Optimal Reactive Power Planning for Loss Reduction and Improvement of Voltage Profile Using Cuckoo Search Algorithm

K.R.VADIVELU and Dr.G.V. MARUTHESWAR

Abstract - This paper proposes an application of Fast Voltage Stability Index (FVSI) to Reactive Power Planning (RPP) using Cuckoo Search Algorithm (CSA). FVSI is used to identify the weak buses for the Reactive Power Planning problem which involves process of experimental by voltage stability analysis based on the load variation. The point at which Fast Voltage Stability Index close to unity indicates the maximum possible connected load and the bus with minimum connected load is identified as the weakest bus at the point of bifurcation. The proposed approach has been used in the IEEE 30-bus system. Results show considerable reduction in system losses and improvement of voltage stability with the use of Fast Voltage Stability Index for the Reactive Power Planning problem.

Keywords - Power systems, Reactive Power Planning, Fast Voltage Stability Index, Differential Evolution.

I. INTRODUCTION

The Reactive Power Planning (RPP) is one of the most complex problems of power systems as it requires the simultaneous minimization of two objective functions. The first objective deals with the minimization of operation cost by reducing real power loss and improving the voltage profile. The second objective minimizes the allocation cost of additional reactive power sources. RPP is a nonlinear optimization problem for a large scale system with lot of uncertainties. During the last decades, there has been a growing concern in the RPP problems for the security and economy of power systems [1-7]. Conventional calculus based optimization algorithms have been used in RPP for years [1-4]. Conventional optimization methods are based on successive linearization and use the first and second differentiations of objective function. Since the formulae of RPP problem are hyper quadric functions, linear and quadratic treatments induce lots of local minima. Over the last decade, new methods based on artificial intelligence have been used for RPP which selects the weak buses randomly or heuristically [5-7]. This paper proposes an application of FVSI to identify the weak buses for the RPP problem using soft computing technique based Differential Evolution (DE) [15]. DE is a mathematical global optimization method for solving multidimensional functions. The main idea of DE is to generate trial parameter vectors using vector differences or perturbing the vector population [8, 10, 11, 17]. DE uses population of solutions, which can move over hills and across valleys to discover a globally optimal point. Since, DE uses the fitness function information directly, not derivatives, therefore can deal with non-differentiable functions. RPP is one of such problems. DE uses probabilistic transition rules to select generations, not deterministic rules, so it can search a complicated and uncertain area to find the global optimum which makes DE, a more flexible and robust than the methods. The slow variation in reactive power loading towards its maximum point causes the traditional load flow solution to reach its non-convergence point. Beyond this point, the ordinary load flow solution does not converge, which in turn forces the system to reach the voltage stability limit prior to bifurcation in the system. The margin measured from the base case solution to the maximum convergence point in the load flow computation determines the maximum load ability at a particular bus in the system. Solvability of load flow can be achieved before a power system network reaches its bifurcation point [13, 15]. In this paper, maximum load ability is estimated through voltage stability analysis. Voltage stability analysis is conducted using the stability index, FVSI [9, 15, 16]. The reactive power at a particular bus is increased until it reaches the instability point at bifurcation. At the instability point, the connected load at the particular bus is determined as the load ability maximum. The maximum load ability for each load bus will be sorted in ascending order with the smallest value being ranked highest. The highest rank

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imply the weak bus in the system that has the lowest sustainable load. The proposed approach has been used in the RPP problems for the IEEE 30-bus system [3] which consists of six generator buses, 21 load buses and 41 branches of which four branches, (6-9), (6-10), (4-12) and (27-28) are under load tap-setting transformer branches. The reactive power source installation buses are 30, 26, 29 and 25 which are identified based on the FVSI technique. There are totally 14 control variables.

II. PROBLEM FORMULATION

List of Symbols

- \( N_l \): set of numbers of load level durations
- \( N_i \): set of branch numbers
- \( N_p \): set of numbers of possible VAR source installment bus
- \( N_{pq} \): set of PQ - bus numbers
- \( N_g \): set of generator bus numbers
- \( N_t \): set of numbers of tap - setting transformer branches
- \( N_{B} \): set of numbers of total buses
- \( h \): per - unit energy cost
- \( d_l \): duration of load level 1
- \( g_k \): conductance of branch k
- \( V_i \): voltage magnitude at bus i
- \( \theta_{ij} \): voltage angle difference between bus i and bus j
- \( c_i \): fixed VAR source installment cost at bus i
- \( C_{i} \): per unit VAR source purchase cost at bus i
- \( Q_{i} \): VAR source installed at bus i
- \( G_{ij} \): mutual conductance between bus i and bus j
- \( B_{ij} \): mutual susceptance between bus i and bus j
- \( G_{ii}, B_{ii} \): self-conductance and susceptance of bus i
- \( Q_{g} \): reactive power generation at bus i
- \( T_k \): tap setting of transformer branch k
- \( N_{V_{lim}} \): set of numbers of buses in which voltage over limits
- \( N_{Q_{glim}} \): set of numbers of buses in which VAR over limits

III. GENERATION OVERLIMTS

The objective function in RPP problem comprises two terms [6]. The first term represents the total cost of energy loss as follows:

\[
W_c = h \sum_{i \in N_l} d_l \cdot P_{loss, i}
\]  

(1)

Where, \( P_{loss, i} \) is the network real power loss during the period of load level 1. The \( P_{loss, i} \) can be expressed in the following equation in the duration \( d_l \):

\[
P_{loss} = \sum_{k \in N_E} g_k \left( V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij} \right) \]

\((2)\)

The second term represents the cost of VAR source installments which has two components, namely, fixed installment cost and purchase cost:

\[
I_c = \sum_{i \in N_C} (c_i + C_{ci} |Q_{ci}|) \tag{3}
\]

The objective function, therefore, can be expressed as follows:

\[
M_{inf} f_c = C + W_C.
\]

Subjected to

\[
0 = P_l - V_i \sum_{j \in N_{PQ} \setminus \{i\}} \left( G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij} \right)
\]

\((4)\)

\[
0 = Q_l - V_i \sum_{j \in N_{PQ} \setminus \{i\}} \left( G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij} \right)
\]

Where, reactive power flow equations are used as equality constraints; VAR source installment restrictions, reactive power generation restrictions, transformer tap-setting restrictions and bus voltage restrictions are used as inequality constraints. \( Q_{g \min} \) can be less than zero and if \( Q_{g} \) is selected as a negative value, say in the light load period, variable inductive reactance should be installed at bus i. The transformer tap setting \( T_k \) generator bus voltages \( V_{i} \) and VAR source installments \( Q_{g} \) are control variables so they are self-restricted. The load bus voltages \( V_{load} \) and reactive power generation \( Q_{g} \) are state variables which are restricted by adding them as the quadratic penalty terms to the objective function. Equation (4) is therefore changed to the following generalized objective function:

\[
\text{Min } F_c = F_c + \sum_{i \in N_{V_{lim}}} \lambda_i \left( V_i - V_{i \text{lim}} \right)^2
\]

\[
+ \sum_{i \in N_{Q_{glim}}} \lambda_{Q_{g}} \left( Q_{g} - Q_{g \text{lim}} \right)^2
\]  

(5)

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Subjected to

\[ 0 = P_i - V_i \sum_{i' \in N_{s-1}} V_{i'} (G_{ij} \cos \theta_{ij} + B_{ij} \sin \theta_{ij}) \]

\[ 0 = Q_i - V_i \sum_{i' \in N_{PQ}} V_{i'} (G_{ij} \sin \theta_{ij} - B_{ij} \cos \theta_{ij}) \]

Where, \( \lambda v_i \) and \( \lambda Q_{gi} \) are the penalty factors which can be increased in the optimization procedure; \( V_i^{\text{lim}} \) and \( Q_{gi}^{\text{lim}} \) are defined in the following equations:

\[ V_i^{\text{lim}} = \begin{cases} V_i^{\min} & \text{if } V_i < V_i^{\min} \\ V_i^{\max} & \text{if } V_i > V_i^{\max} \end{cases} \]

\[ Q_{gi}^{\text{lim}} = \begin{cases} Q_{gi}^{\min} & \text{if } Q_{gi}^{\min} < Q_{gi}^{\min} \\ Q_{gi}^{\max} & \text{if } Q_{gi}^{\max} > Q_{gi}^{\max} \end{cases} \]

Setting the equation of discriminant be greater than or equal to zero yields

\[ \left( \frac{8}{\lambda} \sin \delta + \cos \delta \right) V_1 V_2 + \left( X + \frac{r^2}{X} \right) Q_2 = 0 \quad (7) \]

Rearranging (2), we obtain

\[ \frac{4z^2 Q_2 x}{V_1^2 (R \sin \delta + X \cos \delta)^2} < 1 \quad (9) \]

The Fast Voltage Stability Index is used to identify the weak buses. The characteristics of the FVSI are same with the existing techniques proposed by Mughavenmi et al. [14] and Mohamed et al. [12] whereby, the discriminant of quadratic equation is greater than or equal to zero. The maximum threshold is set to unity as the maximum value beyond this limit, system bifurcation will be experienced.

IV. FVSI FORMULATION

The FVSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system [15]. The general 2-bus representation is illustrated in Figure 1.

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IV. FVSI FORMULATION

The FVSI is derived from the voltage quadratic equation at the receiving bus on a two-bus system [15]. The general 2-bus representation is illustrated in Figure 1.

From the figure, the voltage quadratic equation at the receiving bus is written as

\[ V_1^2 \left( \frac{8}{\lambda} \sin \delta + \cos \delta \right) V_1 V_2 + \left( X + \frac{r^2}{X} \right) Q_2 = 0 \quad (7) \]

Rearranging (2), we obtain

\[ \frac{4z^2 Q_2 x}{V_1^2 (R \sin \delta + X \cos \delta)^2} < 1 \quad (9) \]

Since “i” as the sending bus and “j” as the receiving bus. Since \( \delta \) is normally very small, then, \( \delta \approx 0 \), \( R \sin \delta \approx 0 \) and \( X \cos \delta \approx X \). Taking the symbols i as the sending bus and j as the receiving bus, FVSI can be calculated

\[ \text{FVSI}_{ij} = \frac{4z^2 Q_j x}{V_i^2 (R \sin \delta + X \cos \delta)^2} \quad (10) \]

Where, \( z \) and \( x \) is the line impedance and reactance, \( Q_j \) is the reactive power at the receiving end, and \( V_i \) is the sending end voltage.

A. DETERMINING THE MAXIMUM LOADABILITY FOR WEAK BUS IDENTIFICATION

The following steps are implemented.

1. Run the load flow program for the base case.
2. Evaluate the FVSI value for every line in the system.
3. Gradually increase the reactive power loading by 0.01pu at a chosen load bus until the load flow solution fails to give results for the maximum computable FVSI.
4. Extract the stability index that has the highest value
5. Choose another load bus and repeat steps 3 and 4.
6. Extract the maximum reactive power loading for each load bus.
The Maximum reactive power loading is referred to as the Maximum loadability of a particular bus.
7. Sort the maximum loadability obtained from step 6 in ascending order. The smallest maximum loadability is ranked the highest, implying the weakest bus in the System.
8. Select the weak buses as the reactive power installation site for the RPP problem.

V. CUCKOO SEARCH ALGORITHM

Cuckoo search (CSA) is an optimization algorithm developed by Xin-she Yang and Suash Deb in 2009. The CS was inspired by the obligate brood parasitism of some cuckoo species by laying their eggs in the nests of host birds. Some cuckoos have developed in such a way that female parasitic cuckoos can duplicate the colors and patterns of the eggs of a few chosen host species [17]. This reduces the probability of the eggs being unrestricted and, therefore, raises their re-productivity (Payne 2005). It is worth revealing that numerous host birds engage direct conflict with intruding cuckoos. In this case, if host birds discover the eggs are not...
their own, they will either throw them away or abandon their nests and build new ones, elsewhere [18].

A. Cuckoo Search Implementation

Each egg in a nest characterizes a solution, and a cuckoo egg characterizes a new solution in a nest [17]. The aim is to employ the new and possibly better solutions to replace not-so-good solutions in the nests shown in Fig. 1 [18]. In the simple form, each nest has only one egg. The algorithm can be extended to more complex cases in which each nest has multiple eggs representing a set of solutions (Yang 2009; Yang 2010) [17]. The CS is based on three idealized rules:

1. Each cuckoo lays one egg at a time, and dumps it
2. When generating new solutions x(t+1) for, say cuckoo i, an Lévy flight is performed
3. Abandon a fraction (pa) of worst nests

Where YiG+1 is a mutant vector; r1, r2 and r3 are the randomly selected, mutually different vectors; F is a real constant factor [0 - 2] which controls the amplification of the differential variation. Each cuckoo lays one egg at a time, and dumps it in a randomly selected nest; the best nests with high quality of eggs (solutions) will carry over to the next generations; the number of accessible host nests is fixed, and a host can discover an unfamiliar egg with probability pa ∈ [0, 1] (11)

In this case, the host bird can either throw the egg away or abandon the nest to build a completely new nest in a new location (Yang 2009) [18]. For simplicity, this last assumption can be approximated by a fraction pa of the nests being replaced by new nests (with new random solutions at new locations). For a maximization problem, the quality of fitness of a solution can simply be proportional to the objective function. In cuckoo search fitness can be defined in similar way to the fitness function in genetic algorithms. Based on these three rules, the basic steps of the Cuckoo Search (CS) can be summarized as the pseudo code shown in algorithm I.

When generating new solutions x(t+1) for, say cuckoo i, an Lévy flight is performed

\[ X_{i}^{(t+1)} = x_{i}^{(t)} i + \alpha \oplus \text{Lévy}(\lambda), (12) \]

Where \( \alpha > 0 \) is the step size which should be related to the scales of the problem of interest. In most cases, we can use \( \alpha = 0 \) (1). The product \( \oplus \) means entry-wise multiplications. Lévy flights essentially provide a random walk while their random steps are drawn from an Lévy distribution for large steps.

\[ \text{Lévy} \sim u = \Gamma_{-}, (13) \]

This has an infinite variance with an infinite mean. Here the successive jumps/steps of a cuckoo basically form a random walk process which obeys a power-law step-length distribution with a heavy tail. It is worth pointing out that, in the real world, if a cuckoo’s bird egg is very analogous to a host’s eggs, then this cuckoo’s bird egg is less likely to be exposed, thus the fitness should be related to the variance in solutions [17].

Algorithm I. Cuckoo Search [18]

Start

Objective function \( f(x), x = (x_1, x_2, \ldots, x_m) \);

Initialize a population of n host nests \( x_i (i = 1, 2, \ldots, n) \);

While (\( t < \text{Max Generation} \) or (stop condition));

Generate a cuckoo randomly by taking Lévy flights; evaluate its fitness \( F_i \);

Randomly choose a nest among \( n \) (say j) available nests;

If (\( F_i > F_j \))

Substitute j by the new solution;

End

Abandon a fraction (pa) of worst nests [and build new nest at new locations via Lévy flights]; Keep the best solutions (or nests with quality solutions); Rank the solutions and find the recent best;

End while Post process results and visualization;

End

VI. NUMERICAL RESULTS

Simulation results have been obtained by using MATLAB 7.5 (R2007b) software package on a 2.93 GHz, Intel® Core™2 Duo Processor. Fig. 2 shows IEEE 30-bus system [3] has been used to show the effectiveness of the algorithm. The network consists of 6 generator-buses, 21 load-buses and 41 branches, of which four branches, (6, 9), (6, 10), (4, 12) and (28, 27) are under load-tap setting transformer branches. The buses for possible VAR source installation based on max load buses are 25, 26, 29 and 30. The maximum load ability and FVSI values for the IEEE 30 bus system are given in Table I.

![Figure 2.IEEE 30 bus system](image)

| Table 1. Bus Ranking and FVSI Values |
|---|---|---|---|
| Rank | Bus | Qmax(p.u) | FVSI |
| 1 | 30 | 0.26 | 0.9786 |
| 2 | 26 | 0.29 | 0.9649 |
| 3 | 29 | 0.33 | 0.9946 |

TABLE I. Bus Ranking and FVSI Values
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The parameters and variable limits are listed in Tables II and III. All power and voltage quantities are per-unit values and the base power is used to compute the energy cost.

TABLE II. Parameters.

<table>
<thead>
<tr>
<th>Sb (MVA)</th>
<th>h ($/puWh)</th>
<th>e ($)</th>
<th>Cc ($/puVAR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>6000</td>
<td>1000</td>
<td>30,00,000</td>
</tr>
</tbody>
</table>

TABLE III. Limits.

<table>
<thead>
<tr>
<th>Qc</th>
<th>Vc</th>
<th>V load</th>
<th>Tg</th>
</tr>
</thead>
<tbody>
<tr>
<td>min</td>
<td>max</td>
<td>min</td>
<td>max</td>
</tr>
<tr>
<td>0.12</td>
<td>0.35</td>
<td>0.9</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Three cases have been studied. Case 1 is of light loads whose loads are the same as those in [3]. Case 2 and 3 are of heavy loads whose loads are 1.25% and 1.5% as those of Case 1. The duration of load level is 8760 hours in both the cases [6].

Initial Power Flow Results

The initial generator bus voltages and transformer taps are set to 1.0 pu. The loads are given as:

Case 1: Pload = 2.834 and Qload = 1.262
Case 2: Pload = 3.5425 and Qload = 1.5775
Case 3: Pload = 4.251 and Qload = 1.893

TABLE IV. Initial generations and power losses.

<table>
<thead>
<tr>
<th>Pg</th>
<th>Qg</th>
<th>Ploss</th>
<th>Qloss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>3.008</td>
<td>1.354</td>
<td>0.176</td>
</tr>
<tr>
<td>Case 2</td>
<td>3.840</td>
<td>2.192</td>
<td>0.314</td>
</tr>
<tr>
<td>Case 3</td>
<td>4.721</td>
<td>3.153</td>
<td>0.461</td>
</tr>
</tbody>
</table>

TABLE V. Optimal generator bus voltages.

<table>
<thead>
<tr>
<th>Bus</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>8</th>
<th>11</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1.10</td>
<td>1.09</td>
<td>1.05</td>
<td>1.09</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Case 2</td>
<td>1.10</td>
<td>1.10</td>
<td>1.09</td>
<td>1.10</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.10</td>
<td>1.10</td>
<td>1.08</td>
<td>1.09</td>
<td>1.09</td>
<td>1.09</td>
</tr>
</tbody>
</table>

TABLE VI. Optimal transformer tap settings.

<table>
<thead>
<tr>
<th>Branch</th>
<th>(6,9)</th>
<th>(6,10)</th>
<th>(4,12)</th>
<th>(28,27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>1.0433</td>
<td>0.9540</td>
<td>1.0118</td>
<td>0.9627</td>
</tr>
<tr>
<td>Case 2</td>
<td>1.0133</td>
<td>0.9460</td>
<td>0.9872</td>
<td>0.9862</td>
</tr>
<tr>
<td>Case 3</td>
<td>1.0131</td>
<td>0.9534</td>
<td>0.9737</td>
<td>0.9712</td>
</tr>
</tbody>
</table>

TABLE VII. Optimal var source installments.

<table>
<thead>
<tr>
<th>Bus</th>
<th>26</th>
<th>28</th>
<th>29</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.0527</td>
<td>0.030</td>
<td>0.022</td>
<td>0.031</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.0876</td>
<td>0.029</td>
<td>0.027</td>
<td>0.047</td>
</tr>
</tbody>
</table>

TABLE VIII. Optimal generations and power losses.

<table>
<thead>
<tr>
<th>CSA</th>
<th>DE</th>
<th>CSA</th>
<th>DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pgsave %</td>
<td>Qgsave %</td>
<td>WCsave ($)</td>
<td>WCsave ($)</td>
</tr>
<tr>
<td>Case 1</td>
<td>8.644</td>
<td>8.012</td>
<td>8.4225*10^6</td>
</tr>
<tr>
<td>Case 2</td>
<td>12.452</td>
<td>12.137</td>
<td>1.4408*10^7</td>
</tr>
<tr>
<td>Case 3</td>
<td>13.311</td>
<td>12.936</td>
<td>2.2017*10^7</td>
</tr>
</tbody>
</table>

Figure 3. Voltage profile of the system for Case-2
The optimal generator bus voltages, transformer tap settings, VAR source installments, generations and power losses are obtained as in Tables IV-VIII. The real power savings, annual cost savings and the total costs are calculated as,

\[
P_{\text{save}} = \frac{P_{\text{loss}}^\text{opt} - P_{\text{loss}}^\text{int}}{P_{\text{loss}}^\text{int}} \times 100\%\]

\[
W_{\text{C}} = \frac{h_d}{\pi} \left( P_{\text{loss}}^\text{int} - P_{\text{loss}}^\text{opt} \right)
\]

Table IX gives the cost comparison. From the comparison, the FVSI based RPP gives more savings on the real power, annual cost and the total cost for the cases 1, 2 and 3 respectively. Figures 3, shows the voltage profile of the system for 125% loading. From the plots, the bus voltage magnitudes are better for the FVSI based RPP using CSA than the bus voltage magnitudes without considering the voltage stability and CSA also, most of the voltage magnitude and reactive power violations are eliminated while using the FVSI and RPP. From plots 4 and 5, the Convergence Rate of CSA is able to reach the close vicinity of final solution with in the respective iteration for 125% and 150% loading.

VI. CONCLUSION

FVSI based approach has been developed for solving the weak bus oriented RPP problem. Based on FVSI, the locations of reactive power devices for voltage control are determined. The individual maximum load ability obtained from the load buses will be sorted in ascending order with the smallest value being ranked highest. The highest rank implies the weakest bus in the system with low sustainable load. These are the possible locations for reactive power devices to maintain stability of the system. The application studies on the IEEE 30-bus system shows that the Cuckoo Search Algorithm (CSA) approach gives more savings on real power, annual and the total costs for different loading conditions comparing Differential Evolution (DE). The proposed approach a proper planning can be done according to the bus capacity to avoid voltage collapse of the system

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