V_i \) is the number of versions available for component of type \( i \) Fig.1.

The multi-state electrical power system redundancy optimization problem can be formulated as follows: find the minimal cost system configuration \( k_1, k_2, \ldots, k_N \), such that the corresponding reliability exceeds or is equal to a specified required reliability \( A_0 \).

![Series-Parallel Power System Structure](image)

Minimize  
\[
C = \sum_{i=1}^{\text{num}} \sum_{j=1}^{V_i} k_{ij} c_{ij}
\]  
Subject To  
\[
A = (d, t, k_1, k_2, \ldots, k_N) \geq A_0
\]

3. Availability Evaluation Method

The problem defined above is one of combinatorial optimization problem, it is necessary to enumerate a huge number of possible system states. Thus, it is required to use an effective and fast procedure for structure reliability estimation. As shown above, the main problem is to evaluate the index \( R \) for arbitrary series and parallel systems. The probability that the total capacity of the electrical power system is not less than a specific load demand level \( W \) must be calculated as (equation(2)):

\[
R(W) = P\{ \Xi > W \} = 1 - P\{ \Xi \leq W \}
\]  

The procedure used to estimate this index is based on a modern mathematical technique: the UMGF (or u-transform) technique in [7,8,9]. This method was first applied to real power system reliability assessment and optimization in [10], and represents an extension of ordinary moment generating function [11]. The UMGF of a discrete variable \( E \), assumed in this paper, is defined as a polynomial:

\[
u(z) = \sum_{j=1}^{\text{num}} p_j z^{j}\]
Consider single devices with total failures and each device \( i \) has nominal performance \( \Xi_i \) and reliability \( A_i \). The UMGGF of such device has only two terms and can be defined as:

\[
u_i(z) = (1 - A_i)z^0 + A_i z^{\Xi_i} = (1 - A_i) + A_i z^{\Xi_i}
\]

(4)

To evaluate the series-parallel Multi state system (MSS) availability, two basic composition operators are introduced. These operators determine the polynomial \( u(z) \) for a group of devices: \( \bar{\mathcal{A}} \) and \( \mathcal{B} \).

3.1. Parallel devices

\[
\bar{\mathcal{A}}(u_1(z), u_2(z)) = \bar{\mathcal{A}}(\sum_{i=1}^n P_i z^{a_i}, \sum_{j=1}^m Q_j z^{b_j}) = \sum_{i=1}^n \sum_{j=1}^m P_i Q_j z^{a_i+b_i}
\]

(5)

3.2. Series devices

\[
\delta(u_1(z), u_2(z)) = \delta(\sum_{i=1}^n P_i z^{a_i}, \sum_{j=1}^m Q_j z^{b_j}) = \sum_{i=1}^n \sum_{j=1}^m P_i Q_j z^{\min[a_i,b_j]}
\]

(6)

Applying composition operators \( \bar{\mathcal{A}} \) and \( \delta \) consecutively, one can obtain the UMGGF of the entire series-parallel system. To do this we must first determine individual UMGGF of each device.

4. Bat Algorithm

4.1. A Brief Review

The bat algorithm (BA) was first presented in [5] and it was tested for benchmark functions. The standard bat algorithm was applied in lot of area of optimization such as economic power dispatch problems [12], bloom filter optimization [13], and phishing website detection [14]. Authors in [15] studied K-means clustering using bat algorithm. It was combined with fuzzy logic in the context of e-learning [16,17,18] and to classify micro array data [19]. Marichelvam and Prabaharan, used bat algorithm to minimize the makespan and mean flow time in multi processers flexible flow shop scheduling problems [20]. In the area of image processing, it was used to full body human pose estimation [21], image matching [22]. In Other Applications, one can find its application in: optimal capacitor placement for loss reduction in distribution systems [23], energy modeling [24, 25] and data compression technique [26].

4.2. Echolocation of Bats

Bats are fascinating animals and most of them have the advanced capability of echolocation. The bat algorithm (BA) is inspired from an idealization of echolocation that can be summarized as follows:

A virtual bat flies randomly at position (solution) \( x_i \) with a velocity \( v_i \) with a varying frequency or wavelength \( F_i \) and loudness \( A_i \). As it searches and finds its prey, it changes frequency, pulse emission rate \( r \) and loudness. Search is step up by a local random walk. Selection of the best continues until certain stop criteria are met.

The algorithm, for simplicity, uses the following idealized principles:

- All bats use echolocation to sense distance, and they also know the difference between prey and background barriers in some magical way;
- Bats fly randomly with velocity \( v_i \) at position \( x_i \) with a fixed frequency \( f_{\min} \), varying wavelength and loudness \( A_0 \) to search for prey. They can automatically adjust the wavelength (or frequency) of their emitted pulses and adjust the rate of pulse emission \( r \) depending on the proximity of their target;

Although the loudness can vary in many ways, it is assumed that the loudness varies from a large (positive) \( A_0 \) to a minimum constant value \( A_{\min} \) [1,5]. Another assumption is that the frequency \( f \) in range \([f_{\min}, f_{\max}]\) corresponds to wavelength range \([\lambda_{\min}, \lambda_{\max}]\) like frequency range of \([20,500]\) (in KHz) corresponds to range of wavelength from \([0.7, 17]\) (in mm) [1,27]. It is also assumed that \( f \in [0, f_{\max}] \) because higher frequencies have short wavelengths and
travel shorter distance like in case of bats, so rate of pulse can be simple be in range of [0,1] where 0 means no pulses and 1 means maximum rate of pulse emission [1,5].

4.3. Bat Algorithm Parameters

- **Frequency Representation**: The frequency \( f \) is an integer or a float number depending on the selected minimum and maximum frequency.
  \[
  f_i = f_{\min} + (f_{\max} - f_{\min}) \text{rand}() \\
  \text{rand} \in [0,1]
  \] 

- **Velocity Representation**: The velocity \( v \) of each bat is represented as a positive integer number. Velocity suggests how many of the bat’s attributes should be changed at a certain instant. The bats will communicate with each other through the global best \( g_{\text{best}} \).
  \[
  v_i = v_i + (x_i - g_{\text{best}}) f_i
  \]

- **Position**: the position is updated according to equation
  \[
  x_i = \text{best}_i + v_i
  \]
  It can be around the global best with loudness:
  \[
  x_i = g_{\text{best}} + (-1,1) A_{\text{moy}}
  \]
  Or randomly:
  \[
  x_i = \text{best}_i + \text{random}(-1,1) A_{\text{moy}}
  \]

- **Loudness Representation**: \( A \) is the average sound loudness of all the bats. It has a range, between the maximum and minimum loudness. It can decrease.
  \[
  A_i = \alpha A_i, \alpha \in [0,1]
  \]

- **Pulse Rate Representation**: Pulse rate \( r_i \) value will play a role in whether a local search procedure around the global best solution should be conducted or skipped.
  \[
  r_i = r_i^0 \left(1 - e^{-\gamma \text{iter}}\right) \quad r_i^0 \text{ initial pulse, } \gamma > 0
  \]

4.4. Pseudo Code

Using all assumptions, the pseudo-code of Bat algorithm can be as follow [5]:

<table>
<thead>
<tr>
<th>Algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; \alpha &lt; 1; \gamma \geq 0 //for example ( \alpha = \gamma = 0.9 )</td>
</tr>
<tr>
<td>Initialize ( f_{\text{min}} = 0; f_{\text{max}} = 100; ) //to be adjusted</td>
</tr>
<tr>
<td>Initialize bats population ( x_i ) and their velocity ( v_i )</td>
</tr>
<tr>
<td>Define impulsion frequencies ( f_i = f_{\text{min}} + (f_{\text{min}} - f_{\text{max}}) \text{rand}() )</td>
</tr>
<tr>
<td>Initialize impulsions: ( r_i^0 [0,1] ) and intensities: ( A_i [1,2] )</td>
</tr>
<tr>
<td>Evaluate ( f(x_i) ) and find global best(( g_{\text{best}} )) and ( f_{\text{gbest}} )</td>
</tr>
<tr>
<td>Fitness( (i) = f(x_i) ), best( (i) = x_i )</td>
</tr>
<tr>
<td>For ( \text{iter} = 1 ) to ( \text{max} _{\text{gen}} ) do</td>
</tr>
<tr>
<td>adjust frequencies (equation 1)</td>
</tr>
<tr>
<td>update velocities (equation 2)</td>
</tr>
<tr>
<td>generate new bats ( x_i ) (equation 3)</td>
</tr>
<tr>
<td>for ( i = 1 ) to ( \text{nb} ) do //for all bats</td>
</tr>
<tr>
<td>if ( \text{rand} &gt; r_i )</td>
</tr>
</tbody>
</table>
generate a new position around the best (equation 10)
end if
generate new position by flying randomly (equation 11)
if rand < A_i and f(xi) < fitness(i))
accept new solutions
Increase r_i and reduce A_i (equation 12 and 13)
end if
sort bats to find the best
end

Fig. 2. Pseudo code of BAT algorithm.

5. Computational results

5.1. Test Data

In order to test the feasibility and efficiency of the adapted bat algorithm (BA) coupled with the Universal Moment Generating Function (UMGF) to the constrained design optimization, an illustrative example of a power system is given in Table 1. The system has five lines, and in each line, 4 to 5 versions are available with characteristics as capacities, costs and reliabilities. Table 2 shows the cumulative demand curve.

TABLE 1. Characteristics of reliability system components on the market [28]

<table>
<thead>
<tr>
<th>Subsystems</th>
<th>Versions</th>
<th>Reliability</th>
<th>Cost (mln $)</th>
<th>Capacity (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Power Units</td>
<td>1</td>
<td>0.985</td>
<td>0.202</td>
<td>120</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.980</td>
<td>0.195</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.974</td>
<td>0.154</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.968</td>
<td>0.145</td>
<td>85</td>
</tr>
<tr>
<td>2 HT Transformer</td>
<td>1</td>
<td>0.961</td>
<td>0.455</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.949</td>
<td>0.295</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.938</td>
<td>0.222</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.932</td>
<td>0.107</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>0.925</td>
<td>0.083</td>
<td>21</td>
</tr>
<tr>
<td>3 HT lines</td>
<td>1</td>
<td>0.915</td>
<td>0.258</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.903</td>
<td>0.132</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.893</td>
<td>0.082</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.9882</td>
<td>0.065</td>
<td>40</td>
</tr>
<tr>
<td>4 HT/MT Transformers</td>
<td>1</td>
<td>0.789</td>
<td>0.622</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.785</td>
<td>0.602</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.714</td>
<td>0.564</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.782</td>
<td>0.364</td>
<td>72</td>
</tr>
<tr>
<td>5 MT Lines</td>
<td>1</td>
<td>0.985</td>
<td>0.987</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.980</td>
<td>0.844</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.961</td>
<td>0.445</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.949</td>
<td>0.319</td>
<td>40</td>
</tr>
</tbody>
</table>

TABLE 2. Parameters of the cumulative demand curve [29]

<table>
<thead>
<tr>
<th>Wm (%)</th>
<th>100</th>
<th>80</th>
<th>50</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tm (h)</td>
<td>4203</td>
<td>788</td>
<td>1228</td>
<td>12536</td>
</tr>
</tbody>
</table>
5.2. Optimization results and discussion

One of the ways to enhance system reliability and to adapt system capacity to meet the demand is to optimize the power structure. For each study period a new redesign is obtained by the proposed Bat algorithm for different values of availability $A_0$ (0.96, 0.97 and 0.99). Table 3 illustrates the computed costs and availabilities index corresponding to their generated new design.

To implement the algorithm presented in this paper, a C++ code was written and executed on a machine with a DELL-i3 2.8GHz CPU and 500 MB RAM.

In these experiments, BAT algorithm parameters are set to the following values: $\alpha = \gamma = 0.9$ and $f_{\text{min}} = 0; f_{\text{max}} = 100$. The choice of these values affects strongly solutions. The Bat algorithm is tested for quite a range of these values.

Once parameters are fixed, the program is executed 10 times. For each simulation instance, 500 iterations is allowed and 20 bats are used.

<table>
<thead>
<tr>
<th>Availability Constraint $A_0$</th>
<th>Availability A (%)</th>
<th>Cost C(ML$)</th>
<th>Topology</th>
<th>Optimal Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.960</td>
<td>0.990</td>
<td>5.637</td>
<td>Subsystem 1</td>
<td>2(3)-4(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 2</td>
<td>7(5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 3</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 4</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 5</td>
<td>5(4)</td>
</tr>
<tr>
<td>0.970</td>
<td>0.991</td>
<td>5.710</td>
<td>Subsystem 1</td>
<td>2(3)-4(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 2</td>
<td>3(4)-4(5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 3</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 4</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 5</td>
<td>5(4)</td>
</tr>
<tr>
<td>0.990</td>
<td>0.995</td>
<td>6.710</td>
<td>Subsystem 1</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 2</td>
<td>5(4)-1(5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 3</td>
<td>3(3)-4(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 4</td>
<td>6(4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Subsystem 5</td>
<td>3(2)-3(3)</td>
</tr>
</tbody>
</table>

6. Conclusion

In this study, the bio-inspired bat algorithm has been proposed to determine the best configuration of no homogeneous series-parallel power system with minimum total investment cost. The problem has been subject to given reliability constraints. The BAT meta-heuristic has constructed best system structures by selecting elements from a list of available products according to their reliabilities, performances and costs. The global optimization or resolution process was based on combination of discrete version of bat algorithm to find the best costs and on the universal moment generating function to evaluate reliabilities the according to the required one and to verify solutions feasibility. BAT algorithm gives satisfactory solutions in few milliseconds. The application of Bat algorithm on other redundancy problem extensions and the validation of this metaheuristic on literature benchmarks are currently in the study.

References


