Impact of DGs on Reconfiguration of Unbalanced Radial Distribution Systems

J.B.V. SUBRAHMANYAM and C. RADHAKRISHNA

Abstract - In this paper a new approach using the 0-1 integer programming method for reconfiguration of unbalanced radial distribution systems with the presence of distributed generators for voltage profile improvement and power loss minimization is presented. In practice, unbalanced distribution feeders of power utilities are characterized by low power quality, low voltage profile, more investment and high operating costs. By installing Distributed generators, voltage profile and reliability of unbalanced power distribution systems can be improved with minimization of power losses. In this paper the distributed generators have been modeled as photovoltaic (PV) systems in the unbalanced distribution system. Reconfiguration of unbalanced feeders is a good technique to balance the unbalanced distribution systems to improve the voltage profile and minimize the power losses. The results obtained with the proposed methodology on an example unbalanced power distribution system demonstrate its applicability.

Keywords: distribution systems, distributed generators, photovoltaic systems

1. INTRODUCTION

Distribution feeders supply power to various types of loads namely residential, commercial, industrial and agricultural. Each feeder has different loads and different load variations. Consequently peak loads at different feeders occur at different times. A configuration set for minimum loss at a certain instant is no longer a minimum loss configuration at a different instant of time. Hence there is a need for feeder reconfiguration for loss minimization whenever there is a change in the system loading pattern [1, 2]. To improve the reliability, efficiency and service quality distribution networks should be automated. Automation is possible with advanced microprocessor control technology. Under normal operating conditions systems will be reconfigured to reduce the power losses and under condition of permanent failure networks will be reconfigured to restore the services [5,6]. Different algorithms have been used to solve the reconfiguration problem: combinational optimization with discrete branch and bound methods, expert system techniques and heuristic methods [5]. First work on reconfiguration was presented by Merlin and Back (an integer mixed non linear optimization). But it requires checking a great number of configurations for a real sized system.

Castro proposed characteristic of the neighborhood structure which reduces the number of reconfigurations. But the CPU time is more. Castro and Franca propose modified heuristic algorithms to restore the service and load balance. Wang and Rizy proposed an integrated scheme for distribution system loss minimization with consideration of line capability limits via reconfiguration [6]. Lieu and vent proposed an application of expert system to the restoration of distribution system by group restoration, zone restoration and/or load transfer. Morelato and Nonticelli proposed a heuristic search approach based on a binary decision tree. In this approach the search space is quite large and a sub optimal solution is found. Taylor and Lubkeman proposed a heuristic search strategy to handle feeder reconfiguration for overloads, voltage problems and for load balancing [7]. This study extends these works by considering the comprehensive switching problem.

Distributed generation is related with the use of small generating units to meet load requirements installed in strategic points nearer to load centers [4]. The technologies applied in DG comprise gas turbines, Photovoltaic Systems (PV), fuel cell, wind energy etc. The planning of the distribution network for DG requires definition of several factors, such as number of DGs to be installed, technology to be used, location of each DG and capacity of each unit etc. the selection of capacity and number of DGs, location of DGs is a complex combinational optimization problem [9].

This paper presents the effect of DG units on electric power losses and voltage profile of unbalanced distribution systems. On the same system reconfiguration based on 0-1 integer programming is proposed for further minimization of the power losses. This method uses multiple switching at a time and finds the overall minimum loss network configuration.

2. IMPACT OF DISTRIBUTED GENERATION

If the Distributed generators are correctly installed at optimal locations and if units are correctly coordinated, they will have positive impact in unbalanced Distribution system. Main use of DG is for generation back up. Another popular advantage of DG
is injection of excess power into unbalanced distribution network when the DG capacity is higher than the local loads.

Distributed generators in unbalanced distribution systems perform the tasks like Load voltage stabilization, Uninterruptible power supply, Reactive power support for power factor correction, Balance the source voltages in case of unbalanced load system and Active power support.

For radial analysis of the unbalanced distribution systems, DGs can be modeled as negative loads. That means negative active and reactive power injection independent of the system voltage. Distribution systems are also regulated through tap changing transformers, by using voltage regulators and capacitors in feeders [9].

Lot of research work has been done on distribution systems reconfiguration but not on distributed generators impact on unbalanced distribution network reconfiguration.

3. PROBLEM FORMULATION

The objective of reconfiguration technique is to minimize the power flows in order to minimize the power losses. By taking voltage constraints in to consideration, a simple 0-1 integer programming technique is developed. Optimization of power flows that result in the minimum power loss configuration is possible by penalizing flows through higher resistance branches and encouraging flows through lower resistance branches.

Generally optimal power flow requires solving a set of nonlinear equations, describing optimal and/or secure operation of an unbalanced power distribution system expressed as

\[
\text{Minimize } F(x,u) \tag{1}
\]

While satisfying

\[
g(x,u)=0 \tag{2}
\]

\[
H(x,u) \leq 0 \tag{3}
\]

Where:

\(g(x,u)\): set of nonlinear equality constraints (power flow equations);

\(H(x,u)\): set of inequality constraints of bus voltage magnitudes and phase angles, as well as MVAr loads, fixed bus voltages, line parameters, and so on;

\(X\) is a vector of optimal solution to minimize power loss function;

\(U\): a vector of control variables.

The vector ‘u’ includes the following:

- Control voltage settings;
- Load tap changer transformer settings.

**Network reconfiguration problem of the unbalanced distribution system:**

The problem is formulated as a multi objective combinatorial optimization problem as described below.

For a radial unbalanced distribution system with \(k\) nodes and known topology, the problem is to find an optimal switching configuration among all possible combinations \(R_i\), with the switching changes, that minimizes the objective function, doesn’t disturb the network load flow and operational constraints.

Objective function:

\[
\text{Min } C(x, R_i) \tag{4}
\]

Subject to:

\[
F(x, R_i)=0 \tag{5}
\]

And

\[
G(x, R_i) \leq 0 \tag{6}
\]

Where

\(X\) is a vector of optimal solution to minimize power loss function

\(X = (P, Q, V)\) where \(P\) and \(Q\) represents active and reactive power  of branch receiving end  and \(V\) is the magnitude of voltage at system nodes.

\(C(x, R_i)\) is the objective function to be minimized.

\(F(x, R_i)\) is the vector of equality constraints and represents the load flow equations.

\(G(x, R_i)\) is the vector of inequality constraints and corresponds to operational constraints for the network.

**[Constraints]**

\[
F(x_1, x_2)=0
\]

\[
G(x_1, x_2) \leq 0
\]

Where \(C_1, C_2\) are mean distribution power loss and feeder power balance respectively. Here \(x_1\) represents discrete variables to show switch status and \(x_2\) represents continuous variables to calculate power flow of unbalanced distribution system.

The objective function to be minimized can be expressed as

\[
C(x, R_i) = \sum_{i=1}^{k-1} Z_{ia} P_{ia}^2 + Q_{ia}^2 + \sum_{i=1}^{k} Z_{ib} P_{ib}^2 + Q_{ib}^2 + \sum_{i=1}^{k-1} Z_{ic} P_{ic}^2 + Q_{ic}^2 \tag{7}
\]

Where \(i\) is any feeder branch; \(k\) is number of network busses; \(Z_e\) is the pu impedance of the branch.

**Power Flow Methods:** Traditional load flow methods are not enough to directly apply on unbalanced radial distribution systems. Load flow calculation method should use low memory resource and should have good convergence. Various load flow methods in use are: ladder method, current summation method and power summation method. Out of these methods, power summation method has got better convergence characteristic.
Power Summation Method: it has got two processes. In the first process, a node is taken and the active and reactive power demand from the network is determined seen from second process. This process is initialized assuming a voltage profile. In second process, using the calculated powers in previous process, magnitude of the voltage at nodes is recalculated. Convergence will be checked with voltage magnitudes only. From magnitudes it is possible to calculate the respective angles.

\[ V_i^2 + A_i V_i^2 + B_i = 0 \]  

(6)

Where

\[ A_i = 2(P_i R_i + Q_i X_i) - V_{i+1}^2 \]  

(7)

\[ B_i = (P_i^2 + Q_i^2)(R_i^2 + X_i^2) \]  

(8)

\[ \tan \beta_i = \frac{P_i X_i + Q_i R_i}{P_i R_i + Q_i X_i + V_i^2} \]  

(9)

\[ B_i = \text{ang}(V_{i+1}) - \text{ang}(V_i) \]  

(10)

\[ P_i = P_{i,i+1} + \sum_{k=1}^{N_{Ai}} P_k + \sum_{k=1}^{N_{Ai}} X_k \frac{P_k^2 + Q_k^2}{V_i^2} \]  

(11)

\[ Q_i = Q_{i,i+1} + \sum_{k=1}^{N_{Ai}} Q_k + \sum_{k=1}^{N_{Ai}} X_k \frac{P_k^2 + Q_k^2}{V_k^2} \]  

(12)

Where

\( V_{i+1}, V_i \) : Voltage magnitudes at nodes i-1 and i

\( R_i, X_i \) : Resistance and inductive reactance of section i

\( N_{Ai} \) : set of nodes directly fed from node i

\( \beta_i \) : Voltage angle difference between i-1 and i

4. PROPOSED METHODOLOGY

Network reconfiguration is the procedure of varying the topological structure of distribution feeders by changing the open/closed states of the sectionalizing and tie switches. Reconfiguration is used to reduce real power losses, relieve network from overloads by load balancing, improve system voltage profile and improve system security. In order to achieve a radial operation scheme, certain number of closed and normally open switches will be rearranged. As the number switches are generally high, the number switching combinations are also high, making the feeder reconfiguration a complex and time consuming process. Due to addition of Distributed generator in a radial structured feeder, reconfiguration in an unbalanced distribution system will be more complex [5, 8].

In this paper a simplified reconfiguration approach using the 0-1 integer programming technique is developed and applied to an unbalanced distribution system containing two Distributed generators to demonstrate its applicability. A non conventional energy source (Photo Voltaic cell) has been taken as the distributed generator. A simulation circuit has been developed to study the impact of Distributed generation on power quality of unbalanced distribution system.

To solve the above objective function by 0-1 integer programming in identifying the variable (0 or 1) for each element and power loss function for each element, the algorithm proposed is as follows.

Algorithm proposed:

1. Each element of the unbalanced distribution system is assumed to contain a sectionalizing switch so that any element can be switched for reconfiguration purpose. While the proposed reconfiguration technique is applied, each element is described by either 0 or 1 variable. 0 is assigned to an element when it is in open position and 1 is assigned when it is in closed position.

2. Each node of the circuit is assigned with another variable 1 or (-1). If the node is a switching node then assign (1) and if the node is a neighboring node then assign (-1). Each variable of the circuit is associated with a variable \( y_i \) which takes the value 1 if the node is a switching node and -1 if the node is neighboring node of the circuit.

3. Distributed generators are modeled as positive active and reactive power suppliers in the objective function. Identify the load currents that contribute to the loss function in each element of the circuit.

4. Identify the load voltages that contribute to the power loss function of each element of each circuit on each and every element in the network.

5. Find the second order and third order terms of power loss function of each circuit by finding all possible combinations of elements. The number of second order terms in the loss function of a circuit can be obtained by finding all possible combinations of 0-1 integer variables \( x_i \) taken two at a time. The number of first order terms would be equal to the number of 0-1 variables in a circuit. The coefficients contributed \( y_i \) first order terms can be obtained as follows. The coefficient \( x_m \) contributed by an element is equal to:

\[ r_i \left[ I_m^2 + 2y_i I_m (I_{m',i}) \right], \]  

where \( I_{m',i} \) is equal to sum of the load currents that contribute to the current in element i.

6. Determination of coefficients of the terms in power loss function: the coefficients of the terms in power loss function of a circuit can be obtained by taking summation of the load voltages that contribute to the power loss function of the various elements in the circuit to the respective coefficients.

7. Minimize the above objective function by 0-1 integer programming. To solve the optimization problem generalized interactive non linear optimizer has been used.

8. Based on the solution obtained in step 7, the elements to be switched have been determined.

9. end

This method uses multiple switching at a time and finds the overall minimum loss network configuration.
5. SIMULATION/MODELING OF DG

The DG can be treated as PV or PQ model in the unbalanced distribution system. The PV model represents a DG which delivers power at a specific terminal voltage; while PQ model DG delivers power irrespective of the node voltage. The latter DG model representation is adopted in this paper. Such source is modeled as a positive load delivering real and reactive power to the unbalanced distribution system.

In this section determination of the amount of standard DG that can be added at the identified nodes without loss increase and operational constraints violation is presented. Given information on the available distributed generation and assuming no expected load growth in the region of interest, the objective is to minimize the total active power loss in the system.

\[
\min f = \sum_{i} P_{t}^{\text{abc}}
\]

Where \( P_{t}^{\text{abc}} \) is the active power loss in the \( i^{th} \) branch and ‘m’ is the no. of branches in the system. The equality constraints are the power flow equations and the inequality constraints are

- voltage operational tolerance limits at all buses
  \[
  V_{i\min} \leq V_{i} \leq V_{i\max}
  \]  

- limit on losses
  \[
  \sum_{ij} P_{\text{lossG}} \leq \sum_{ij} P_{\text{lossx}}
  \]

Where \( P_{\text{loss}} \) is the power loss in the line from node ‘i’ to node ‘j’ without distributed generation and \( P_{\text{lossG}} \) with distribution generation.

- Limit on total power generated by DG subject to a penetration level of 20% (i.e. it must not exceed 20% of feeder load)
  \[
  \sum_{i} P_{Gi} \leq 0.2 \sum_{i} P_{Li}, \quad \sum_{i} Q_{Gi} \leq 0.2 \sum_{i} Q_{Li}
  \]

Where \( P_{Li} \) and \( Q_{Li} \) are the real and reactive loads at bus i.

- Branch flows limits (e.g. they must remain below thermal limits)

6. EFFECT OF PV EMBEDDED DISTRIBUTED GENERATOR SOURCE ON THE UNBALANCED DISTRIBUTION SYSTEM

6.1. Effect on voltage profile

Voltage of the unbalanced distribution system at each tapping point of the unbalanced load has been taken in to account for this study. Sufficient improvement in voltage profile of radial unbalanced distribution system has been obtained by the integration of the PV distributed generator.
6.2. Effect on power losses

With the integration of the PV embedded distributed generator, power losses due to the resistance of the radial unbalanced distribution system have been minimized. From the power loss minimization characteristics, it has been observed that the optimum point of integration of PV source on radial unbalanced distribution system is at the end load tap in the line.

6.3. Effect on load absorbed power

The power absorbed by the loads has been observed to be improved by the integration of embedded PV distributed generation on the unbalanced distribution system. Power absorbed by the load at a particular point will be improved when the load tap is integrated with PV. The improvement in the absorbed power at a particular load tap will become constant when the point of integration is shifted away from the load tap. The end load tap absorbed power increases and it is found to be maximum, when the PV source is integrated with the last load tap in the line.

The Maximum Power Point Tracker (MPPT) is integrated in the inverter control, as there is no DC-DC converter in the chosen configuration. The whole system has been simulated in Matlab-Simulink.

7. PV ARRAY SIMULATION

The PV array is simulated using a model with moderate complexity. In this model, a PV cell is represented by a current source. The photo-current $I_{ph}$ depends on the irradiance $G$ and the cell temperature $T_c$. The current $I_c$ provided by the cell can be calculated as:

$$I_c = I_{ph} - I_D = I_{ph} - I_0 \left(1 - e^{\frac{e(V_{oc} - I_{sc}R_{sh})}{n k T_c}} \right)$$

(17)

Where

- $I_0$ is the saturation current dependent on temperature
- $e$ is the charge of an electron
- $k$ is the Boltzmann’s gas constant
- $n$ is the idealizing factor of the diode.

The module is a combination of solar cells in parallel and series.

The equivalent circuit of the general model which consists of a photo current, a diode, a parallel resistor expressing a leakage current, and a series resistor describing an internal resistance to the current flow, is shown in Fig.

The photocurrent mainly depends on the solar insolation and cell’s working temperature, which is described as

$$I_{ph} = \left[ I_{sc} + K_t \left( T - T_{ref} \right) \right]$$

(18)

Where

- $I_{sc}$ is the cell’s short circuit current at 25°C and 1 kW/m²
- $K_t$ is the cell’s short circuit current temperature coefficient
- $T_{ref}$ is the cell’s reference temperature and
- $T$ is the solar isolation in kW/m².

7.1. MPPT algorithm

Maximum Power Point Tracking, frequently referred to as MPPT, is an electronic system that operates the Photovoltaic (PV) modules in a manner that allows the modules to produce all the power they are capable of. MPPT is not a mechanical tracking system that “physically moves” the modules to make them point at the sun more directly. MPPT is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. Additional power harvested from the modules is then made available as increased battery charge current. MPPT can be used in conjunction with a mechanical tracking system, but the two systems are completely different. When a conventional controller is charging a discharged battery, it simply connects the modules directly to the battery. This forces the modules to operate at a battery voltage, typically not the ideal operating voltage at which the modules are able to produce their maximum available power. The PV Module Power/Voltage/Current graph shows the traditional Current/Voltage curve for a typical 75W module at standard test conditions of 25°C cell temperature and 1000 W/m² of isolation. This graph also shows PV module power delivered vs module voltage. For the example shown, the conventional controller simply connects the module to the battery and therefore forces the module to operate at 12V. By forcing the 75W module to operate at 12V the conventional controller artificially limits power production to about 53W where as the solar boost MPPT controller operates the module at its maximum power voltage extracting full 75W.
7.2. DG simulation results

The distorted source voltages without compensation are shown in below fig.

The distorted source voltages with compensation are shown in below fig.

The fundamentals of the voltages have an unbalance of ±10%. The total harmonics distortion in phase a, b and c are 5%, 7% and 8% respectively.

7.3. Example: 31 node radial distribution system with unbalanced loads

The 31 node unbalanced radial distribution system shown in above fig. is composed of five circuits and each circuit is composed of various elements. Circuit 1 comprises of 1, 27, 28, 29, circuit 2 comprises of elements 3, 21, 22, 23, 24, 25, 26, circuit 3 comprises of elements 18, 19, 20, circuit 4 comprises of elements 9, 10, 11, 12, 13, 14 and circuit 5 comprises of elements 15, 16, 17. Elements 5 & 8 are initially open.

7.4. Reconfiguration simulation results

The simulation results of reconfiguration for the example radial distribution system with unbalanced loads are summarized in the table; from the table it is observed that the power losses have been minimized by applying the proposed algorithm. Due to inclusion of voltage constraints, the voltage profile of the system improved, reducing the power losses to minimum in the best configuration obtained.

<table>
<thead>
<tr>
<th>Network Configuration</th>
<th>Open branches</th>
<th>Losses(kW)</th>
<th>Min Voltage (p u)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>Existing without DG</td>
<td>21,18, 10, 16</td>
<td>73.16</td>
<td>78.76</td>
</tr>
<tr>
<td>Best without DG</td>
<td>23, 19, 10, 16</td>
<td>60.19</td>
<td>65.79</td>
</tr>
<tr>
<td>Existing With DG</td>
<td>23, 28, 19, 11</td>
<td>62.51</td>
<td>68.11</td>
</tr>
<tr>
<td>Best With DG</td>
<td>24, 18, 12, 16</td>
<td>44.26</td>
<td>49.86</td>
</tr>
</tbody>
</table>

8. CONCLUSION

Unbalanced power distribution systems reconfiguration in the presence of distributed generators has been investigated in this paper. A 0-1 integer program algorithm has been proposed to obtain optimal system configuration with improvement in system voltage, minimum power losses and optimum power delivered by DG, modeled as photovoltaic (PV) system. DG Simulation results show that by installing neutral clamped inverter, load currents can be balanced at source side and THD of source current can be reduced. To maintain optimum feeder reconfiguration at any point of time, it requires communication between distribution substation, nodes and DG units. The results obtained with the proposed methodology on a sample unbalanced power distribution system demonstrate its applicability.

REFERENCES

Details of the Example: 31 node radial distribution system with unbalanced loads.

<table>
<thead>
<tr>
<th>Element No.</th>
<th>Start Node</th>
<th>End Node</th>
<th>Impedance (ohms/km)</th>
<th>Receiving end load in kVA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phase A</td>
</tr>
<tr>
<td>1</td>
<td>31</td>
<td>1</td>
<td>0.13+j0.62</td>
<td>40+j20</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>0.17+j0.63</td>
<td>25+j15</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>3</td>
<td>0.19+j0.55</td>
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<tr>
<td>4</td>
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<td>0.13+j0.66</td>
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<tr>
<td>5</td>
<td>4</td>
<td>5</td>
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<td>35+j28</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
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<td>0.12+j0.78</td>
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<td>6</td>
<td>21</td>
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</table>

J.B.V. Subrahmanyam (jbvsjnm@gmail.com) received the B.Tech degree from JNTU Kakinada, and M.E degree from Jadavpur University Kolkata and presently pursuing Ph.D from JNTU-Hyderabad, India. He has very rich experience in application of latest condition monitoring techniques to reduce industry equipment breakdowns & application of modern GPS & GIS technologies to power utilities to reduce power losses & manage the power distribution utility business effectively. At present he is a professor in the Electrical & Electronics Engineering Department, TRREC, AP, India. He is actively involved in the research of planning and optimization of unbalanced power distribution systems. His research interests are computer applications in power systems planning, analysis and control.

C. Radhakrishna has more than 35 years of experience in teaching & research in Electrical engineering and published more than 85 papers in international, national journals & conferences. He is the recipient of Best Teacher award from Govt. of Andhra Pradesh, India and Jawaharlal Birth Centenary award from IE(I), India. He was associated with Jawaharlal Nehru Technological University (JNTU)-Hyderabad for several years in various positions and was the founder Director of Academic Staff College-JNTU-Hyderabad, India.