Optimal Voltage Regulators Placement in Radial Distribution System Using Fuzzy Logic

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Abstract
The main aim of this paper is to obtain optimal voltage control in radial distribution system with voltage regulators and then to decrease the total cost of voltage regulators and losses, to obtain the net saving by using Back Tracking Algorithm (BTA) and Fuzzy Expert System (FES). A computer algorithm for optimal voltage control with voltage regulators, suitable for large radial distribution networks is given in this paper. Algorithm determines tap setting of the voltage regulators to provide a smooth voltage profile along the network. Algorithm is also used to obtain the minimum number of the initially selected voltage regulators, by moving them in such a way so as to control the network voltage with minimum cost. In Fuzzy logic the results are obtained by giving the Voltage and Power Loss Index as inputs to FES, the output of the FES is the tap setting and optimal location of the voltage regulator (VR). Algorithms have been implemented using MATLAB along with Fuzzy logic tool box and the results of both Back Tracking Algorithm and Fuzzy Expert System (FES) are compared.

Keywords: Radial Distribution System, Voltage Control, Voltage Regulators, Back Tracking Algorithm and Fuzzy Expert System.

1. INTRODUCTION
The voltage drop along radial distribution systems has been a crucial operating problem. Utilities look for solutions for this problem, from both technical and economical standpoints. Various devices such as capacitors and voltage regulators (VR’s) can be installed to reduce the voltage drop. In this paper an algorithm for optimal voltage control with voltage regulators is developed. The main objective is to reduce the line losses and controlling the voltage in the radial distribution system with optimal voltage regulators placement. The load flow method used in this paper is the back forward sweep method. It presents excellent convergence characteristics and can be applied to radial as well as weakly meshed systems. The proposed Back tracking algorithm determines the optimal number, location and tap positions of voltage regulators in a 47 bus Radial Distribution system to maintain voltage profile with in the desired limits and reduces the losses in the system which in turn maximizes the net savings in the operation of the system. In addition to the back tracking algorithm a method using Fuzzy is also proposed and the results of FES are compared with the results of back tracking algorithm.

2. LOAD FLOWS
The backward-forward sweep method is used to carry load flow analysis. It presents excellent convergence characteristics and can be applied to radial as well as weakly meshed systems. It also allows incorporating limits and controls. In the back sweep step, currents are accumulated starting from the end buses towards the substation. In the forward sweep step, bus voltages are updated starting from the substation towards the end buses. In any radial distribution network, the electrical equivalent of a branch-i, which is connected between nodes 1 and 2 having resistance r(i) and inductive reactance x(i) is shown in Fig.1.

Figure 1 Electrical equivalent of a typical branch- i
From Figure 1 current flowing through the branch-i is given by

\[ I(\text{Re}(i)) = \left( \frac{P(\text{Re}(i)) + j \cdot Q(\text{Re}(i))}{V(\text{Re}(i))} \right) \]  

... (2.1)

where,

Se(i) = Sending end node
Re(i) = Receiving end node

Let

\[ I(i) = I(\text{Re}(i)) \]  

... (2.2)

\[ V(\text{Re}(i)) = V(\text{Se}(i)) - I(i) \times (R(i) + jX(i)) \]  

... (2.3)

where,

R = Resistance of branch i
X = Reactance of branch i

The active and reactive power losses in branch i are given by

\[ P(i) = |I(i)|^2 \times R(i) \]  

... (2.4)

\[ Q(i) = |I(i)|^2 \times X(i) \]  

... (2.5)

In = number of branches
nd = number of nodes

Normally the substation voltage \( V_{(1)} \) is known and is taken as 1.0 (p.u) Initially, \( P(i) \) and \( Q(i) \) are set to zero for all i. Then the initial estimate of \( P(2) \) and \( Q(2) \) will be the sum of the loads of all the nodes beyond node 2 plus the local load of node 2. For all the branches \( i = 1,2, \ldots, \ldots, nd-1 \), compute \( P_{(i+1)} \) and \( Q_{(i+1)} \) . Compute \( |I_{(i+1)}| \), \( P(i) \) and \( Q(i) \) using Eqns. (2.3), (2.4) and (2.5). This will complete iteration. Update the loads \( P_{(i+1)} \) and \( Q_{(i+1)} \) (by including losses) and repeat the same procedure until all the voltage magnitudes are computed to a tolerance level of 0.0001 p.u. in successive iterations.

Once all the nodes and branches are identified, then voltage magnitudes of all the nodes are calculated by using the Eqn. (2.3). It is necessary to obtain the exact feeding through all the receiving end nodes and the voltage magnitudes of all the nodes as the voltage of the substation is known \( V_{(1)} \). Then compute the branch losses using Eqns. (2.4) and (2.5). The convergence criterion is that if the magnitude of voltage difference of successive iterations is less than the error (i.e., 0.0001) value, the solution is converged. The backward-forward sweep method is used to carry load flow analysis.

3. Voltage Regulators Placement And Control

3.1 Objective Function

The problem of determination of optimal number and location of voltage regulator can be formulated as an optimization problem. This algorithm is to obtain the optimal location for placing Voltage regulators that maintain the voltages within the limits of the RDS so as to maximize an objective function, which consists of capital investment and capitalized energy loss costs.

The objective function is formulated as maximizing the cost function,

\[ \text{Max. } F = K_e \times P_{lr} \times 8760 \times LLf \times K_{VR} \times N \times (\alpha + \beta) \]  

...............(3.1)

Where

\[ P_{lr} = \text{Reduction in power losses due to installation of VR} \]
\[ = \text{(Power loss before installation of VR - Power loss after installation of VR)} \]
\[ K_e = \text{Cost of energy in } Rs./kWh \]
\[ LLf = \text{Loss load factor} = 0.8 \times (Lf)^2 + 0.2 \times Lf \]
\[ Lf = \text{load factor} \]
\[ N = \text{Number of voltage regulators} \]
\[ K_{VR} = \text{Cost of each VR} \]
\[ \alpha = \text{the rate of annual depreciation charges for VR} \]
\[ \beta = \text{Cost of installation of VR. (Generally it is taken as percentage of cost of VR)} \]
The VR problem consists of two sub problems, that of optimal placement and optimal choice of tap setting. The first sub problem determines the location and number of VRs to be placed and the second sub problem decides the tap positions of VR. The first step involves the selection of VRs at the buses where the voltage is violating the upper and lower limits. The optimal number and placement of voltage regulators required is obtained by applying the proposed back tracking algorithm.

![Figure2](Image)  The 19 bus RDS before installation of regulators

![Figure3](Image)  The 19 bus RDS after installation of voltage regulators

Let the initial voltage regulators are located at buses 8, 11, 13 and 18 as shown in Fig.2

It is proposed to reduce the number of VRs in a practical system by shifting the VR’s to the junction of laterals (such as from buses 11 and 13 to bus 10) and observe the voltage profile and the objective function by computing voltages at each bus. If it satisfies the above two constraints, then this will be taken as optimal position for the single VR at bus 10 instead of two VRs at buses 11 and 13 (shown in Fig 2). This procedure is repeated starting from the tail end buses towards the source bus and find the optimal number and location of VRs.

3.2 Selection of Tap Positions of VR’s

By finding the optimal number and location of VRs then tap positions of VR is to be determined as follows.

In general, VR position at bus ‘j’ can be calculated as

\[ V_j^t = V_j \pm \text{tap} \times V_{\text{rated}} \]  (3.2)

where

- \( V_j^t \) = the voltage at bus ‘j’ after VR installation at this bus in p.u.
- \( V_j \) = the voltage at bus ‘j’ before a VR installation at this bus in p.u.
- \( V_{\text{rated}} \) = Rated voltage in p.u.

Tap position (tap) can be calculated by comparing voltage obtained before VR installation with the lower and upper limits of voltage

- ‘+’ for boosting of voltage.
- ‘-’ for bucking of voltage.

The Bus voltages are computed by load flow analysis for every change in tap setting of VR’s, till all bus voltages are within the specified limits. Then obtain the net savings, with above tap settings for VR’s. The algorithm for finding optimal place for location of voltage regulators using back tracking algorithm is given below.

3.3 Algorithm Using Proposed Back Tracking Algorithm

1: Read line and load data.
2: Run load flows for the system and compute the voltages at each bus, real and reactive power losses of the system.
3: Identify the buses, which have violation of voltage limits.
4: Obtain optimal number of VRs and location of VRs by using back tracking algorithm.
5: Obtain the optimal tap position of VR using Eqn. (3.1), so that the voltage is within the specified limits.
6: Again run the load flows with VR, then compute voltages at all buses, real and reactive power losses. If voltages are not within the limits, go to step 3.
7: Determine the reduction in power loss and net saving by using objective function (Eqn. 3.2).
8: Print results.
9: Stop.
4. FUZZY IMPLEMENTATION

The entire framework to solve the optimal voltage regulator placement problem includes the use of numerical procedures which are coupled to the fuzzy. First, a vector-based load flow calculates the power losses in each line and voltages at every bus. The voltage regulators are placed at every bus and total real power losses are obtained for each case. The per unit voltages at every bus and the power losses obtained are the inputs to the Fuzzy Expert System (FES) which determines the bus most suitable for placing voltage regulator without violating the limits. The FES contains a set of rules which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy interfacing for determining the suitability of voltage regulator placement at a particular bus, a set of multiple antecedent fuzzy rules have been established.

4.1 Fuzzy Rules

<table>
<thead>
<tr>
<th>AND</th>
<th>VOLTAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
<td>Low-medium</td>
</tr>
<tr>
<td>Low-medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Medium</td>
<td>High-Medium</td>
</tr>
<tr>
<td>High-medium</td>
<td>High-medium</td>
</tr>
<tr>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Fuzzy rules are summarized in the fuzzy decision matrix given in Table 1, inputs to these rules are the voltages and power loss indices and the output consequent is the suitability of the voltage regulator placement. Fuzzy variables of PLI (power loss index) are low, low-medium, medium, high-medium, high. The membership functions for power loss index, voltage and voltage regulator suitability index are shown in figure 4, figure 5, figure 6 respectively.

Figure 4 :Membership function for power loss index
Figure 5 :Membership function for voltage
Figure 6: Membership function for voltage regulator suitability index

4.2 Algorithm for optimum voltage regulator placement in RDS using FES

1: Read line and load data.
2: Run load flows for the system and compute the voltages at each bus, real and reactive power losses of the system.
3: Install the voltage regulator at every bus and compute the total real power loss of the system at each case and convert into normalized values.
4: Obtain optimal number of VRs and location of VRs by giving voltages nd Power loss indices as inputs to FES.
5: Obtain the optimal tap position of VR using Eqn. (3.1), so that the voltage is Within the specified limits.
6: Again run the load flows with VR, then compute voltages at all buses, real and reactive power losses. If voltages are not within the limits, go to step 3.
7: Determine the reduction in power loss and net saving by using objective Function (Eqn. 3.2).
8: Print results.
9: Stop.

5. RESULTS AND ANALYSIS

5.1 Results of back tracking algorithm:
The proposed method is illustrated with 47- bus radial distribution system. For the positioning of voltage regulators, the upper and lower bounds of voltage are taken as ±5% of base value. The voltage regulators are of 11kV, 200MVA with 32 steps of 0.00625 p.u. each.

![Figure 7 Single line diagram of 47 bus RDS](image)

Load flow solution for 47 bus practical RDS without and with voltage regulators is performed. Observing the voltage levels, it is found that all bus voltages except bus 1 violate the lower limit of 0.95 p.u. ideally; voltage regulators are to be installed at all buses except at bus 1. However, in practice, it is not economical to have more number of voltage regulators at all buses to get the voltages within specified limits and hence by applying proposed back tracking algorithm the required optimal number of voltage regulators that will maintain the voltage profile within above limits is determined. By applying the above algorithm for the above systems it is found that voltage regulators at buses 2, 36 and 42 are sufficient to maintain the voltage profile at all buses. The reduction in real power loss, net saving and %voltage regulation for the system are given in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before VRs placement</th>
<th>With VRs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VRs at all buses (except at bus 1)</td>
<td>After (VR at buses 2, 36, 42)</td>
</tr>
<tr>
<td>$P_{\text{loss}}$ (%)</td>
<td>16.6835</td>
<td>13.1796</td>
</tr>
<tr>
<td>Net saving (Rs.)</td>
<td>-----</td>
<td>(-) 1.14,850</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>16.7039</td>
<td>6.7039</td>
</tr>
</tbody>
</table>

It is observed that from Table 2, without voltage regulators in the system the percentage power loss is 16.6835 and percentage voltage regulation is 16.7039. With voltage regulators at all buses (except at bus 1), the percentage power loss is 13.1796 and percentage voltage regulation is 6.7039 but the net saving is (-) Rs.1, 14,850 (cost of voltage regulators itself is more than cost of total energy losses), with voltage regulators at optimal locations of buses 2, 36, and 42 using Back Tracking Algorithm, the percentage power loss is reduced to 13.0954 and percentage voltage regulation is reduced to 4.6964. The optimal net saving is increased to Rs.2,79,380.

5.2 Results of FES:
By applying the FES algorithm for the 47 bus system, it is found that two voltage regulators at bus 2 are sufficient to maintain the voltage profile at all buses. One voltage regulator with 10% tapping and another voltage regulator with 0.625% tapping.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before VR placement</th>
<th>After (two VRs at bus 2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{\text{loss}}$ (%)</td>
<td>16.6835</td>
<td>12.9647</td>
</tr>
<tr>
<td>Net saving</td>
<td>-----</td>
<td>Rs.3,26,169</td>
</tr>
<tr>
<td>Voltage regulation (%)</td>
<td>16.7039</td>
<td>4.8106</td>
</tr>
</tbody>
</table>

Table 3 Summary of Results of 47 bus RDS with FES
It is observed that from Table 3, without voltage regulators in the system the percentage power loss is 16.6835 and percentage voltage regulation is 16.7039.

With two voltage regulators at optimal location of bus 2 using Fuzzy Expert System, the percentage power loss is reduced to 12.9647 and percentage voltage regulation is reduced to 4.8106.

The optimal net saving is increased to Rs.3,26,169.

5.3 Analysis of results

The bus voltages obtained without and with voltage regulators placed at different busses by using BACK TRACKING ALGORITHM and FUZZY EXPERT SYSTEM are given in Table 4.

### Table 4 Bus voltages with out and with voltage Regulators using BTA and FES

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Bus Voltages before VR placement</th>
<th>Bus Voltages with Voltage regulators at buses 2, 36, 42 by using BTA</th>
<th>Bus Voltages with Voltage regulators at bus 2 by using FES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0000</td>
<td>1.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>2</td>
<td>0.9378</td>
<td>1.0378</td>
<td>1.0440</td>
</tr>
<tr>
<td>3</td>
<td>0.9376</td>
<td>1.0377</td>
<td>1.0439</td>
</tr>
<tr>
<td>4</td>
<td>0.9132</td>
<td>1.0160</td>
<td>1.0224</td>
</tr>
<tr>
<td>5</td>
<td>0.9128</td>
<td>1.0156</td>
<td>1.0220</td>
</tr>
<tr>
<td>6</td>
<td>0.9126</td>
<td>1.0155</td>
<td>1.0218</td>
</tr>
<tr>
<td>7</td>
<td>0.9090</td>
<td>1.0122</td>
<td>1.0184</td>
</tr>
<tr>
<td>8</td>
<td>0.9087</td>
<td>1.0120</td>
<td>1.0187</td>
</tr>
<tr>
<td>9</td>
<td>0.9004</td>
<td>1.0046</td>
<td>1.0110</td>
</tr>
<tr>
<td>10</td>
<td>0.9001</td>
<td>1.0043</td>
<td>1.0108</td>
</tr>
<tr>
<td>11</td>
<td>0.8997</td>
<td>1.0040</td>
<td>1.0105</td>
</tr>
<tr>
<td>12</td>
<td>0.8911</td>
<td>0.9963</td>
<td>1.0028</td>
</tr>
<tr>
<td>13</td>
<td>0.8863</td>
<td>0.9921</td>
<td>0.9986</td>
</tr>
<tr>
<td>14</td>
<td>0.8861</td>
<td>0.9919</td>
<td>0.9984</td>
</tr>
<tr>
<td>15</td>
<td>0.8852</td>
<td>0.9911</td>
<td>0.9977</td>
</tr>
<tr>
<td>16</td>
<td>0.8848</td>
<td>0.9908</td>
<td>0.9973</td>
</tr>
<tr>
<td>17</td>
<td>0.8846</td>
<td>0.9905</td>
<td>0.9971</td>
</tr>
<tr>
<td>18</td>
<td>0.8842</td>
<td>0.9902</td>
<td>0.9967</td>
</tr>
<tr>
<td>19</td>
<td>0.8839</td>
<td>0.9900</td>
<td>0.9965</td>
</tr>
<tr>
<td>20</td>
<td>0.8760</td>
<td>0.9830</td>
<td>0.9896</td>
</tr>
<tr>
<td>21</td>
<td>0.8754</td>
<td>0.9825</td>
<td>0.9891</td>
</tr>
<tr>
<td>22</td>
<td>0.8751</td>
<td>0.9822</td>
<td>0.9888</td>
</tr>
<tr>
<td>23</td>
<td>0.8555</td>
<td>0.9645</td>
<td>0.9716</td>
</tr>
<tr>
<td>24</td>
<td>0.8536</td>
<td>0.9632</td>
<td>0.9699</td>
</tr>
</tbody>
</table>

6. Comparison of results:

The results of 47 bus RDS, without and with voltage regulators using back tracking algorithm and FES are given Table 5. Without voltage regulators the percentage voltage regulation is 16.704, by applying Back Tracking Algorithm the Energy loss is reduced to 58.5229 MW and percentage voltage regulation is improved to 4.6961 and the net saving is
Rs. 2, 79,380. By applying Fuzzy Expert System (FES) the Energy loss is reduced to 60.6319 MW and percentage voltage regulation is 4.8106 and the net saving is further increased to Rs. 3, 26,169.

<table>
<thead>
<tr>
<th></th>
<th>VOLTAGE REGULATION (%)</th>
<th>Total energy loss (MWyr)</th>
<th>Energy saved (MWyr)</th>
<th>Loss reduction (MW)</th>
<th>Benefit (Rs)/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before VR placement</td>
<td>16.704</td>
<td>60.0466</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>After VR placement using BTA</td>
<td>4.6961</td>
<td>47.1270</td>
<td>1.2926</td>
<td>58.5229</td>
<td>2, 79,380</td>
</tr>
<tr>
<td>After VR placement using FES</td>
<td>4.8106</td>
<td>46.6620</td>
<td>1.3385</td>
<td>60.6319</td>
<td>3, 26,169</td>
</tr>
</tbody>
</table>

Table 5: Summary of results for 47 bus system with and without VRs using BTA and FES

7. CONCLUSIONS
In radial distribution systems it is necessary to maintain voltage levels at various buses by using capacitors or conductor grading or placing VR at suitable locations. In this project voltage regulator are used to maintain the voltage profile and to maximize net savings. The proposed Back tracking algorithm determines the optimal number, location and tap positions of voltage regulators in a 47 bus Radial Distribution system to maintain voltage profile with in the desired limits and reduces the losses in the system which in turn maximizes the net savings in the operation of the system. In addition to the back tracking algorithm a method using Fuzzy is also proposed and the results of FES are compared with the results of back tracking algorithm. It is concluded that the FES gives the optimal location and number along with the tap setting of the voltage regulators. The proposed FES provides good voltage regulation, and reduces the power loss which in turn increases the net savings when compared to the back tracking algorithm.

References
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