VOLTAGE PROFILES ENHANCEMENT AND LOSS REDUCTION IN WEAK MESHED NETWORKS

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ABSTRACT
This paper explores the use of reactive Power compensation to enhance voltage bus profiles for power system security in weak power system networks. Power-flow analysis is one of the tools used in this paper and it is modelled as a nonlinear problem which is solved using Newton-Raphson-based algorithm. Power-flow is performed in this paper to determine voltage magnitudes and angles at every bus, active and reactive powers, transmission losses for each of the branches in the network and total transmission losses of the network. Buses that have their voltage magnitude outside the prescribed acceptable limits (±10% tolerance value) within the network are therefore identified. The magnitudes of the voltages at these buses are substantially improved when reactive power is injected. Total transmission loss on the line is also reduced to barest minimum after the compensation. MATLAB 2010a is used as a programming tool for this work. A weak meshed network of 28-bus system is used as a test system. The result of the simulation in this paper shows the effectiveness of reactive power compensation using a bank of capacitors in transmission power system networks.

KEY WORDS
Reactive power, compensation, voltage profiles, power-flow, Newton-Raphson, weak meshed, transmission losses

1. Introduction

Shortage of reactive power supports has been a major concern of every power system engineer in recent times. This is because the voltage profiles of the load buses solely depend on the availability of reactive power in the network [1]. Hence, networks whose voltage profiles are below predefined limits as a result of inadequate reactive power could be termed weak networks. This problem is more pronounced in networks that are not fully meshed with high resistance to reactance ratios. All the equipment connected to power system buses are designed to operate within permissible voltage limits. Power systems of today have been forced to be operated close to their operating limits [2], [3] as a result of the inability of the network to supply the required quantity of reactive power. The resultant effect of this shortage of reactive power support may cause voltage collapse of the system which is an undesirable threat to power systems [3], [4], [5]. In power system operation and planning, voltage magnitude and the system frequency are of paramount importance in the delivery of the required power quality from the generating station through the transmission lines to the load [6], [7]. These parameters are expected to be constant independent of the magnitude of the load at the receiving end of the network. This is necessary in order to avoid imbalance as a result from the difference between the available generated power and the power required by the load which may consequently lead to voltage collapse [8]. It is, therefore, important that the buses, to which these equipments are connected, be monitored and controlled in order to keep the voltages within the specified regulation limits. It is believed that losses in power system networks increase by transmission of reactive power through a long distance. The easiest way to tackle this problem is by generating reactive power very close to the load bus [9]. This can be easily accomplished by switching on a shunt capacitor.

Although, considerable works have been done and published on the application of reactive compensation by a bank of capacitors in the distribution networks, there have been very few attempts in its applications to transmission networks. Its advantages are numerous which include power factor improvement, voltage profile improvement and reduction in power losses [6], [9], [10], [11]. The major strength of Shunt capacitor lies in its much lower cost with higher reliability than any other compensating devices for voltage improvement applications.

Quite a number of research papers have been published in the literature using different methods of compensating reactive power in power system networks. The major aim is to find a lasting solution to the power system voltage collapse due to inadequate reactive power injection into the network. In [4], partitioning of the system bus admittance matrix and the application of circuit theory to the power system networks is proposed for the
improvement of network voltage profiles using SVC without considering its effect on the overall transmission losses. In [12], a new concept using multi-agent approach for the improvement of the traditional voltage control and management of reactive power has been introduced. A hybrid approach is adopted in [7] for voltage improvement and power loss calculations. [3] has presented management of reactive power reserves as an optimization problem. The solution to this problem is found using a pseudo-gradient evolutionary programming approach. An improved Genetic algorithm (GA) method is proposed in [8] for voltage stability enhancement. This approach is based on the minimization of the maximum of L-indices of load buses. In [13], Distributed Generation (DG) placement for voltage stability is applied. This method is based on the minimization of losses and maximization of the system. More recently, [14] presented the application of PowerWorld programming tool in the determination of losses and voltage improvement in the northern part of Nigeria. The major challenges with this work are in two folds. No mathematical formulation, to show the variation of the bus voltage to be improved with the reactive power to be injected at the buses, is presented in the work. This is very important, especially for large practical power systems. Secondly, the true picture of the entire Nigerian 330kV grid network is not fully represented in the study. The results obtained from the simulation cannot be used to represent the true simulation results of the entire grid system. This approximate network model cannot be used to predict accurately steady state operation of the power system network being considered.

In this paper, reactive power compensation is provided to the load buses by a bank of capacitors to enhance voltage bus profile and reduce the total transmission losses of power system networks. It presents reactive support modelling which is a Newton-Raphson based power-flow algorithm for the enhancement of bus voltages and reduction of losses in the transmission network of power systems. The organization of other sections of the paper is as follows: Section 2 models power-flow problem as nonlinear algebraic equations starting from first principle. Section 3 presents Newton-Raphson solution algorithm to the power flow model. The reactive power compensation model is derived and presented in section 4. Analysis and discussions of results are presented in section 5. Section 6 gives the concluding remarks.

2. Generalized Power-Flow Equations

The assessment of any power system dynamic simulation involves running power-flow, which can be modelled as a set of nonlinear algebraic equations. Power-flow is useful in security, contingency analysis, state estimation, planning, control and operation stages of power systems [15], [16], [17].

By applying basic circuit theory, the complex power injected into any bus \( i \) of an \( N \)-bus power system can be expressed as

\[
S_i = V_i I_i^* \quad \text{for } i = 1, 2, \ldots, N \quad (1)
\]

\[
S_i^* = V_i^* I_i = P_i - jQ_i, \quad \text{for } i = 1, 2, \ldots, N \quad (2)
\]

Current at bus \( i \) can be written as

\[
I_i = \left[ \sum_{j=1}^{N} Y_{ij} V_j \right] \quad (3)
\]

Substitution of equation (3) into equation (2) gives

\[
S_i = V_i^* \sum_{j=1}^{N} Y_{ik} V_k \quad (4)
\]

Active and reactive powers are obtained from equation (4) respectively as

\[
P_i = \sum_{k=1}^{N} |V_i| |V_k| Y_{ik} \text{cos}(\theta_{ik} - \delta_i + \delta_k) \quad (5)
\]

\[
Q_i = -\sum_{k=1}^{N} |V_i| |V_k| Y_{ik} \text{sin}(\theta_{ik} - \delta_i + \delta_k) \quad (6)
\]

where

\[
|V_i| \quad \text{and} \quad \delta_i \quad \text{are the voltage magnitude and angle at bus } i
\]

\[
|V_k| \quad \text{and} \quad \delta_k \quad \text{are the voltage magnitude and angle at bus } k
\]

\[
|Y_{ik}| \quad \text{and} \quad \theta_{ik} \quad \text{are the magnitude and angle of bus admittance element between buses } i \text{ and } k
\]

3. Newton-Raphson Technique

The techniques that are commonly used when finding solutions to power-flow problems are Gauss-Seidel, Newton-Raphson and Fast Decoupled techniques [17], [18], [19]. Newton-Raphson technique is used in this paper because of its ability to handle large practical and sparse power system networks with higher accuracy, faster convergence and higher efficiency [16], [20], [21], [22] which are of paramount importance in this work. By applying Newton-Raphson technique to solve the sets of nonlinear algebraic equations derived in equations (5) and (6), we have

\[
\begin{bmatrix}
\Delta P_i \\
\Delta Q_i
\end{bmatrix} =
\begin{bmatrix}
L & M \\
O & N
\end{bmatrix}
\begin{bmatrix}
\Delta \delta_i \\
\Delta V_i
\end{bmatrix} \quad (7)
\]
where 
\[ L, M, N \] and \( O \) are the elements of the Jacobian matrix and are defined by

\[
L_{ik} = \frac{\partial P_i}{\partial \delta_k}, \quad (8a)
\]

\[
L_{ii} = \frac{\partial P_i}{\partial \delta_i}, \quad (8b)
\]

\[
M_{ik} = \frac{\partial P_i}{\partial V_k}, \quad (8c)
\]

\[
M_{ii} = \frac{\partial P_i}{\partial V_i}, \quad (8d)
\]

\[
N_{ik} = \frac{\partial Q_i}{\partial \delta_k}, \quad (8e)
\]

\[
N_{ii} = \frac{\partial Q_i}{\partial \delta_i}, \quad (8f)
\]

\[
O_{ik} = \frac{\partial Q_i}{\partial V_k}, \quad (8g)
\]

\[
O_{ii} = \frac{\partial Q_i}{\partial V_i}, \quad (8h)
\]

\[
\begin{bmatrix}
\Delta P_i \\
\Delta Q_i
\end{bmatrix}
\]

represents the column vector of the control variables at the PV and PQ buses.

\[
\begin{bmatrix}
\Delta \delta_i \\
\Delta V_i
\end{bmatrix}
\]

represents the column vector of the state variables at the PV and PQ buses.

Gaussian elimination technique can be applied to equation (7) in order to determine the unknown vectors \( \Delta \delta_i \) and \( \Delta V_i \). Updated values of the voltage magnitude at all the load buses and voltage angles at all the buses except slack bus can then be found using

\[
\delta_i^p = \delta_i + \Delta \delta_i^p \quad (9)
\]

\[
V_i^p = V_i + \Delta V_i^p \quad (10)
\]

where \( p \) represents the iteration number.

After running the power flow program, if any bus voltage magnitude is found to be outside the prescribed limits \( V_{\text{min}} < V_i < V_{\text{max}} \) (for this paper, \( V_{\text{min}} = 0.9 \) per unit and \( V_{\text{max}} = 1.1 \)), VAR is injected into or absorbed from the system by capacitor depending on whether \( V_i \) is less than \( V_{\text{min}} \) (undervoltage condition) or greater than \( V_{\text{max}} \) (overvoltage condition).

Complex power that will flow through the network element \( i-k \) as a result of the injection at bus \( i \) and \( k \) respectively is given by

\[
S_{ik} = V_i^* I_k^* = P_{ik} + jQ_{ik}
\]

\[
S_{ik} = V_i (V_i^* - V_k^*) Y_{ik}^* + V_k Y_{ki}^* k \quad (11)
\]

Similarly,

\[
S_{ki} = V_k I_i = P_{ki} + jQ_{ki}
\]

\[
S_{ki} = V_k (V_k^* - V_i^*) Y_{ki}^* + V_i Y_{ik}^* k \quad (12)
\]

Total real power loss is

\[
P_{\text{loss}} = \Re \{ S_{ik} \} + \Re \{ S_{ki} \} \quad (13)
\]

Total reactive power loss is

\[
Q_{\text{loss}} = \Im \{ S_{ik} \} + \Im \{ S_{ki} \} \quad (14)
\]

Total transmission loss is computed by adding equations (11) and (12). This gives

\[
S_{\text{loss}} = S_{ik} + S_{ki} \quad (15)
\]

4. Reactive Power Modelling

Let \( X_{ci} \) be the capacitive reactance of the equivalent capacitor to be connected to bus \( i \) for the improvement of voltage profile and the reduction in total network losses. Using ohm’s law, the current flowing through \( X_{ci} \) can be written as

\[
I_{ci} = j \frac{|V_i|}{X_{ci}} \text{kA} \quad (11)
\]

The required reactive power can be written as

\[
\therefore \quad jQ_{ci} = |V_i| \times (I_{ci}) \quad (12)
\]
Substitute equation (11) into equation (12).

\[ Q_{ci} = \frac{|V_i|^2}{X_{ci}} \text{ MVAR} \]  

(13)

Equation (13) gives the amount of reactive power by the capacitor bank to be injected into or absorbed from the bus \( i \) where the reactive support is required.

5. Result, Analysis and Discussions

Newton-Raphson-based power-flow results obtained from the output of the developed MATLAB program are given in Tables 1 and 2.

Figure 1 is a bar chart which shows the graphical display of the voltage magnitude with respect to the bus number. This chart gives a clear distinction between the compensated and uncompensated voltage profiles. It shows clearly that the voltage profile of the network has substantially been improved by applying reactive power compensation.

Table 1 presents the bus names, bus voltage profiles before compensation and bus voltage profiles after the application of reactive power support. This table shows that some buses (buses 18, 20, 21, 23, 26 and 28) are outside the acceptable voltage limits. Therefore, there is a need for voltage improvement at these buses.

From this table, it is obvious that, all the voltage magnitudes are now within the tolerable limits of \( \pm 10\% \) of the nominal voltage values.

The amounts of transmission losses with and without reactive power compensation are presented in Table 2. The reduction in the active part of the losses is 3.65MW, which represents only about 2% of the initial active losses. Similarly, the reduction in the reactive part of the losses is 58.96MVAR which represents about 24.697% of the initial reactive losses. The implication of this is that although, there is no significant reduction in the active power loss, the difference in the reactive power before and after compensation is highly significant and the reactive power loss has been substantially reduced.

Figure 1: Bar chart showing effect of Reactive Compensation in Power Systems

![Figure 1: Bar chart showing effect of Reactive Compensation in Power Systems](image-url)
Figure 2: Nigerian 28-bus grid network (source: [23])

Table 1
Summary of Power-flow results before and after compensation

<table>
<thead>
<tr>
<th>Bus no</th>
<th>Bus name</th>
<th>Voltage profiles before compensation</th>
<th>Voltage profiles after compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Voltage magnitude (per unit)</td>
<td>Voltage angle (Degrees)</td>
</tr>
<tr>
<td>1</td>
<td>Egbin</td>
<td>1.000</td>
<td>0.0000</td>
</tr>
<tr>
<td>2</td>
<td>Delta</td>
<td>1.000</td>
<td>5.8680</td>
</tr>
<tr>
<td>3</td>
<td>Ajah</td>
<td>0.996</td>
<td>-0.5870</td>
</tr>
<tr>
<td>4</td>
<td>Akangba</td>
<td>0.997</td>
<td>-4.6660</td>
</tr>
<tr>
<td>5</td>
<td>Ikeja West</td>
<td>1.019</td>
<td>-3.6800</td>
</tr>
<tr>
<td>6</td>
<td>Ajaokuta</td>
<td>0.990</td>
<td>-2.7540</td>
</tr>
<tr>
<td>7</td>
<td>Aladja</td>
<td>1.009</td>
<td>-6.3460</td>
</tr>
<tr>
<td>8</td>
<td>Benin</td>
<td>1.034</td>
<td>-6.9730</td>
</tr>
<tr>
<td>9</td>
<td>Aiyede</td>
<td>1.014</td>
<td>-12.9400</td>
</tr>
<tr>
<td>10</td>
<td>Osogbo</td>
<td>1.054</td>
<td>-10.8590</td>
</tr>
<tr>
<td>11</td>
<td>Atam</td>
<td>0.990</td>
<td>-1.3220</td>
</tr>
<tr>
<td>12</td>
<td>Alaoji</td>
<td>1.015</td>
<td>-2.4550</td>
</tr>
<tr>
<td>13</td>
<td>New Haven</td>
<td>1.049</td>
<td>-5.5500</td>
</tr>
<tr>
<td>14</td>
<td>Onitsha</td>
<td>1.038</td>
<td>-4.2760</td>
</tr>
<tr>
<td>15</td>
<td>Omotosho</td>
<td>1.030</td>
<td>-6.2660</td>
</tr>
<tr>
<td>16</td>
<td>Birnin-Kebbi</td>
<td>1.080</td>
<td>-21.4560</td>
</tr>
<tr>
<td>17</td>
<td>Geregu</td>
<td>0.990</td>
<td>-0.4970</td>
</tr>
<tr>
<td>18</td>
<td>Gombe</td>
<td>0.792</td>
<td>-53.6680</td>
</tr>
<tr>
<td>19</td>
<td>Jebba</td>
<td>1.020</td>
<td>-17.8800</td>
</tr>
<tr>
<td>20</td>
<td>Jos</td>
<td>0.828</td>
<td>-47.0490</td>
</tr>
<tr>
<td>21</td>
<td>Kaduna</td>
<td>0.818</td>
<td>-38.8500</td>
</tr>
<tr>
<td>22</td>
<td>Kainji</td>
<td>1.030</td>
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<tr>
<td>23</td>
<td>Kano</td>
<td>0.814</td>
<td>43.7860</td>
</tr>
<tr>
<td>24</td>
<td>Shiroro</td>
<td>1.050</td>
<td>-26.5560</td>
</tr>
<tr>
<td>25</td>
<td>Sapele</td>
<td>1.020</td>
<td>-6.4880</td>
</tr>
<tr>
<td>26</td>
<td>Katampe (Abuja)</td>
<td>1.109</td>
<td>-32.2290</td>
</tr>
<tr>
<td>27</td>
<td>Okpai</td>
<td>1.050</td>
<td>-2.5920</td>
</tr>
<tr>
<td>28</td>
<td>Yola</td>
<td>0.791</td>
<td>-54.0280</td>
</tr>
</tbody>
</table>
6. Conclusion

In this paper, a reactive power compensation approach for power system security in weak meshed networks has been presented. Starting from the basic circuit theory, the power - flow problem is modelled as sets of nonlinear algebraic equations and solved using Newton-Raphson algorithm. The amount of reactive power required for the compensation is also modelled and presented. An enhancement in the power system voltage profiles and a reduction in the total transmission losses within the network has been presented. A typical weak meshed system of Nigeria power system network (a 28-bus system) shown in figure 2 has been used as the case study in this paper. The test results are presented in both tabular and graphical forms. The results show a substantial improvement in the bus voltage profiles when applied. Therefore, it has been established that reactive power compensation helps in the enhancement of voltage profiles and also reduces power system reactive losses within the network.

Acknowledgement

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References


<table>
<thead>
<tr>
<th>Table 2</th>
<th>Transmission line losses</th>
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<tbody>
<tr>
<td></td>
<td>Total Loss Active</td>
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<tr>
<td>Before Compensation</td>
<td>179.94</td>
</tr>
<tr>
<td>After Compensation</td>
<td>176.29</td>
</tr>
</tbody>
</table>


