2. Modeling of distributed generation (DIG) and Shunt Capacitor (SC)

A. Modeling of DIG

A proper modeling of DIG is important from the standpoint that it needs to be integrated in the load flow model. Here, the DIG is selected to give only active power to the system. Therefore, it is modeled as PQ model to integrate it with the distribution system load flow analysis [12]-[13]. DIG is modeled as negative load in the analysis as discussed with the help of Figure 1.

A sample distribution system is shown in Figure 1 that consists of 3 buses and a DIG is incorporated at bus 2 of the system. The active and reactive load demand of the consumers' at bus is P_L and Q_L, respectively. The active power supplied by DIG is P_D whereas DIG supplies no reactive power. Since DIG is modeled as negative load, the equivalent active and reactive power demand at Bus 2 can be calculated accordingly (1) and (2), respectively.

$$P_L^{eqv} = P_L - P_D \qquad (1)$$

$$Q_L^{eqv} = Q_L - 0 \qquad (2)$$

where,

P_L^{eqv}: Equivalent Active power at Bus 2.

Q_L^{eqv}: Equivalent Reactive power at Bus 2.

P_L: Active power load at Bus 2.

Q_L: Reactive power load at Bus 2.

P_D: Active power supplied by DIG.

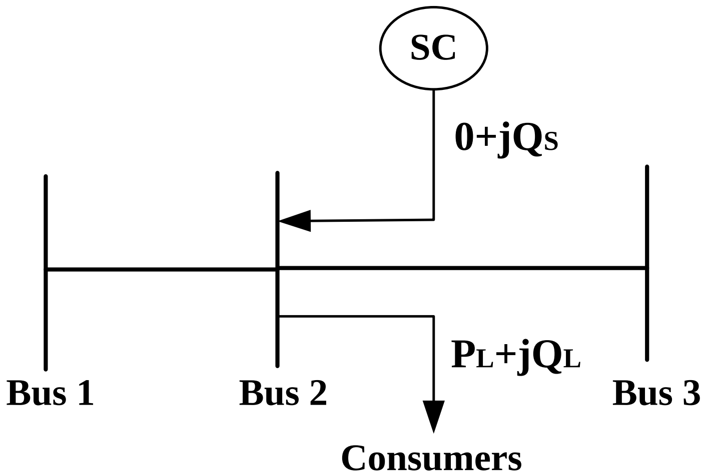

Figure 2. Single line diagram of 3-bus distribution system integrated with Shunt Capacitor.

B. Modeling of Shunt Capacitor

A proper modeling of shunt capacitor is important from the standpoint that it needs to be integrated in the load flow model. Here, the main function of shunt capacitor is to compensate the reactive power demand. Therefore, it is modeled as PQ model to integrate it with the distribution system load flow analysis [14]-[15].

A sample distribution system is shown in Figure 2 that consists of 3 buses and a shunt capacitor is incorporated at bus 2 of the system. The shunt capacitor is denoted as 'SC'. The reactive power supplied by shunt capacitor is Q_S whereas shunt capacitor supplies no active power. The equivalent active and reactive power demand at Bus 2 can be calculated accordingly (3) and (4), respectively.

$$P_L^{eqv} = P_{Load} - 0 \quad (3)$$

$$Q_L^{eqv} = Q_L - Q_S \quad (4)$$

3. OBJECTIVE FUNCTIONS

In this study, the installation cost, maintenance cost, grid energy reduction costs are taken as wider economic objectives whereas the reductions of real and reactive power losses are considered as the technical aspects. This section represents a detailed description of these indexes as given below:

C. Cost Index (CI)

Due to the integration of DIG and shunt capacitor, there is real and reactive power reduction from the electrical grid. As a result, the distribution system owner will get benefitted. However, the cost of incorporation of these devices is very high. Therefore, a cost index (CI) is formulated in this study to check whether the investment of these devices is beneficial for the distribution system owner or not.

$$CI = \frac{\text{Obtained Benefit (OB)}}{\text{Investment Cost (IC)}} \quad (5)$$

$$IC = Cost_{DIG}^{ins} + Cost_{DIG}^{main} + Cost_{SC}^{ins} + Cost_{SC}^{main} \quad (6)$$

$$Cost_{DIG}^{ins} = P_{DIG} \times C_{DIG} \quad (7)$$

$$Cost_{DIG}^{main} = P_{DIG} \times M_{DIG} \times N_{Plan} \quad (8)$$

$$Cost_{SC}^{ins} = Q_{SC} \times C_{SC} \quad (9)$$

$$Cost_{SC}^{main} = Q_{SC} \times M_{SC} \times N_{Plan} \quad (10)$$

where,
$Cost_{DIG}^{ins}$: Installation cost of DIG ($).
$Cost_{DIG}^{main}$: Maintenance cost of DIG ($).
$Cost_{SC}^{ins}$: Installation cost of shunt capacitor ($).
$Cost_{SC}^{main}$: Maintenance cost of shunt capacitor ($).
P_{DIG}: Power output of DIG in KW
Q_{SC}: Power output of shunt capacitor in KVAr.
C_{DIG}: Cost of DIG per KW.
C_{SC}: Cost of shunt capacitor per KVAr.
M_{DIG}: Maintenance cost of DIG.
M_{SC}: Maintenance cost of shunt capacitor.
N_{plan}: The planning horizon that is taken as 10 years.

$$OB = \Delta P_{active} + \Delta Q_{rective} \quad (11)$$

$$\Delta P_{active} = (P_{wod} - P_{wd}) \times C_{ap} \times N_{Plan} \quad (12)$$

$$\Delta Q_{rective} = (Q_{wod} - Q_{wd}) \times C_{rp} \times N_{Plan} \quad (13)$$

where,
P_{wod}: Active power from grid without device.
P_{wd}: Active power from grid with device.
Q_{wod}: Reactive power from grid without device.

Q_{wd}: Reactive power from grid with device.
C_{ap}: Unit price of active power from the grid
C_{rp}: Unit price of reactive power from the grid.

D. Active and Reactive loss reduction index (ALRI & RLRI)

With the incorporation of DIG, it is possible to reduce line losses significantly. A formula namely active and reactive loss reduction index (ALRI & RLRI) is formulated as follows:

$$\text{ALRI} = \frac{(P_L)_{\text{with DIG}}}{(P_L)_{\text{without DIG}}} \quad (14)$$

$$\text{RLRI} = \frac{(Q_L)_{\text{with DIG}}}{(Q_L)_{\text{without DIG}}} \quad (15)$$

where,
P_L: System's active power loss
Q_L: System's reactive power loss.

E. Conversion of multi-objective problem into single-objective problem

After bringing all the considered objectives in the same range and by using the proper weighting coefficient, the multi-objective optimization problem is transformed into a single-objective optimization problem, as shown in the equation (16).
Minimize

$$F = w_1 \times CI + w_2 \times ALRI + w_3 \times RLRI \quad (16)$$

F. Constraints

In this study, different power system constraints are taken into account for the integration of DIG and shunt capacitor into the distribution network. The constraints can be classified as active power balance, reactive power balance, bus voltage magnitude, power flow constraints, and DIG and shunt capacitor capacity constraints.

4. SOLUTION ALGORITHM

The working principle of particle swarm optimization is based on swarm intelligence and is inspired by the social behavior of birds flocking or fish schooling. This technique is an optimization procedure that is stochastic in nature. Dr. Eberhart and Dr. Kennedy had developed this algorithm in 1995. PSO tool is implemented to optimize the solution search space. PSO works on velocity and position updates which is based on local optimum or global optimum. Both conditions suitably work on random function. Multidimensional objective function has to be provided with limits to optimize using either curve fitting or regression analysis technique.

In this algorithm, a group of populations are randomly developed inside a predefined search space. Optimal position can be reached when the population that has the best fitness value guides the other particles. Each particle in the search space has a random velocity that is associated with it. The position and velocity upgrading formula for all the population is based on the equations (17) and (18), respectively.

$$v_d^{it+1} = w \times v_d^{it} + c_1 \times \text{rand}\left(\text{pbest}_d^{it} - s_d^{it}\right) + c_2 \times \text{rand}\left(\text{gbest}_d^{it} - s_d^{it}\right) \quad (17)$$

$$s_d^{it+1} = s_d^{it} + v_d^{it+1} \quad (18)$$

where,

s_d^{it}: The d[th] particle's current position in the d-dimensional space.

v_{id}^{it} : The d[th] particle's current velocity in the d-dimensional space.

$pbest_d^{it}$: The d[th] particle's pbest for it[th] generation. $gbest_d^{it}$: The global best particle of the entire swarm.

v_d^{it+1}: The updated velocity.

s_d^{it+1}: The updated position.

w: The inertia weight.

rand: any random number in [0, 1].

5. RESULTS AND DISCUSSIONS

The developed technique is applied to a 33-bus radial distribution system to solve the optimum deployment problem of DIG and Shunt Capacitor. The bus and line data for the test system can be acquired from [10] and Schematic diagram of the test network is shown in Figure 3. The power flow analysis is conducted using backward forward sweep load flow method. The base power is taken as 100 MVA, and the base voltage is considered to be 12.66 kV.

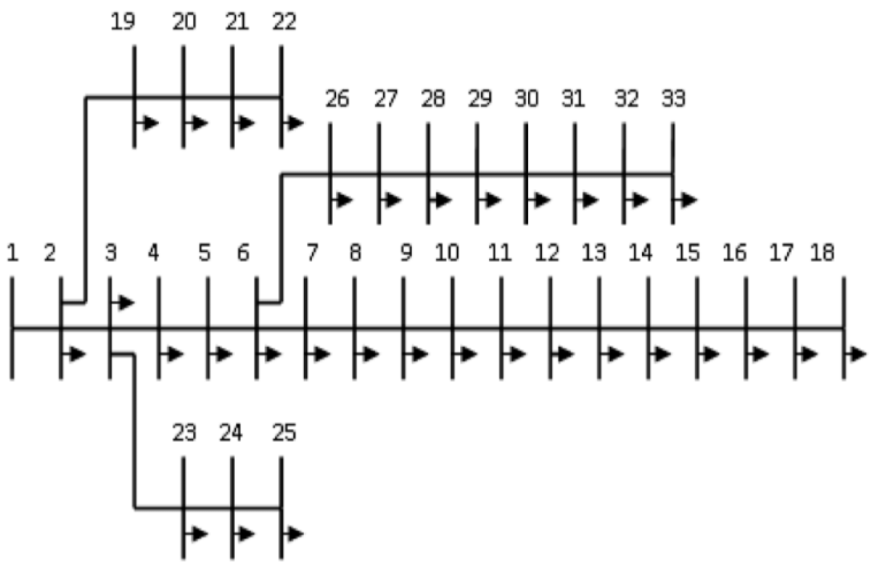

Figure 3: Schematic diagram of 33-bus radial distribution system.

Different scenarios are considered for the analysis purpose:

Scenario 1: System performance at Base case
Scenario 2: System performance with DIG only
Scenario 3: System performance with Shunt Capacitor only
Scenario 4: System performance with DIG and Shunt Capacitor

Table 1: Different scenarios that are taken into account in this study

Devices	Scenarios			
	1	2	3	4
Distribution Generation (DIG)	NC	C	NC	C
Shunt Capacitor	NC	NC	C	C

C: Considered;
NC: Not Considered

Table 2: Optimal location and size of DIG and Capacitor and objective values for different scenarios.

Scenario	Shunt Capacitor		DIG		Value of CI	Value of ALRI	Value of RLRI
	Size	Location	Size	Location			
1	-	-	-	-	0	1.000	1.000
2	-	-	1875.8	Bus 6	2.145	0.538	0.562
3	1352.2	Bus 30	-	-	5.124	0.706	0.710
4	1375.5	Bus 31	1945.5	Bus 6	3.452	0.276	0.311

Table 3: Detail economic analysis of different scenarios.

Scenario	Investment Cost (IC)	Obtained Benefit (OB)	Net Benefit (NB)
1	-	-	-
2	1481882.1	3178637.7	1696755.6
3	94654.2	458008.1	363353.9
4	1576536.8	5442202.3	3865665.5

In the 33-bus distribution system, all the above-mentioned scenarios are analyzed and the obtained

results for location and size of DIG and shunt capacitor and the obtained values of the objectives are presented in Table 2. The table shows that the lowest values of ALRI and RLRI are obtained in the scenario 4, which indicates that the simultaneous incorporation of DIG and capacitor is important from loss reduction viewpoint. On the other hand, compared to shunt capacitor, more loss reduction is possible with DIG.

As shown in Table 2, the value of CI is the highest in case of scenario 3 and the lowest in scenario 2. In such context, a detailed economic analysis is done in Table 3. This table indicates that the highest IC is obtained for scenario 4 due to the incorporation of both the devices simultaneously. However, the net benefit after 10 years of time period is the highest for scenario 4. Moreover, scenario 3 presents the lowest benefits.

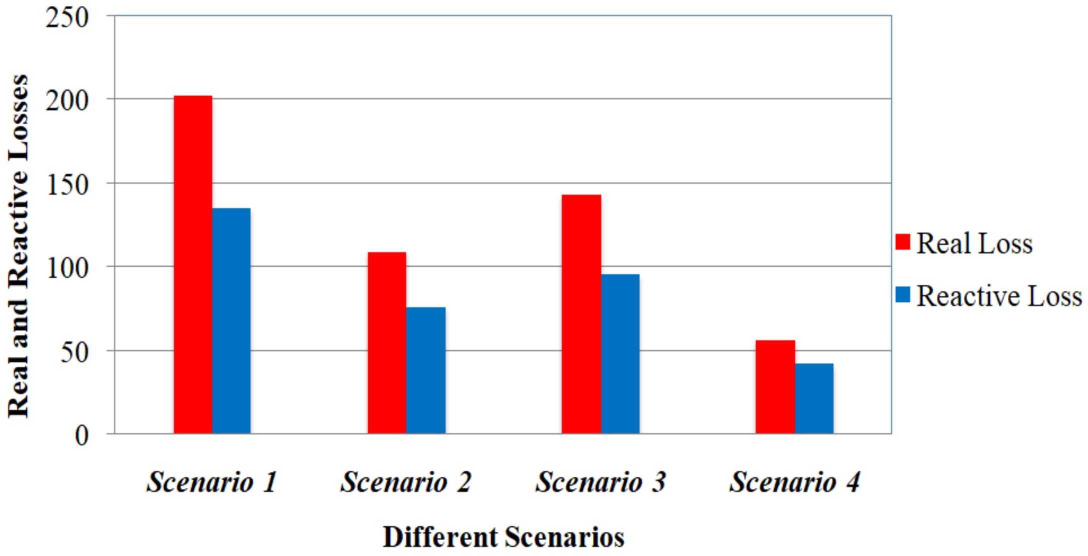

Figure 4: Real and Reactive power loss of different scenarios.

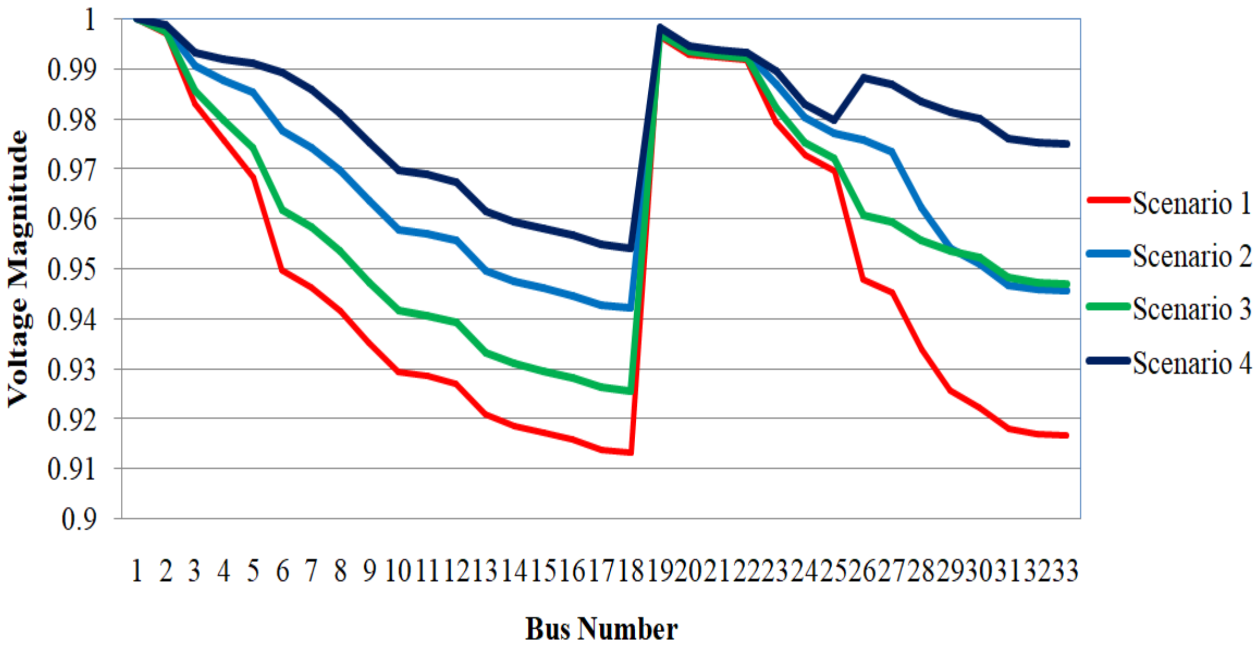

Figure 5: Bus voltage magnitude corresponding to different scenarios.

Figure 4 presents a comparative analysis between considered scenarios on the basis of real and reactive line losses. It is evident from the figure that the active and reactive power is significantly decreased in the radial distribution system in the presence of DIG and shunt capacitor. But the highest reduction of losses occurs when both DIG and shunt capacitor are incorporated simultaneously as compared to their separate utilization. Moreover, DIG is superior to shunt capacitor regarding loss reduction.

The voltage magnitude of different buses of 33-bus radial distribution system at base scenario and after integration of DIG and shunt capacitor is determined to compare in Figure 5. This figure clearly indicates that in base case, most of buses exhibits a lower voltage magnitude as compared to the nominal voltage i.e. 1 P.U. However, there is significant enhancement of voltage profile of all the buses and most of the bus voltage magnitude is obtained more than the minimum voltage limit i.e. 0.95 P.U. with the integration of DIG and shunt capacitor. However, in this case also, the simultaneous integration of DIG and shunt capacitor provides the highest voltage magnitude enhancement.

6. CONCLUSION

In this research article, a PSO based optimization technique is presented to optimally deploy DIG and shunt capacitor in the radial distribution system. The distribution system is operated with low voltage and hence current value is high. Moreover, the resistance of the distribution system is high compared to the reactance value. Due to these reasons, the active and reactive power loss of the distribution system is very high. It also reduces the efficiency of power transfer and deteriorates the system's voltage profile. The key goal is to reduce the system's active and reactive power losses while still maximizing the economic benefits. Different cases are considered to make an in depth analysis. The obtained results reveal that significant amount of potential benefit can be obtained with the incorporation DIG and shunt capacitor. In comparison with the shunt capacitor, DIG presents more reduction of real and reactive power losses. Although the investment cost of DIG is more as compared to shunt capacitor, but DIG provides more economic benefits. However, the highest reduction of system losses and the highest economic benefit are obtained when both DIG and shunt capacitor are incorporated simultaneously.

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