Solving Reactive Power Control Problems in a Stressed Power System Network Using Evolutionary Computation Technique

N. R. H. ABDULLAH*, 1 I. MUSIRIN*, 2 M. M. OTHMAN*, 4 T. K. A. RAHMAN*

*Faculty of Electrical and Electronics Engineering, Universiti Malaysia Pahang (UMP), Pahang, MALAYSIA
1Centre of Electrical Power Engineering Studies (CEPES), Faculty of Electrical Engineering Universiti Teknologi MARA, 40450 Shah Alam, Selangor, MALAYSIA

Abstract: - Lack in reactive power support in a power system network has led to low voltage level at a load bus. This can also occur in a stressed power system network despite no contingency is subjected to the system. Therefore, reactive power support must be properly established in the system in order to secure the system from possible voltage collapse occurrence. This paper presents Evolutionary Computing technique for solving reactive power control (RPC) problem in the attempt to enhance voltage stability, while minimizing transmission loss and maintaining voltage level at an acceptable level. In this study, evolutionary programming (EP) was chosen as the Evolutionary Computing (EC) technique for solving the RPC; taking into consideration two separate objective functions. Static voltage stability enhancement and minimization of real power loss are implemented separately on a reliability test system. Comparative studies performed with respect to Artificial Immune System (AIS) have highlighted that EP outperformed AIS for both objective functions.


1 Introduction
Voltage instability has been recognized as reactive power problem mainly due to inadequacy of reactive power support at some critical buses in power system. Over the past decade, until now utility companies have confronted a serious problem in maintaining their network which has led to major concerns in power system operation and planning studies. The role of reactive power in power system is to maintain the voltage profile while the active power delivered through transmission lines. The shortage of reactive power can cause the generator and transmission line failure, leading to blackout or collapse in a system [1]. Therefore in order to resolve the reactive power problem, synchronous generators, STATCOM, SVC and various types of other reactive power controller devices are injected into the system [2]. By adjusting these reactive power controllers the output voltage have been improved; thus the power system become stable. The objective of the reactive power control (RPC) optimization problem is to minimize the active power loss in the transmission line; as well as to improve the voltage stability and profile of the system. There are various methods to determine the voltage stability in the system as reported in [3]. It proposed the static voltage stability index of the load bus as one of the possible methods. This index gives a scalar number to each load bus and it is in the range of zero to one for voltage stable and voltage collapse detection.

There have been a number of methods available in recent years for optimization in transmission and distributions system, namely the conventional [4, 5] or artificial intelligence (AI) based technique. The conventional optimization methods that have been developed are such as Tabu search (TS), Gradient, and Linear programming (LP), Non-linear programming (NL), Quadratic programming (QP), and Interior point methods. However, the conventional methods have experienced a difficulty due to insecure convergence, sensitive to initial search point and algorithmic complexity [20]. Hence, the artificial intelligence methods such as Simulated Annealing (SA), Genetic Algorithm (GA), Evolutionary Programming (EP), Evolutionary Strategy (ES), Genetic Programming (GP) and Artificial Immune System (AIS) are employed to overcome the problems confronted by these conventional methods [5-7, 14]
The EP method had been thoroughly discussed since its introduction by Fogel in 1960 [7]. The EP method has been successfully applied to various areas of power system to solve the optimization problem related to unit commitment [9], optimal reactive power dispatch [10], reactive power planning [11], and optimal power flow problems [13]. Ma and Lai [6] proposed EP method for solving the reactive power planning compared with the conventional optimization technique. The methods obtained a good result for global optimization especially in non-continuous and non-smooth situations. In [7] and [10]; GA has been used for other power system problems and shows stability, flexible and a better potential of applications of the methods to power system economical operations.

This paper presents the application of EP as an EC based optimization technique for implementing RPC in power system. This technique determines the amount of reactive power to be compensated to the system in enhancing the voltage stability or minimizing real power transmission loss in the system. Comparative studies with respect to AIS has highlighted that EP outperformed AIS for both objective functions.

2 Problem Formulation

In this study, two objective functions are separately implemented namely the SVSI minimization and real power loss minimization. SVSI minimization implies the improvement of voltage stability improvement.

2.1 Minimization of SVSI

In this study, line voltage stability index derived by Li Qi [3] termed as Static Voltage Stability Index (SVSI) was used as the indicator to voltage stability. The mathematical equation for SVSI was formulated from a two-bus power system model as shown in Figure 1; with an impedance of

\[ Z_{ji} = R_{ji} + jX_{ji} \] to bus \( j \).

![Diagram](image_url)

Fig. 1. 2-Bus power system model

The mathematical equation can be written as follows:

\[
SVSI_{ji} = \frac{2\sqrt{(X_{ji}^2 + R_{ji}^2)(P_{ji}^2 + Q_{ji}^2)}}{|V_j|^2 - 2X_{ji} Q_{ji} - 2R_{ji} P_{ji}}
\] (1)

where \( R_{ji} \) and \( X_{ji} \) denotes the line resistance and reactance, \( P_{ji} \) is the real power at the receiving end, \( Q_{ji} \) is the reactive power at the receiving end and \( V_i \) is the sending end voltage. SVSI has to be between 0 and 1 to maintain stability in power system. It will be minimized to imply voltage stability improvement.

2.2 Minimization of Power Loss

The second objective function employed in this study is the minimization of real power loss in the system. The objective function is mathematically stated as follows [15];

\[
\min(f_p),
\]

where

\[
f_p = \sum_{k \in N_e} O_{k,\text{loss}}(V, \theta) = \sum_{k \in N_e \atop k=(i,j)} g_k(V_i^2 + V_j^2 - 2V_i V_j \cos \theta_j)
\] (2)

Subject to the constraint of equality in reactive power balance

\[
Q_j - Q_{Gi} + Q_{Di} = 0
\]

\[
Q_j = Q_{Gi} - Q_{Di} - V_i \sum_{j \in N_i} (G_{ij} \sin \theta_j - B_{ij} \cos \theta_j) = 0
\] (3)

and the inequality constraints for voltage and reactive power capability limits for the generator are:

\[
V_{imin} \leq V_i \leq V_{imax} \quad i \in N_b
\]

\[
Q_{Gimin} \leq Q_{Gi} \leq Q_{Gimax} \quad i \in \{N_{PV}, n_s \}
\] (4)

where, \( n_s \) is the slack (reference) bus number; \( N_{PV} \) is number of PQ bus, \( N_{PV} \) is number of PV bus, \( N_b \) is total number of buses, \( \theta_j \) is difference in voltage angle between bus \( i \) and bus \( j \) (in rad), \( Q_i \) and \( Q_j \) are the reactive power on the sending and receiving buses; \( Q_{Gi} \) is the generated reactive power, \( V_i \) and \( V_j \) are the voltage magnitude at the sending and receiving buses and \( P_{K,\text{loss}} \) is the total active power loss in the system. Equation (2) can be simplified to a generalised objective function as:

\[
f_p = \sum_{k \in N_e} P_{k,\text{loss}}(V, \theta) + \sum_{k \in N_{PV}} \lambda_{V_k} (V_i - V_{lim})^2
\]

\[
+ \sum_{k \in N_{PV}} \lambda_{Q_k} (Q_{Gi} - Q_{lim})^2
\] (5)
\[ Q_{ij} - Q_{Bj} - \sum_{k \in N_k} V_k \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right) = 0 \]  
where \( \lambda_{ij} \) and \( \lambda_{Bj} \) indicate the penalty factor which can increase the optimisation procedure, \( N_{ij} \) is the number of \( PQ \) bus at which the voltage violates the limits and \( N_{Qg} \) denotes the number of buses at which the reactive power generation violates the limits.

\[ V_{i}^\text{max} = \begin{cases} V_{i}^\text{min} & \text{if } V_{i} < V_{i}^\text{min} \\ V_{i}^\text{max} & \text{if } V_{i} < V_{i}^\text{max} \end{cases} \]
\[ Q_{g_{ij}}^\text{max} = \begin{cases} Q_{g_{ij}}^\text{min} & \text{if } Q_{g_{ij}} < Q_{g_{ij}}^\text{min} \\ Q_{g_{ij}}^\text{max} & \text{if } Q_{g_{ij}} < Q_{g_{ij}}^\text{max} \end{cases} \]

3 Evolutionary Programming

In this study EP is used as the main optimization technique to solve the RPC problem; which involves initialization, fitness computation, mutation, combination, tournament selection and transcription of next generation.

3.1 Initialization

Initial populations \( x_i \) are randomly generated parent; selected randomly within their feasible range as denoted below:

\[ x_{in} = \{ Q_{g_{ij}}, Q_{g_{ij}}, Q_{g_{ij}}, Q_{g_{ij}} \} \]

3.2 Mutation

It is a process to breed population termed as offsprings. It uses the Gaussian mutation operator to the selected individual (parents), \( x_{ij} \) randomly by using a standard deviation, \( \sigma \) defined as the square root of the variance. Each element of the offspring individual is calculated based on to the following equation:

\[ x_{ij} = x_{ij} + N \left( 0, \beta \left( x_{ij}^\text{max} - x_{ij}^\text{min} \right) \left( \frac{f_i}{f_{\text{max}}} \right) \right) \]

\( \beta \) is a search scale which determines the speed of convergence. Lower \( \beta \) value implies fast search space and vice versa.

3.3 Tournament Selection

EP employs a tournament selection scheme as to choose the survivals for the next generation. The populations of individuals with better fitness values were sorted in ascending order; then the first half or the population would be retained as the new individuals.
3.4 Convergence criterion
The optimal solution is achieved when there is no significant change between the new generation and the last generation. The mathematical equation is given by:

\[ \text{fitness}_{\text{max}} - \text{fitness}_{\text{min}} \leq 0.0001 \]  \hspace{1cm} (10)

4 Methodology
The proposed EP algorithm for the study is shown in the form of flowchart appeared in Figure 2. In this case, five variables i.e. \( x_1, x_2, x_3, x_4 \) and \( x_5 \) were generated to represent the reactive power to be controlled at generators 2, 5, 8, 11 and 13 during the initialization process with the objective; either to minimize SVSI or total losses with load subjected to the system. The constraints are (i) \( \text{SVSI} \leq \text{SVSI}_{\text{set}} \), (ii) \( \text{loss} \leq \text{loss}_{\text{set}} \) and (iii) \( V_{\text{bus}} \leq V_{\text{set}} \).

5 Result and Discussion
Tests were conducted on the IEEE 30-Bus RTS. It has 5 voltage control buses, 24 load buses, 1 slack bus, 41 interconnected lines and 4 transformer tap changers. The base power is 100MVA.

5.1 SVSI Minimization
Test was initially conducted to identify the maximum loadability [19] for few load buses utilizing SVSI; namely buses 14, 26 and 30. The loading factor is gradually increased until the system reaches its instability point, where the maximum reactive power loading for the selected buses are identified. The maximum loadability for these buses are shown in Table 1, recorded at the highest possible computable SVSI value prior to the divergence of load flow.

<table>
<thead>
<tr>
<th>Bus No</th>
<th>( Q_{\text{max}} ) (MVAr)</th>
<th>Voltage (V)</th>
<th>SVSI (p.u)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>70</td>
<td>0.8336</td>
<td>0.3585</td>
</tr>
<tr>
<td>26</td>
<td>32</td>
<td>0.6358</td>
<td>0.6431</td>
</tr>
<tr>
<td>29</td>
<td>38</td>
<td>0.7389</td>
<td>0.4678</td>
</tr>
</tbody>
</table>

From the table, it is apparently observed that bus 26 is the weakest among the others; while the most secure bus among them is bus 14.

Fig. 3 and Fig. 4 illustrate the effect of loading factor \( \lambda \) increment to voltage and SVSI for load subjected to buses 14 and 26; considering pre- and post-RPC optimization. The voltage profile reduces accordingly as the \( \lambda \) increases in both cases. SVSI profile also increases with the load factor increment; implying that the system is going towards instability point. On the other hand, with the implementation of RPC optimization, the voltage profiles for both buses are higher indicating voltage have been increased. The SVSI profiles are lower with the RPC implementation indicating voltage stability improvement.

5.2 Real Power Loss Minimization
The performances of the optimization technique for loss minimization are plotted at Fig. 5 and Fig. 6. Similar process was conducted considering loss as the fitness; except that there are two constraints assigned for the RPC optimization. The constraints were total loss less than the \( \text{loss}_{\text{set}} \) and voltage at the loaded bus higher than \( V_{\text{set}} \). The \( \text{loss}_{\text{set}} \) is total loss in the system for pre-EP, while \( V_{\text{set}} \) is the voltage at the loaded bus before the optimisation. At bus 14, for \( \lambda = 1.0 \) p.u to 7.2 p.u, the percentage of power loss was gradually reduced from 75% to 60% with the implementation of optimal RPC in the system. Similarly, bus 26 shows a similar pattern for a \( \lambda \) interval set to 1.0 up to 3.2. In addition, the SVSI values for both cases were reduced and voltage profile was improved at each \( \lambda \).
5.3 Comparative Studies with AIS

A comparative study has been performed to the system by implementing similar scheme using AIS. The comparisons are made in terms of SVSI minimization, total loss minimization and voltage profile improvement. For the purpose of appearance, only the results for bus 14 are shown due to limited space.

The results for comparative studies when load was subjected to bus 14 are shown in Fig. 7. From the figure, it is observed that when EP was used to optimise the RPC, it gives better results as compared to AIS in terms of SVSI and total losses. For instance, at $\lambda = 6.5$ p.u., EP method managed to reduce the SVSI value from 0.3251 to 0.2913, while AIS only managed to reduce SVSI value to 0.3068. It has also decreased the total loss in the system from 24.71 MW to 10.63 MW for EP, while it is 10.97 MW using AIS as shown in Fig. 8.

As for the voltage profile, the results are shown in Fig. 9. This figure indicates the performance of voltage profile using EP and AIS. From the figure, when EP was used to optimise the RPC, it gives better results as compared to AIS.

At loading factor, $\lambda = 2.0$ p.u the voltage profile obtained using AIS started to drop slowly until the loading factor reaches $\lambda = 6.0$ p.u. The major difference can be seen at loading factor, $\lambda = 5.0$ p.u., EP method has improved the voltage profile from 0.9049 p.u to 0.9410 p.u but the condition is worst after the implementation of AIS since the voltage
profile has dropped to 0.8454 p.u. Therefore it can be assumed that the implemented of AIS is limited only for the weak bus and not practical to optimize the RPC for secure bus because of its failure to improve the performance at this bus.

The results for comparative studies performed using EP and AIS for minimizing the transmission loss are shown in Fig. 9. It reveals that EP outperformed AIS indicated by lower losses at most loading conditions. For loading condition subjected to bus 14; at loading factor of 1.0 p.u until 7.2 p.u, the percentage of total losses for both optimization techniques was gradually reduced from 75% to 60%.

6 Conclusion
This paper has presented application of evolutionary computing technique in solving reactive power control problems. In this study, EP and AIS methods are applied at weak and secure bus for the minimization of static voltage stability index and real power loss. Maximum loadibility study was initially conducted to determine the condition of the load bus in the system. Simulation is carried out on the IEEE 30-bus RTS system. Both EP and AIS performed well in most cases. Nonetheless, EP outperformed AIS for both studies at the selected test buses. For future work, rescheduling of reactive and real power can be incorporated together to achieve similar task.

References:


