Optimal Placement of Distributed Generation and D-STATCOM in Radial Distribution Network

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ABSTRACT

Analytical approach-based technique was used in this work for finding the optimized size and location for distributed generations (DG) and Distribution Static Compensator (D-STATCOM) placement in a distribution network. Optimum placement of DG and D-STATCOM mitigated the power losses and improved the voltage profile in a radial distribution system. This technique was tested on a 33-bus radial distribution system through a voltage stability index and loss sensitivity factor, thereby determining the best possible size and optimal location for DG and D-STATCOM. The changes in voltage profile and active power losses were compared before and after installation of these devices in the distribution system.

1. Introduction

An electrical power system consists of three major parts namely; generation, transmission, and distribution. Generation system generates electricity, transmission system transmits energy from generating stations to the distributed system, while distributed lines provides electricity to the nearby loads, homes, industries, etc. In twentieth century, the power systems and electronic devices have both grown tremendously. Power quality issues have risen in the form of voltage fluctuations/spikes, variations in current or frequency that leads to failure or irregular operation of end user equipment. Due to these problems in power distribution networks industrial loads, sensitive loads, etc. suffer. So, now-a-days, power sources are located near the load to be served by the distribution system, thereby reducing the transmission losses [1]. Power quality defines the fitness value of electrical power to consumer devices. Today, the most severe power quality problems are low power factor, harmonic distortions, and the most critical voltage sags causing overheating and deterioration of the electrical equipment [2]. Therefore, power electronics devices such as Flexible...
AC Transmission Systems (FACTS) and custom power devices were invented in order to provide the power system with new control capabilities [3] and to enhance the power transfer capabilities by improving the controllability and stability of the AC systems.

Distributed generations (DG) also known as on-site generation can reduce the cost, complexities, and interdependencies of the transmission and distribution system [4]. As reactive power is the main ingredient in electricity distribution from high voltage transmission lines to low voltage end, FACTS devices are used in transmission or distribution system for enhancing the power quality, power factor, and voltage regulations. Distribution static compensator (D-STATCOM) is one of the most efficient and reliable reactive power generation devices. In this work, loss sensitivity indices have been used to obtain the optimal location for DG and proposed stability indicator is used for determining optimal location of D-STATCOM in a radial distribution network. The optimal size for both the devices has been obtained through mathematical techniques.

2. Direct Load Flow Analysis

Electricity distribution is a part of power portage infrastructure that transmits energy from high voltage transmission networks to the customers. Transmission systems have low resistance to reactance ratio whereas distribution systems have inverse ratio that results in huge power loss and is more sensitive to voltage instability. Due to these issues, conventional load flow analysis methods such as Newton Raphson, Fast decoupled, Gauss Seidel method, etc. are not able to give voltages and line flows. Therefore, another approach known as direct load flow (DLF) method is used to find the parameters [5].

A bus system of 33 nodes arranged in a radial system as shown in Figure 1 is analyzed in this paper. Power and current injection equations are used in tandem to evaluate the nodal current. A matrix representation of the relationship of injected and nodal current is formed by application of Kirchoff’s Current Law (KCL). Using KCL in distribution network, injected bus current and branch current can be related by following set of equations:

\[
B_1 = I_1 + I_2 + I_3 + I_4 + I_5 + \ldots + I_{29} + I_{30} + I_{31} + I_{32}
\]

\[
B_2 = I_2 + I_3 + I_4 + I_5 + I_6 + \ldots \ldots \ldots + I_{31} + I_{32}
\]

\[
B_{25} = I_{25} + I_{26} + \ldots \ldots + I_{30} + I_{31} + I_{32}
\]

\[
B_{27} = I_{27} + I_{28} \ldots \ldots + I_{31} + I_{32}
\]

\[
B_{28} = I_{28} + I_{29} + \ldots + I_{31} + I_{32}
\]

\[
B_{30} = I_{30} + I_{31} + I_{32}
\]

\[
B_{31} = I_{31} + I_{32}
\]

\[
B_{32} = I_{32}
\]

Thus, based on above equations, branch injection current can be related to bus currents in the following manner.

\[
[\Delta V] = [BIBC][I]
\]

\[
[B] = [BIBC][I]
\]

Figure 1. Single line diagram of 33 bus radial distribution system.
\[ [\text{BCBV}] = [\text{BIBC}]^T Z \]  
\( Z \) is the branch impedance matrix

\[ [\Delta V] = [\text{BCBV}][\text{BIBC}^T][I] \]  
(5)

\[ [\text{DLF}] = [\text{BCBV}][\text{BIBC}^T] \]  
(6)

\[ [\Delta V] = [\text{DLF}^T][I] \]  
(7)

For the radial distribution system load flow can be obtained by solving the Equations (5)–(7) iteratively.

\[ I_m^c = \frac{S_m}{V_m^c} \]  
(8)

\[ [\Delta V^{c+1}] = [\text{DLF}^T][F] \]  
(9)

\[ [V^{c+1}] = [v_0][\Delta V^{c+1}] \]  
(10)

where \( c \): iteration count and \( v_0 \): is initial voltage.

### 3. Distributed Generation

Traditional power generation units including large hydroelectric dams, nuclear plants, solar/thermal, etc. are setup at a static facility and provide electricity transmission over large distances. On the contrary, distributed energy resource-based systems also known as on-site generations are suburbanized, customizable, and more adapted towards locations adjacent to the load they serve. They typically have a capacity of 1 kW to 10 MW and provide an alternative route for the enhancement of traditional power system. They have high initial capital cost per kilowatt [4]. DGs are mainly used in small-scale industries, commercial purposes, households, etc. to supply generated electricity. It is the most efficient, highly reliable and environment friendly source of electricity. It plays a crucial role in electric power distribution. DG collects and store renewable energy from different resources, reduces the environmental impacts and improves the security and stability of the supplied energy. DG allows bidirectional flow of electricity by supplying electricity to the grid, while providing electricity to the customer as well. It also ensures higher power reliability and security. Electric power distribution system has thus improved significantly by the use of DG.

### 3.1. Optimal Location of DG

DG can be utilized to reduce the total distribution system power losses which include active as well as reactive power under some of the working constraints (inequality and equality). The main purpose of installing DG in a bus system is to enhance the active power by reducing the real power losses i.e. \( P \)R loss. The objective can thus be stated in the form of the following mathematical function:

\[ \min(f) = \min(P_{\text{loss}}) \]  
(11)

\( P_{\text{loss}} \): Total real power loss in a radial distribution system.

The power generated should be optimally delivered at the consumer’s load and not be lost in the transmission or distribution networks. Hence, the main aim is to reduce the active power losses. According to survey reports 10–13% of the total energy generated is lost in the transmission and distribution networks, therefore to overcome these losses, DGs are used that can supply or inject active power losses and improves the power quality and efficiency of the system.

### 3.2. Loss Sensitivity Factor

Search space reduction is applied by Loss Sensitivity method to find the best solution for the allocation of the distributed generators [6]. Here real and reactive powers can be expressed as:

\[ P_{\text{lineloss}(q)} = \frac{\left\{ (P_{eq(q)} \times P_{eq(q)}) + (Q_{eq(q)} \times Q_{eq(q)}) \right\} \times R_{(k)}}{V_{(q)} \times V_{(q)}} \]  
(12)

\[ Q_{\text{lineloss}(q)} = \frac{\left\{ (P_{eq(q)} \times P_{eq(q)}) + (Q_{eq(q)} \times Q_{eq(q)}) \right\} \times X_{(k)}}{V_{(q)} \times V_{(q)}} \]  
(13)

where \( P_{eq(q)} \) and \( Q_{eq(q)} \) are the total real and reactive power supplied henceforth of node ‘q’.

\[ P_{eq(q)} = \text{BIBC} \times \text{PRLPM} \ (\text{active power matrix}) \]

\[ Q_{eq(q)} = \text{BIBC} \times \text{QREPM} \ (\text{reactive power matrix}) \]

This frames the calculations fast and uncomplicated, hence real power loss is counterpoised by placing DG and imaginary power loss by some other power electronic-based device.

\[ \frac{\partial P_{\text{lineloss}(q)}}{\partial P_{eq(q)}} = \frac{2 \times P_{eq(q)} \times R_{(k)}}{V_{(q)} \times V_{(q)}} \]  
(14)
and a controller connected in shunt to the distribution networks. Figure 2 shows the schematic diagram of D-STATCOM.

4.1. Optimal Location of D-STATCOM

D-STATCOM is used to mitigate power quality complications such as voltage fluctuations, reduced power factor, total harmonic distortions, and at the same time improves overall reliability and efficiency of distribution systems by reinforcing reactive power to enhance the voltage profile and to minimize line losses. Different sensitivity indices are utilized to find the optimal position for placing D-STATCOM in a bus network, some of them are as follows [9]:

- Fast voltage stability index (FVSI)
- Combined power loss sensitivity (CPLS)
- Voltage stability index (VSI)
- Voltage sensitivity index (VSEI)
- Proposed stability index (PSI)

In this work, proposed stability indices have been used for obtaining optimal location for D-STATCOM.

4.2. Proposed Stability Index

At normal operating conditions value of PSI should be less than or equal to one, if the value is more than unity then the system is more vulnerable to instability.

$$\text{PSI} = \frac{4R}{V_i^2} \left( \frac{Q_i^2}{P_j} + P_j \right) \leq 1$$

Thus, the bus with a large PSI value is picked up for optimum placement of D-STATCOM.

4.3. Optimal Size for D-STATCOM

Procedure to evaluate the optimum size of the D-STATCOM is as follows [10]:

(a) First of all base case power flow must be run.
(b) Identify the optimal size of DG for the candidate buses selected through LSF values using the relation \( \frac{dP_{\text{DGi}}}{dP_i} = 0 \) which gives [7]:

$$P_{\text{DGi}} = P_i + P_{\text{loadi}}$$

(c) Now calculate the total power (real and apparent) losses for individual bus by placing optimal sized DG to that bus.
(d) The bus having minimum power losses after installing DG at optimal location is selected for further calculations.
(e) Repeat the procedure till the bus does not match the limits.
4.4. Price of D-STATCOM

The investment cost of the device per year can be calculated by using following equation [11]:

$$DSTAT_{\text{ann.cost}} = DSTAT_{\text{cost}} \times \frac{(1 + B)^n \times B}{(1 + B)^n - 1} \quad (19)$$

where $n$: the longituit of D-STATCOM in years = 30 years;
$B$: the asset breakeven point = 0.1; $DSTAT_{\text{cost}}$: The investment cost of D-STATCOM = 50 $/kVAR or 3200 Rs/kVAR.
where $K_p = 0.06$ ($/kWh$) or 3.84 Rs/kWh; $K_c^2 = 1$; $T = 8760$.

5. Simulation Results and Analysis

The discussed technique is simulated on 33-bus radial distribution network. Using the sensitivity analysis, the location of DG is obtained as bus 28, 13, and 9.

In the results, we have considered placement of only DGs at buses 28, 13, and 9 in one case whereas in other

Figure 5. Reactive power loss in each line with DG alone.

Figure 6. Real and reactive power variation for D-STATCOM of various sizes.

Figure 7. Per unit voltage at each bus with both DG and D-STATCOM.

4.4.1. Total Annual Cost Saving

Total annual cost saving (TACS) is the residue between cost of total energy lost before placement and cost of overall energy lost and yearly D-STATCOM cost after installation which is expressed as follows:

$$TACS = K_p(T \times P_{\text{Th}}) - K_p(T \times P_{\text{Th}}^\text{withDSTAT}) - (K_c \text{DSTAT}_{\text{ann.cost}})$$ (20)
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Figure 5 gives the reactive power loss in each line of 33-bus radial distribution system with placement of DG at bus 28, 13, and 9.

D-STATCOM is placed optimally at bus 30 using PSI. For determining the optimal sized D-STATCOM, it is placed at bus 30 with different sizes as indicated in Figure 6. From the figure, it can be inferred that optimal size of D-STATCOM is 1250 kVAR for maximum reduction in active and reactive power losses.

Table 1. Active and reactive power losses with and without D-STATCOM.

| Size of DG (kW) | Total active power loss (kW) | Total reactive power loss (kVAR) | Size of D-STATCOM (kVAR) at 30th bus | Total active power loss (kW) | Total reactive power loss (kVAR) |
|----------------|-----------------------------|---------------------------------|-------------------------------------|-----------------------------|---------------------------------|
| Without DG     | –                           | 201.8925                        | 1250                                | 141.9609                    | 95.3274                         |
| DG at 28th bus | 41.4                        | 197.7210                        | 131.9246                            | 138.1611                    | 92.8549                         |
| DG at 13th bus | 67.8                        | 193.2881                        | 128.7674                            | 133.7732                    | 89.7350                         |
| DG at 9th bus  | 44.1                        | 197.3648                        | 131.5380                            | 137.6711                    | 92.3846                         |

case DGs are placed at these buses with placement of D-STATCOM in the network. The size of DG is 41.4 kW at bus 28, 67.8 kW at bus 13, and 44.1 kW at bus 9.

After placement of DGs at bus 28, 13, and 9, per unit voltage at each bus is obtained as indicated in Figure 3. There is slight improvement in voltage profile with placement of DGs at appropriate buses.

Figure 4 represents the improvement in active power loss in each line with placement of DG at bus 28, 13, and 9.

Figure 8. Active power loss in each line with both DG and D-STATCOM.

Figure 9. Reactive power loss in each line with both DG and D-STATCOM.
Table 2. Total active and reactive power losses with DSTATCOM and with DG of same size at different buses.

| Fix D-STATCOM at 30th bus | Size of D-STATCOM (kVAR) | Size of DG (kW) | Total active power losses (kW) | Total reactive power losses (kVAR) |
|---------------------------|--------------------------|-----------------|-----------------------------|---------------------------------|
| DG at 28th bus            | 1250                     | 41.4            | 138.1611                    | 92.8549                         |
| DG at 13th bus            | 136.8952                 |                 |                            |                                 |
| DG at 9th bus             | 137.9001                 |                 |                            |                                 |
| DG at 28, 13 and 9th bus  | 41.4 at each bus         |                 | 129.3058                    | 86.7936                         |

Table 3. Total active and reactive power losses with DSTATCOM and with DG of same size at different buses.

| Fix D-STATCOM at 30th bus | Size of D-STATCOM (kVAR) | Size of DG (kW) | Total active power losses (kW) | Total reactive power losses (kVAR) |
|---------------------------|--------------------------|-----------------|-------------------------------|---------------------------------|
| DG at 28th bus            | 1250                     | 67.8            | 135.7892                      | 91.3135                         |
| DG at 13th bus            | 133.7732                 |                 | 89.7350                       |                                 |
| DG at 9th bus             | 135.4183                 |                 | 90.8412                       |                                 |
| DG at 28, 13 and 9th bus  | 67.8 at each bus         |                 | 121.7023                      | 81.6761                         |

Table 4. Total active and reactive power losses with DSTATCOM and with DG of same size at different buses.

| Fix D-STATCOM at 30th bus | Size of D-STATCOM (kVAR) | Size of DG (kW) | Total active power losses (kW) | Total reactive power losses (kVAR) |
|---------------------------|--------------------------|-----------------|-------------------------------|---------------------------------|
| DG at 28th bus            | 1250                     | 44.1            | 137.9167                      | 92.6960                         |
| DG at 13th bus            | 136.5721                 |                 | 91.6454                       |                                 |
| DG at 9th bus             | 137.6711                 |                 | 92.3846                       |                                 |
| DG at 28, 13 and 9th bus  | 44.1 at each bus         |                 | 128.5116                      | 86.2587                         |

DG is placed individually at bus 28, 13, and 9 with D-STATCOM at bus 30 for voltage profile improvement as shown in Figure 7.

Figure 8 gives the active power loss in each line after placement of D-STATCOM at bus 30 and placement of DG at bus 28, 13, and 9.

From Tables 2–4, after placement of DGs having same size at bus 28, 13, and 9, optimal location for DG is selected as 13th bus. The optimal size of DG is 67.8 kW at bus 13.

6. Conclusions

From the proposed stability index and sensitivity index, we concluded that optimal location for D-STATCOM placement was at bus number 30. Buses 28, 13, and 9 were the candidate bus for placing DG. After considering different sizes for maximum active and reactive power loss reduction, bus 13 was the optimal position for DG placement. Optimal size for D-STATCOM was 1250 kVAR which reduces total reactive power loss from 134.6413 to 95.3274 kVAR. Optimal size for DG was 67.8 kW and it resulted in reduction of total active power loss from 134.6413 to 121.7023 kW, per unit voltage increased from 0.9222 to 0.9546 pu. The techniques for determination of optimal location and sizes of DG and D-STATCOM were successfully tested on 33-bus radial distribution system. The application of DG resulted in reduction of active and reactive power losses, but placement of D-STATCOM at optimal location has resulted in significant reduction in power losses. This approach can be used in some future research work with incorporation of multi-DGs and multi-DSTATCOMs or other FACTS devices in place of DSTATCOM.

Table 3 gives the active and reactive power losses with DG size of 67.8 kW at bus 28, 13, and 9 whereas Table 4 gives the active and reactive power losses with DG size of 44.1 kW.

From Tables 2–4, after placement of DGs having same size at bus 28, 13, and 9, optimal location for DG is selected as 13th bus. The optimal size of DG is 67.8 kW at bus 13.

Cost of D-STATCOM:

\[
DSTAT_{ann.cost} = DSTAT_{cost} \times \frac{(1 + B)^n \times B}{(1 + B)^n - 1}
\]

Substituting the values for all the parameters the cost of D-STATCOM was Rs. 404800 (6325 $).

Total annual cost saving (TACS):

\[
TACS = K_p (T \times P_{Tloss}) - K_p (T \times P_{Tloss}^{withDSTAT}) - (K_c \times DSTAT_{ann.cost})
\]

\[
K_p = 0.06 ($/kWh), K_c = 1, T = 8760
\]

\[
= 0.06(8760 \times 201.8925) - 0.06(8760 \times 141.9609)
\]

\[
- 1 \times 6325 = 24,875$ = 1592000 INR
\]

Substituting the values for different parameters in above equation the TACS of D-STATCOM was Rs.1592000 (24,875 $).

Table 2 gives total active and reactive power losses with DG of same size 41.4 kW at bus 28, 13, and 9 along with D-STATCOM of 1260 kVAR placed at bus 30.
Disclosure Statement

No potential conflict of interest was reported by the authors.

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