Power quality and reliability enhancement in distribution systems via optimum network reconfiguration by using quantum firefly algorithm

H. Shareef\textsuperscript{a}, A.A. Ibrahim\textsuperscript{a,\textastripem}, N. Salman\textsuperscript{b}, A. Mohamed\textsuperscript{a}, W. Ling Ai\textsuperscript{a}

\textsuperscript{a} Department of Electrical, Electronic and Systems Engineering, University Kebangsaan Malaysia, Bangi, 43600 Selangor, Malaysia
\textsuperscript{b} Department of Electrical Power and Machines Engineering, College of Engineering, Diyala University, 32001 Baqubah, Iraq

\textbf{A R T I C L E   I N F O}

Article history:
Received 2 July 2013
Received in revised form 7 January 2014
Accepted 18 January 2014

Keywords:
Voltage sag
Reliability
Network reconfiguration
Firefly algorithm
Optimization

\textbf{A B S T R A C T}

Network reconfiguration (NR) is the process of varying the topological arrangement of distribution feeders by changing the open/closed status of sectionalizing and tie switches. This paper presents a method to improve the power quality (PQ) and reliability of distribution systems by employing optimal NR. Optimal NR is applied independently to a system in a specified period to minimize the number of propagated voltage sags ($N_{\text{sag}}$) and other reliability indexes such as the average system interruption frequency index, sustained average interruption frequency index, and momentary average interruption frequency index. The quantum-inspired binary firefly algorithm (QBFA) is used to find the optimal NR. The QBFA performance for the application of optimal NR to minimize $N_{\text{sag}}$ is first compared with other established optimization methods such as the standard binary firefly algorithm and gravitational search algorithm. Case studies are conducted by using other objective functions, and reliability assessment is performed to observe the reliability improvement caused by the new network topology. Simulation results show that the proposed optimum NR effectively enhances system reliability level and PQ.

\textcopyright 2014 Elsevier Ltd. All rights reserved.

1. Introduction

A modern electric power system must be designed to supply acceptable levels of electrical energy to customers. Simple power quality (PQ) disturbance events, such as voltage sags, may cause considerable economic losses because industrial processes rely on electronic power-control devices. Thus, the power supplied to utilities must be reliable and of good quality. Electrical PQ is defined as the degree in which electrical power deployment and delivery affect equipment functions [19]. Reliability denotes the capability of a system to perform its required functions under declared conditions in a specified period. Available reliability assessment indexes are categorized into three clusters, namely, load-related indexes, continued interruption indexes, and short-term indexes [11]. Load-related indexes, such as the average system interruption frequency index (ASIFI), and continued interruption indexes, such as the sustained average interruption frequency index (SAIFI), are the most common reliability assessment indexes in addressing voltage sag.

Voltage sags, which are normally caused by system faults that last over 0.01 s, may induce the breakdown of sensitive equipment and process downtime. A disrupted process may require several hours before resuming operations even though the power supply has been restored. Thus, the reliability level may be affected by voltage sag propagation in distribution systems. Voltage sag is defined as a reduction in root-mean-square (RMS) voltage magnitude between 0.1 and 0.9 pu at durations of 0.01 s to 60 s [10]. Chen et al. [3] used a series of strategies based on network reconfiguration (NR) to mitigate voltage sags and improve system reliability. Yun et al. [29] applied a feeder transfer scheme to alleviate voltage sag propagation in power distribution systems. GA was recently improved by using the edge-window-decoder encoding technique in NR to identify new network topologies with minimal power losses [26]. Jazebi et al. [14] the applied differential evolution algorithms for optimal NR and DSTATCOM allocations to mitigate power losses and improve voltage profiles in power distribution networks. They also indicated that PQ improvement, voltage stability, system loadability, and reconfiguration management stability should be considered in future. [22–24] adopted an integrated method by combining NR and DSTATCOM placement to mitigate the voltage sag problem. Jazebi and Vahidi [12] used the differential evolution algorithm to address the ability of NR to enhance PQ issues such as harmonics and voltage sags while mitigating power losses.

Studies have focused on system reliability assessment and improvement instead of PQ mitigation. Mohammadi and Akbari Nasab [19] developed a reliability enhancement algorithm by using a static series voltage regulator. Mohammadi and Akbari Nasab [19] considered the effects of distributed generation units, system...
reconfiguration, load shedding, and load addition were considered in the assessment of distribution system reliability. Skoonpong and Sirisumrannukul [25] considered the use of NR to minimize customer interruption costs and enhance the reliability of electric power supplies. The aforementioned studies recommended GA for optimal reconfiguration. Monte Carlo simulations and historical data were used for reliability assessment in a related research [27]. Zhang et al. [30] considered uncertainties in loads, power generation, and electrical and reliability parameters to improve system reliability and reduce losses. They used a neighborhood search algorithm to obtain the optimal solution. Kumar and Jayabarathi [15] used the bacterial foraging optimization algorithm in distribution NR to minimize system losses. Kavousi-Fard et al. [16] recently proposed an NR strategy to overcome the uncertainty problem in wind-turbine output power variations and forecasting errors with regard to system voltage profile, power loss, and total cost. They used self-adaptive modified teacher learning optimization (MTLO) to address the multi-objective optimization problem concurrently.

Niknam et al. [20] used MTLO and NR to obtain the optimal power loss, total cost, and total emission of a fuel cell power plant and extended the optimal NR concept in terms of reliability. Kavousi-Fard and Niknam [17] investigated the role of the NR problem as a reliability reinforcement strategy in reliability indexes such as SAIFI, average energy not supplied (AENS), and utility-oriented objective functions such as the MW power production cost and active power loss. To solve the uncertainty problem in wind turbines, they proposed an adaptive bat algorithm to explore the total search space globally. Their results showed that the adaptive bat algorithm is the most suitable algorithm for finding the optimal NR. A similar work can be found in the study of Kavousi-Fard and Akhbari-Zadeh [18], who applied an improved shuffled frog leaping algorithm to solve NR problems with the multi-objective function including SAIFI, AENS, system average interruption duration index, and power losses. However, all of these previous works do not consider voltage sag propagation and voltage-sag-related reliability indicators, such as the system average RMS variation frequency index (SARFI), for a costless NR solution to the reliability problem.

Load outages are often caused by voltage sag; thus, the reliability levels of the distribution systems are adversely affected by voltage sag propagation. In this paper, a method for reducing the number of voltage sags experienced at each load point in a distribution system is developed by using optimal NR. The quantum binary firefly algorithm (QBFA) is proposed in the current study to determine the optimal solutions [28]. The QBFA algorithm is validated by using proven heuristic computational optimization tools such as the standard binary firefly algorithm (BFA) and binary gravitational search algorithm (BGSA) [21]. After the effectiveness of QBFA for optimal NR and for minimizing voltage sags is verified, other reliability indexes, such as SAIFI, ASIFI, and MAIFI, are used as objective functions in optimal NR with QBFA. The effect of optimal NR on various objective functions is assessed by using the voltage sag index SARFI [2]. Reliability assessment is conducted by using SAIFI, ASIFI, and MAIFI.

2. PQ and reliability assessment indices

System PQ performance is often specified by using SARFI, which represents the average number of RMS variations over the assessment period per customer served. SARFI-90 calculates all voltage sags with remaining voltages of less than 90% regardless of sag duration. Therefore, the sum of the expected number of sags \( N_{\text{sag}} \) caused by every registered fault event can be used to obtain the SARFI of the entire system [2]. \( N_{\text{sag}} \) represents the number of customers affected by all possible fault events during the assessment period. The customers served in the assessment area are considered the customers supplied by all system buses \( N_{\text{bus}} \). SARFI can be defined as follows:

\[
\text{SARFI} = \frac{\text{number of sags (} N_{\text{sag}} \text{)}}{\text{total number of customers served (} NT \text{)}} \tag{1}
\]

The number of sags in SARFI can be transformed into continued interruptions, short-term interruptions, and load outages to access system reliability. The reliability assessment indexes of distribution systems can be grouped into three categories, namely, load-related indexes, continued interruption indexes, and short-term indexes [11]. ASIFI, MAIFI, and SAIFI can indicate load-related, continued interruption, and short-term indexes, respectively, in reliability assessment [11]. These indexes are defined in the following equations [11]:

\[
\text{ASIFI} = \frac{\text{sum of total connected kVA of load interrupted (} Li \text{)}}{\text{total connected kVA served (} LT \text{)}} \tag{2}
\]

\[
\text{MAIFI} = \frac{\text{sum of customer short-term interruptions}}{\text{total number of customers served (} NT \text{)}} \tag{3}
\]

\[
\text{SAIFI} = \frac{\text{sum of all customer continued interruptions due to each event}}{\text{total number of customers served (} NT \text{)}} \tag{4}
\]

ASIFI can be used to indicate the financial losses caused by load outages, whereas MAIFI can be used to represent customer disruption because of protection-device operations. SAIFI can be used to indicate sustained customer interruptions.

3. Materials and methods

This section describes the necessary components required to perform NR for the improvement of system PQ and reliability. These components include the system sag calculation, problem formulation for optimization, proposed optimization method, and procedure.

3.1. Determining the number of voltage sags and interruptions

Voltage sag propagation is dependent on the fault position in a system, and buses that are far from faults have low severity [9]. The sag-exposed area of each fault point can be identified by fault analysis. However, identifying the system component that causes considerable voltage sag propagation during a fault is important in PQ and reliability improvement and in the determination of fault occurrence probability. Line faults are frequent and are the main cause of voltage sags. Therefore, fault analysis can determine the system branches inducing great sag exposure. Possible fault components, such as bus and transformer faults, can also be investigated.

If the fault rate of a faulted line with length \( L \) is \( \lambda_{fL} \), the estimated number of line faults per year \( f_L \) can be defined as follows [1,9]:

\[
f_L = \sum_{k=1}^{4} \sum_{l=1}^{N_{L}} L_{k,l} \lambda_{fL} \tag{5}
\]

where \( k \) represents the three-phase, line-to-ground, line-to-line, and line-to-line-to-ground faults; \( N_{L} \) is the total number of lines in the system. The annual number of transformer faults \( f_p \) and bus faults \( f_b \) can be obtained via the fault rates. The total number of faults can then be obtained by using all of these faults [1,9]:

\[
f_{\text{fault}} = f_L + f_p + f_b \tag{6}
\]

\( N_{\text{sag}} \) and the total number of interruptions \( (N_{\text{int}}) \) can be determined by monitoring the individual bus voltage magnitude (\( V_i \)) in the
system and identifying the type and location of load bus \(i\). Annual \(N_{sag}\) can be obtained as follows [2,10]:

\[
N_{sag} = \sum_{i=1}^{N_{bus}} \sum_{j=1}^{N_{load}} 1 \text{ if } 0.1 \text{ p.u.} < V_i < 0.9 \text{ p.u}
\]  
(7)

The portion of \(N_{sag}\) corresponding to sensitive buses is equal to the total number of continued interruptions because most processes involving sensitive equipment experience long downtimes. The total number of interruptions per year for non-sensitive loads can be obtained as follows [2,10]:

\[
N_{int} = \sum_{i=1}^{N_{bus}} \sum_{j=1}^{N_{load}} 1 \text{ if } V_i \leq 0.1 \text{ p.u}
\]  
(8)

The interruptions highlighted in Eq. (8) can be divided further into continued interruptions if the non-sensitive load bus is the fault bus or if the non-sensitive load bus is located downstream from the fault because all of these buses are isolated when opening the circuit breaker to clear the fault. Otherwise, such interruptions can be registered as short term or momentary interruptions because the fault will be cleared by the protection system after service restoration. By using Eqs. (7) and (8), the above mentioned categories of interruptions can be used to calculate the PQ index SARFI per year and reliability indexes (e.g., ASIFI, MAIFI and SAIFI) per year caused by NR.

### 3.2. Distribution NR

NR alters the topological arrangement of distribution feeders by altering the open/closed status of tie and sectionalizing switches. A feeder may either be partially or fully fed by an alternate feeder by activating a tie switch that connects both feeders. The appropriate sectionalizing switch must be deactivated to preserve radial structures [4]. NR is commonly used to reduce system losses, balance loads, and enhance voltage fluctuation in power distribution networks. NR can also be used to alleviate voltage sag propagation in the system by escalating line impedance in the fault current during faults. Several system buses occasionally encounter voltage sag when the fault occurs at certain buses. Thus, system PQ and reliability may be affected by faults in the weak area. NR is mainly used to reduce \(N_{sag}\) and reliability indexes, such as ASIFI, MAIFI, and SAIFI, by distancing the weak area from the main power source. However, NR must be restrained to avoid increasing the total system line losses. A balance between the increase of line losses and the enhancement of system PQ reliability must be made. Therefore, optimization methods are necessary to determine a suitable configuration that can achieve both low voltage sag count and low or acceptable power loss.

### 3.3. Proposed QBFA for optimum NR

A binary version of the firefly algorithm (FA), that is, QBFA, is developed and used to optimize the NR problem. This technique avoids the drawbacks of conventional BFA.

FA is based on the social activities of fireflies. Standard FA considers two important parameters, namely, variation in light intensity \(I\) and the formulation of attractiveness \(\beta\). When \(\beta\) is proportionate to \(I\), \(\beta\) which varies with distance \(r\), can be expressed as follows [28]:

\[
\beta(r) = \beta_0 e^{-\gamma r^m}, (m \geq 1)
\]  
(9)

where \(\beta_0\) is the attractiveness at \(r = 0\), \(\gamma\) is the light absorption coefficient, and \(r\) is the distance between two fireflies.

The distance between any two fireflies, \(i\) and \(j\), at \(x_i\) and \(x_j\) can be expressed as the Cartesian distance \(r_{ij}\):

\[
r_{ij} = ||x_i - x_j|| = \sqrt{\sum_{k=1}^{d} (x_{ik} - x_{jk})^2}
\]  
(10)

where \(x_{ik}\) is the \(k\)-th component of the spatial coordinate \(x_i\) of the \(i\)-th firefly. A firefly \(i\) is attracted to a brighter firefly \(j\); this movement is expressed as follows:

\[
x_i = x_i + \beta_0 e^{-\gamma r_{ij}^m} (x_j - x_i) + \alpha (\text{rand} - \frac{1}{2})
\]  
(11)

\[
\alpha(t - 1) = \alpha(t) \times 0.99
\]  
(12)

where the second term represents the attraction, and the third term corresponds to the randomization of the randomization parameter. \(\alpha\) and \(\gamma\) are uniformly distributed random number generator random changes in value with each iteration.

The position of firefly \(i(x_i)\) changes from a binary number to a real number when firefly \(i\) becomes attracted to firefly \(j\) in discrete FA. Therefore, the sigmoid function \(S(x_i)\) shown in Eq. (13) limits the continuous output between zero and one. The value of \(S(x_i)\) determines the probability that the value of bit \(x_i\) is “1” as shown in Eq. (14).

\[
S(x_i) = \frac{1}{1 + \exp(-x_i)}
\]  
(13)
where $r$ is a uniform random variable between "0" and "1."”

The distance between fireflies may increase when the algorithm iterates further with Eq. (13). The probability that the value of $x_i$ is “0” or “1” is 0.5 regardless of the previous position $x_i$. This probability may worsen the convergence of the algorithm.

The use of quantum computing theory easily solves the BFA-related problem mentioned above. A quantum bit (Q-bit) is the smallest unit in quantum computing and can be either “1,” “0,” or in a linear superposition of the two [6]:

$$x_i = \begin{cases} 1, & \text{if } S(x_i) > r \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

![Fig. 2. Actual 47-bus test distribution system.](image)

<table>
<thead>
<tr>
<th>Bus no.</th>
<th>kV</th>
<th>Load P MW</th>
<th>Load Q Mvar</th>
<th>Load type</th>
<th>No. of customers</th>
<th>Bus no.</th>
<th>kV</th>
<th>Load P MW</th>
<th>Load Q Mvar</th>
<th>Load type</th>
<th>No. of customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>132</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>25</td>
<td>11</td>
<td>1.25</td>
<td>0.605</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>26</td>
<td>11</td>
<td>0.351</td>
<td>0.149</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>0.85</td>
<td>0.527</td>
<td>1</td>
<td>1</td>
<td>27</td>
<td>11</td>
<td>0.276</td>
<td>0.118</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>0.342</td>
<td>0.194</td>
<td>4</td>
<td>1</td>
<td>28</td>
<td>11</td>
<td>0.314</td>
<td>0.134</td>
<td>4</td>
<td>63</td>
</tr>
<tr>
<td>5</td>
<td>11</td>
<td>0.244</td>
<td>0.145</td>
<td>3</td>
<td>24</td>
<td>29</td>
<td>11</td>
<td>0.613</td>
<td>0.261</td>
<td>2</td>
<td>63</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>0.244</td>
<td>0.177</td>
<td>3</td>
<td>24</td>
<td>30</td>
<td>11</td>
<td>0.592</td>
<td>0.252</td>
<td>3</td>
<td>59</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>31</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>3.3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>32</td>
<td>11</td>
<td>6.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>3.3</td>
<td>1.275</td>
<td>0.513</td>
<td>1</td>
<td>1</td>
<td>33</td>
<td>11</td>
<td>0.032</td>
<td>0.024</td>
<td>6</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>0.433</td>
<td>1.594</td>
<td>0.641</td>
<td>1</td>
<td>1</td>
<td>34</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>11</td>
<td>0.146</td>
<td>0.098</td>
<td>3</td>
<td>14</td>
<td>35</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>11</td>
<td>0.294</td>
<td>0.143</td>
<td>3</td>
<td>29</td>
<td>36</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>11</td>
<td>0.488</td>
<td>0.341</td>
<td>2</td>
<td>4</td>
<td>37</td>
<td>11</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>14</td>
<td>11</td>
<td>0.437</td>
<td>0.199</td>
<td>2</td>
<td>4</td>
<td>38</td>
<td>11</td>
<td>7.65</td>
<td>4.741</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>15</td>
<td>11</td>
<td>1.776</td>
<td>1.006</td>
<td>2</td>
<td>8</td>
<td>39</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>11</td>
<td>0.297</td>
<td>0.098</td>
<td>3</td>
<td>30</td>
<td>40</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>41</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>18</td>
<td>11</td>
<td>0.616</td>
<td>0.43</td>
<td>3</td>
<td>61</td>
<td>42</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>19</td>
<td>11</td>
<td>0.388</td>
<td>0.23</td>
<td>3</td>
<td>39</td>
<td>43</td>
<td>11</td>
<td>33</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>20</td>
<td>11</td>
<td>0.732</td>
<td>0.354</td>
<td>1</td>
<td>1</td>
<td>44</td>
<td>11</td>
<td>12.75</td>
<td>7.902</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>21</td>
<td>3.3</td>
<td>1.063</td>
<td>0.427</td>
<td>1</td>
<td>1</td>
<td>45</td>
<td>11</td>
<td>12.75</td>
<td>7.902</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>22</td>
<td>11</td>
<td>0.525</td>
<td>0.549</td>
<td>2</td>
<td>5</td>
<td>46</td>
<td>11</td>
<td>6.8</td>
<td>4.214</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>23</td>
<td>11</td>
<td>0.582</td>
<td>0.345</td>
<td>2</td>
<td>3</td>
<td>47</td>
<td>11</td>
<td>4.8</td>
<td>3.6</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>24</td>
<td>11</td>
<td>0.504</td>
<td>0.23</td>
<td>4</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
\[
|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \tag{15}
\]
where \(\alpha\) and \(\beta\) are complex numbers that specify the probability amplitudes of the corresponding states. \(|\alpha|^2\) and \(|\beta|^2\) show the probability for a Q-bit to be in the “0” or “1” state, respectively. Therefore, the states can be normalized to unity as follows:

\[
|\alpha|^2 + |\beta|^2 = 1 \tag{16}
\]
The Q-bit state is updated by using a quantum gate and can be represented as a unitary operator \(U\). The types of quantum gates include NOT, controlled NOT, rotation, and Hadamard gates [7]. The rotation gate is used (Eq. (17)) in the current study because several heuristic search algorithms have applied this gate [6, 13, 5, 8].

\[
U(\Delta \theta_i) = \begin{bmatrix}
\cos(\Delta \theta_i) & -\sin(\Delta \theta_i) \\
\sin(\Delta \theta_i) & \cos(\Delta \theta_i)
\end{bmatrix} \tag{17}
\]

where \(\Delta \theta_i, i = 1, 2, 3, \ldots, n\) denotes the rotation angle of each Q-bit toward either the “0” or “1” state depending on the Q-bit sign.

This proposed rotation gate involves two techniques, namely, the coordinate rotation gate approach and the dynamic rotation angle approach; these methods are used to update Q-bits and determine the rotation angle magnitude, respectively. Therefore, pre-specified lookup tables are not required and the rotation angle can be formulated as follows:

\[
\Delta \theta_i = \theta \times (|\beta_i|^2 + |\alpha_i|^2 |\alpha_i - |\beta_i|^2) + \text{alpha rand} \left(\frac{1}{2} - \frac{1}{2} \right) \tag{18}
\]

where \(\theta\) is the rotation angle magnitude along the iteration and decreases monotonously from \(|\theta|_{\text{max}}\) to \(|\theta|_{\text{min}}\). The Q-bit individual string is then updated based on the rotation angle and rotation gate (Eq. (19)). Finally, the firefly’s position is updated based on the probability of \(|\beta|^2\) by using Eq. (20).

\[
\begin{bmatrix}
\alpha_i(t + 1) \\
\beta_i(t + 1)
\end{bmatrix} = U(\Delta \theta_i) \times \begin{bmatrix}
\alpha_i(t) \\
\beta_i(t)
\end{bmatrix} \tag{19}
\]

\[
x_i = \begin{cases}
1, & \text{if } |\beta_i(t + 1)|^2 > r \\
0, & \text{otherwise}
\end{cases} \tag{20}
\]

### 3.4. Objective functions and constraints

The purpose of the optimization is to determine a suitable NR that can reduce \(N_{\text{ag}}\) and reliability indexes and improve system
PQ and reliability without increasing the total line losses. Objective functions can be formulated to minimize the following: (i) $N_{\text{sag}}$ (Eq. (21)), (ii) $N_{\text{sag}}$ and total power loss ($P_{\text{loss}}$) (Eq. (22)), (iii) ASIFI (Eq. (23)), (iv) MAIFI (Eq. (24)), and (v) SAIFI (Eq. (25)) via optimization. These objective functions are expressed as follows:

$$\text{Fitness} = \min(N_{\text{sag}})$$  \hfill (21)

$$\text{Fitness} = \min\left(\frac{N_{\text{sag}}}{N_{\text{sag,max}}} + \frac{P_{\text{loss}}}{P_{\text{loss,max}}}ight)$$  \hfill (22)

$$\text{Fitness} = \min(\text{ASIFI})$$  \hfill (23)

$$\text{Fitness} = \min(\text{MAIFI})$$  \hfill (24)

$$\text{Fitness} = \min(\text{SAIFI})$$  \hfill (25)

where $N_{\text{sag,max}}$ and $P_{\text{loss,max}}$ in Eq. (22) are the maximum number of sags and maximum power loss in the system, respectively. $N_{\text{sag,max}}$ and $P_{\text{loss,max}}$ are used to normalize individual objectives in the function.

In evaluating all the above objective functions, the optimization solution is subjected to the operation constraints of the distribution system; that is, the network structure must be radial, the nominal bus voltages must remain within standard limits, all of the network nodes and loads must be connected, and the power flows must be within the thermal limits of the lines. $P_{\text{loss}}$ must also be within acceptable limits in all cases except in Eq. (22).

### 3.5. QBFA implementation for optimal NR

On the basis of the objective functions and constraints indicated in Section 3.4, reconfiguration can be performed by changing the predefined status of the tie and sectionalizing switches in the distribution network. $N_{\text{sag}}$, SARFI, ASIFI, MAIFI, SAIFI, and $P_{\text{loss}}$ are calculated by using the short circuit analysis and steady state load flow algorithm in Matlab environment for every modification in network configuration.

An encoding and decoding technique presented by Salman et al. [23] is used to avoid generating unfeasible solutions as a result of system constraints on the initial random population during optimization. Only feasible configurations are generated by radial structures in the encoding technique. The main binary string is deconstructed into the original substrings in the decoding technique, and the binary number of each substring is changed to a decimal number that represents the open switch location in the corresponding loop [23]. Additional details regarding the encoding and decoding process are provided in the study of Salman et al. [23]. The implementation of the overall optimum NR algorithm is detailed in the flowchart shown in Fig. 1.

### Table 5

<table>
<thead>
<tr>
<th>System status</th>
<th>Due to weak area fault</th>
<th>System losses</th>
<th>System sag index</th>
<th>System reliability indices</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Healthy buses $V &lt; 0.9$ pu</td>
<td>Sag exposed area %</td>
<td>$N_{\text{sag}}$</td>
<td>SARFI</td>
</tr>
<tr>
<td>Without NR</td>
<td>19</td>
<td>61.70</td>
<td>2.09</td>
<td>11577</td>
</tr>
<tr>
<td>After Optimal NR</td>
<td>42</td>
<td>10.77</td>
<td>2.33</td>
<td>4752</td>
</tr>
<tr>
<td>Overall performance</td>
<td>Improved 121.1%</td>
<td>Reduced 82.5%</td>
<td>Raised 11.5%</td>
<td>Reduced</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>134.8%</td>
</tr>
</tbody>
</table>

Fig. 5. Performance of QBFA, BGSA, and BFA in obtaining an optimal NR solution and minimizing $N_{\text{sag}}$ in a 47-bus system.

Fig. 6. QBFA, BGSA, and BFA convergence characteristics for minimizing $N_{\text{sag}}$ in a 47-bus system.
4. Results and discussions

A practical 47-bus distribution network is shown in Fig. 2 and is used to validate the proposed technique. The system consists of 47 buses and 42 branches supplied by a 132 kV transmission system. Four major substations are connected at Buses 2, 17, 34, and 39. Substation Buses 2 and 17 are fed by 132/11 kV and 30 MVA transformers, whereas Substation Buses 34 and 39 are fed by 132/33 kV and 45 MVA transformers. Bus 1 is the swing bus. The seven tie switches between Buses 25 and 38, 29 and 38, 24 and 29, 16 and 18, 4 and 19, 20 and 23, and 4 and 14 may be used to change the system topology in case of unexpected events or contingencies. The details of the system bus are given in Table 1.

The fault distributions and fault rates of the system elements are obtained from Zhang [31] and Aung et al. [1]. These data are listed in Tables 2 and 3.

All loads and voltages are assumed to be balanced in the optimal NR simulations. Faults do not occur in the main substations, and each load point is considered a group of customers in the reliability evaluation. All industrial loads are sensitive to the voltage sag problem in the reliability evaluation.

4.1. Base case test results

Base case analyses, such as load flow and fault analyses, are conducted to assess the performance of the 47-bus distribution system prior to the optimum NR. Fault analysis simulations are conducted on all buses, except for major substations. $P_{\text{loss}}$, $N_{\text{sag}}$, SARFI, SAIFI, ASIFI, and MAIFI are 2.09, 11577, 2.97, 18.88, 55.07, and 4.33, respectively (Table 5).

All four types of fault simulations are conducted on all buses with voltage levels below 33 kV, except for the main substations and buses supplied by more than one feeder, to determine the weak area or the bus that causes sag propagation in the system. The voltage levels at all system buses given by the LLL fault with zero fault resistance are shown in Fig. 3. Sensitive buses (weak areas) that may affect PQ and reliability can be determined by observing the dark points and the color bar representing the voltage magnitude. Buses 19, 20, 22, 23, and 24 are the most sensitive to voltage sag propagation throughout the system, and Bus 22 influences most system buses. Fig. 4 shows the system voltage profile during normal condition and the LLL fault at Bus 22.

4.2. NR optimization results

Optimal NR is conducted to improve PQ and reliability by using the new QBFA. QBFA is validated by standard BFA and BGSA, which is another commonly used algorithm. All optimization parameters are standardized (Table 4) to compare the algorithms fairly. The table below displays the necessary parameter settings for all optimization techniques used in this study.

4.2.1. Analysis with $N_{\text{sag}}$ as the objective function

Three optimization algorithms, namely, QBFA, BGSA, and standard BFA, are used to formulate a unique optimal NR solution. These algorithms possess different searching patterns and convergence characteristics. Optimum NR with QBFA, BGSA, and BFA is repeated 30 times by using Eq. (21) to determine the effectiveness of the proposed QBFA. The capabilities of QBFA, BGSA, and standard BFA to generate an optimal NR solution for the 47-bus system after 30 iterations are shown in Fig. 5. QBFA, BGSA, and standard BFA are compared in terms of convergence rate (the number of iterations required to converge), quality of the optimal solution (fitness value), and the time consumed by optimization. The box plot corresponding to the fitness values shows that QBFA performs better than other algorithms because the 25th and 75th percentiles of the QBFA samples lean toward the minimum solution with a narrow interquartile range. The mean and median values of the QBFA are ideal, as indicated by the red line in Fig. 5, thus indicating that the probability of obtaining the ideal solution is high in QBFA.

Table 6

Open switches attributed to different optimal NRs with various objective functions.

<table>
<thead>
<tr>
<th>System status</th>
<th>Open switches</th>
</tr>
</thead>
<tbody>
<tr>
<td>After NR with objective function $N_{\text{sag}}$</td>
<td>2–18, 3–4, 15–16, 17–26, 17–33, 18–19, 20–23, 22–23, 24–29</td>
</tr>
<tr>
<td>After NR with objective function $N_{\text{sag}} + P_{\text{loss}}$</td>
<td>2–18, 3–4, 16–18, 17–26, 17–33, 18–19, 20–23, 24–25, 24–29</td>
</tr>
<tr>
<td>After NR with objective function MAIFI</td>
<td>2–18, 3–4, 15–16, 17–26, 17–33, 18–19, 20–23, 22–24, 24–29</td>
</tr>
<tr>
<td>After NR with objective function SAIFI</td>
<td>2–18, 3–4, 15–16, 17–33, 18–19, 20–23, 24–25, 24–29, 28–29</td>
</tr>
</tbody>
</table>

Fig. 7. Voltage sag distribution of system buses attributed to the LLL fault in all fault locations after optimal NR by QBFA when $N_{\text{sag}}$ is the objective function.
compared with other algorithms. QBFA evidently outperforms standard BFA in terms of computation time, with outliers close to the interquartile range. QBFA is also consistent in terms of convergence rate, with whiskers close to the interquartile range. The whiskers of the other algorithms extend to the maximum generation criterion of 30 sets in the simulation.

The best convergence characteristics in the three optimization algorithms are depicted in Fig. 6. QBFA converges quickly with

Fig. 8. Performance indicators of optimal NRs given various objective functions: (a) healthy buses, (b) $N_{	ext{sag}}$, (c) sag-exposed areas, (d) $P_{	ext{loss}}$, (e) ASIFI, (f) MAIFI, (g) SARFI, (h) SAIFI.
minimum fitness value. BGSA and BFA are slightly slower than QBFA in finding the optimal solution.

The best $N_{sa}$ minimization results obtained by using the three simulated optimization methods are summarized in Table 5. System PQ and reliability can be improved by applying any of the optimization methods proposed in this study because each algorithm generates similar ideal solutions after several simulation iterations (30 iterations in this study). However, QBFA generates the ideal fitness value 70% of the time, whereas BGSA and BFA only generates the ideal fitness value 30% of the time in 30 runs. System PQ and reliability are enhanced without NR by reducing $N_{sa}$ to 143.6%, whereas SARFI is improved by 143.4% without NR. Network reliability is also optimized when SAIFI, ASIFI, and MAIFI are reduced to 8.19%, 134.80%, and 86.60%, respectively. System losses increase by only 11.50% with the increase in PQ and reliability. The outage of heavy loads as a result of poor system PQ and reliability may induce considerable financial losses compared with the slight increment in line losses.

QBFA efficiently generates the optimal NR solution based on the results. PQ and system reliability are considerably improved despite the slight increase in system loss caused by NR. Fig. 7 shows the voltage distribution of all system buses attributed to the LLL fault in various fault locations after optimal NR by QBFA when $N_{sa}$ is the objective function. The voltage sag performances of most system buses are significantly improved compared with the base case in Fig. 3, as shown in the dark points and the color bar representing the voltage magnitude. Table 6 depicts various reconfigured systems represented by sets of open switches located between two nodes. Considering the effectiveness of QBFA, only this algorithm is used to evaluate the performance of the reconfigured network with the objective functions.

4.2.2. Analysis with the other objective function

The QBFA procedure shown in Fig. 1 is executed 30 times for each of the objective functions provided in Eqs. (22)–(25) to evaluate the optimal NR performance. The best results are summarized in Fig. 8. $N_{sa}$ is the most appropriate objective function for PQ (Fig. 8). However, the multi-objective function in Eq. (22), which includes $N_{sa}$ and $P_{loss}$ is ideal if PQ, power loss, and reliability are equally important. The use of the multi-objective function (Eq. (22)) in NR can reasonably increase the number of healthy buses to 40, decrease $N_{sa}$ to 4906, and reduce the number of sag-exposed areas, ASIFI, MAIFI, SARFI, and SAIFI to 14.89%, 33.73%, 1.89%, 1.26%, and 17.21%, respectively. The power losses incurred at 2.25 MW are higher than the base case load at 2.09 MW; however, the loss incurred by the multi-objective function is less than the 2.33 MW lost when $N_{sa}$ is the objective function. SAIFI is unsuitable for PQ improvement compared with the performances of other objective functions. Fig. 8 shows that most PQ indicators, such as $N_{sa}$, exposed sag areas, ASIFI, and SARFI, are high when SAIFI is the objective function compared with other objective functions. Table 6 shows the open switches attributed to different optimal NRs of the 47-bus system when various objective functions are considered.

5. Conclusion

A novel optimal NR method with various objective functions is presented in this study to enhance the PQ and reliability of electric power distribution systems. FA is greatly improved by quantum theory integration and is used as an optimization tool during NR. The results obtained by using the proposed method are compared with other well-known optimization algorithms for validation. The proposed QBFA is more effective than BGSA and standard BFA. $N_{sa}$ is the most suitable objective function for PQ. However, the multi-objective function, including $N_{sa}$ and $P_{loss}$, is more appropriate than other objective functions if both PQ and reliability are equally important. System PQ index, SARFI, and reliability indexes (e.g., SAIFI, ASIFI, and MAIFI) can be significantly reduced by applying the proposed method with the objective functions and QBFA.

Acknowledgements

The authors are grateful to Universiti Kebangsaan Malaysia (UKM) for supporting this study under Grants DIP-2013-30 and ETP-2013-044.

References


