Chapter 5

Feeder Load-Balancing using Re-phasing of Single Phase DGs

Single phase distributed generation (DG) along with reactive support has been sized and sited to mitigate phase unbalance, thereby reducing non-positive sequence currents at root node. This is an MINLP problem attempted with Butterfly Optimization technique. The results reveal that suitably sized and sited DG can reduce line losses, improve main transformer utilization besides improving voltage profile at buses as an additional advantage.

5.1 Introduction

Distribution system loads tend to have preponderance of single phase loads, which naturally makes a distribution system susceptible to phase unbalance. Balancing of phase currents has been conventionally dealt with by manually allocating loads to different phases as part of planning, a process which is at best ad-hoc and decidedly sub-optimal. With assumption of balance in phases of distribution systems, the neutral conductors are designed to carry smaller current. Apart from the above mentioned problem due to unbalanced phase currents, one of the major concerns that is of overloading of main substation transformer. Due to unbalance the phase having the maximum loading decides the capacity of the substation transformer. Even though the transformer is underloaded on the other two phases, it cannot further be loaded to take by the extra load. Phase unbalance leads to voltage quality issues, sub-optimal utilisation of transformers, zero- and negative-sequence currents. Power Electronic based interventions have been proposed [60], an approach which is expensive. In case voltage control equipment are present, they can be used in coordinated manner to regulate the currents in three phases. Local flow concept has been used by [62]. Reference [63] examined use of load switching arrangements. The other method to redistribute the phase currents is to use load switching arrangement. Most of the studies assume that the load switching arrangement is available on all the load buses. It is also assumed that change in phase sequence does not affect the operations of three phase loads such as induction motors. A method of re-phasing of loads to achieve feeder phase-balancing has been proposed in [74]. When a single-phase load changes its phase at any given bus, following problems occur.

1. It causes momentary interruption in the load service.

2. It results in change of phase sequence due to which this method is not suitable for a network comprising of sequence sensitive $3-$phase loads such as $3-$phase inductions motors.

Feeder phase balancing using single phase DGs-the method proposed in this chapter alleviates above problems because while a single-phase DG at a given bus switches from one phase to the other (i) service of load is not interrupted, even momentarily, and (ii) phase-sequence does not change hence this method shall be suitable for the distribution networks comprising of sequence sensitive $3-$phase loads such as $3-$phase induction motors.

Penetration of DGs in distribution system offers possible solution for phase balancing, which present work seeks to explore. This work examines optimal sizing and siting of single phase DGs and reactive power support at candidate buses to reduce phase unbalance at the root node. This work seeks to use Butterfly Optimizer (BO) based search [58].

5.2 Problem Formulation

The problem is framed in three parts. First part deals with mathematical representation of DG-switch which seeks to place the single phase DG at a particular phase of the selected bus. Next step seeks to place DG in current injection based power flow. Lastly, sizing and placement of DGs is decided.

5.2.1 Mathematical representation of DG-Switch

Vector S^k decision state of DG-switch for n^{th} DG at k^{th} iteration.

$$S_n^k = \begin{pmatrix} b_n^k \\ Ph_n^k \\ DGp_n^k \\ DGq_n^k \end{pmatrix} \tag{5.1}$$

where, $b_n^k \in (2, B)$, $Ph_n^k \in (1, 3)$, B is number of buses, and $DGp_n^k + jDGq_n^k$ is the complex power provided by the n^{th} DG.

5.2.2 Inclusion of DGs in 3-phase distribution load flow

DGs are in general modelled as negative load. An approach based on current injection method [17], is used for power flow. Suitable changes in the algorithm [17] were made to accommodate DGs.

Size of n^{th} DG connected to particular phase ($l == Ph_n^k$) of particular bus ($i == B_n^k$) at k^{th} iteration is expressed as:

$$P\_in_{i,l}^k = P\_sp_{i,l}^k - DGp_n^k \tag{5.2}$$

$$Q\_in_{i,l}^k = Q\_sp_{i,l}^k - DGq_n^k \tag{5.3}$$

where $l \in \{a, b, c\}$, suffix in denotes the injection and sp denotes specified power.

BO has been used in present work to find optimal siting and sizing of DGs. The objective function considered here is minimization of negative and positive sequence currents at the main transformer. The objective function can, thus, be stated as follows.

minimize

$$RMSI(S) = (|I_0(1)|^2 + |I_2(1)|^2) \tag{5.4}$$

such that the load flow constraints are satisfied, where I_0 is zero-sequence and I_2 is negative-sequence current at node.

5.3 Result and Discussion

5.3.1 Test system

A 25-bus, 3-phase test system [73] shown in Fig. 5.1, having base load data and line parameters as given in [73]has been used to study proposed phase balancing.

5.3.2 Parameter Settings for BO

The parameters of BO algorithm used are as follows: $N = 100$, $F = 0.5$ and $D = 20$. The positions of individual butterflies x_i^k's in the matrix P_1 is according to following scheme.

x_i^k for $i = 1..5$, $\quad x_i^k \in [2, 25]$

x_i^k for $i = 6..10$, $\quad x_i^k \in [1, 3]$

x_i^k for $i = 11..15$, $\quad x_i^k \in [DGp_n^{min}, DGp_n^{max}]$

x_i^k for $i = 15..20$, $\quad x_i^k \in [DGq_n^{min}, DGq_n^{max}]$

where DGp_n^{min} and DGp_n^{max} are minimum and maximum active power capacity of n^{th} DG and DGq_n^{min} and $DGq_n^{max}$are the minimum and maximum reactive power capacity at n^{th} bus. While performing the current injection load flow the values of x_i^k are translated to appropriate elements of switch matrix S_n^k.

The stopping criteria used is quite stringent one i.e. the BO is assumed to converge when for last 1000 iterations, (i) there is no change in $RMSI$, and (ii) $\|\bar{x}_k - \bar{x}_{k-1000}\|_1 \leq 0.0001$

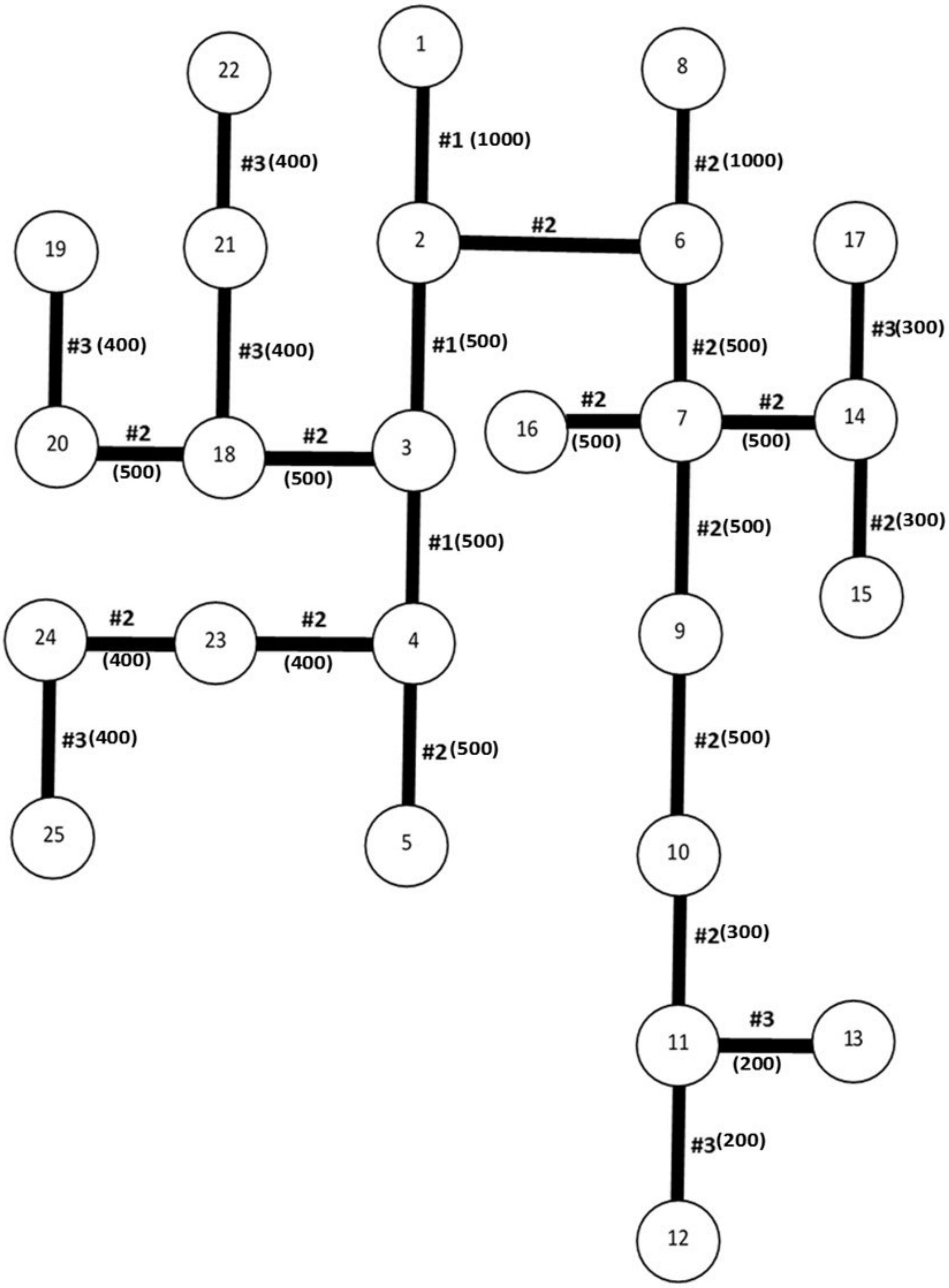

Figure 5.1: Test system showing line type(#) and line length (ft.).

5.3.3 Studies Performed

The studies have been performed for the following three scenario.

1. Scenario 1: Base-loading scenario.

Table 5.1: Optimal location and Sizing of Single base DGs calculated by Butterfly Optimizer

DGs	Bus number	phase	Real Power	Reative power
1	3	a	0.498373	0.704109
2	11	a	1.650338	0.182720
3	12	c	0.451973	0.596339
4	20	a	1.589350	1.316118
5	25	c	1.616666	0.660875

2. Scenario 2: 24-hour loading scenario.

3. Scenario 3: Effect of Voltage-dependency on DG placement.

5.3.3.1 Scenario 1: Base loading scenario

This scenario considers that at base load five single-phase DGs are available for the given system, BO has been applied to find (i) optimal bus and phase locations of these five DGs and, (ii) optimal sizes of these five DGs.

For the 25-bus system, phase-wise active and reactive loads for a typical 24-hour loading scenario are shown in Fig. 5.2 and Fig. 5.7 respectively. For this system, it was decided to identify five location to place five single-phase DGs for phase balancing. To perform this task, optimal-DG placement was done for the system peak MVA load scenario(12^{th} hour). In this case, optimal location and sizes for these five DGs were obtained using Butterfly Optimizer (BO). The placement and sizing was decided according to minimization of negative- and zero-sequence currents (RMSI) at root node.

The result of optimization problem solved by BO is depicted in Table 5.1. The real and reactive powers obtained through optimization are assumed to be maximum capacity of the DGs placed at these buses. It is also assumed that the DGs have switching capacitors to provided reactive support suggested by the optimization. The resulting phase-wise distribution of loads after placing DGs at their optimal locations with optimal sizes are given in Table 5.2. It is observed

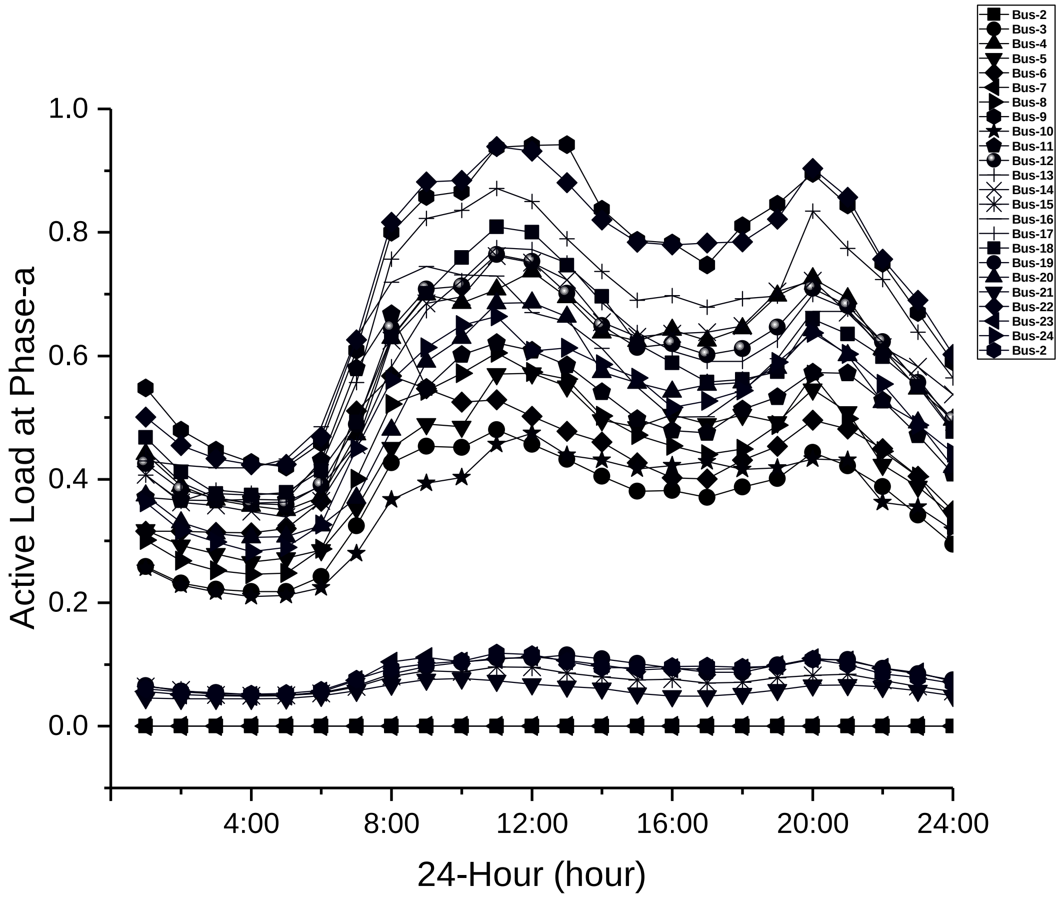

Figure 5.2: Active load for all the buses at phase-a for 24 hours.

that, on the main sub-station, the load among the three phases gets balanced after optimally locating and sizing the five DGs as is obvious from the values of active and reactive power at bus 1. The load flow results for base-case system and system with DGs are given in Table 5.3. From Table 5.3, it is observed that minimum system voltages in each of the phases ($Min(V^a)$, $Min(V^b)$, and $Min(V^c)$ get improved and more balanced after placing the optimally sized DGs as compared to the base case (without DGs). Thus, after installing DGs, the overall system voltage profile improves along the phases. The maximum voltage unbalance at each bus (δV_{max}^{ph}) in case of base case is quite high as compared to one with DG case. Thus, after installing DGs, the phase-wise maximum voltage unbalance, Max(δV_{max}^{ph}), reduces considerably i.e. from 0.027 p.u to 0.018 p.u. The

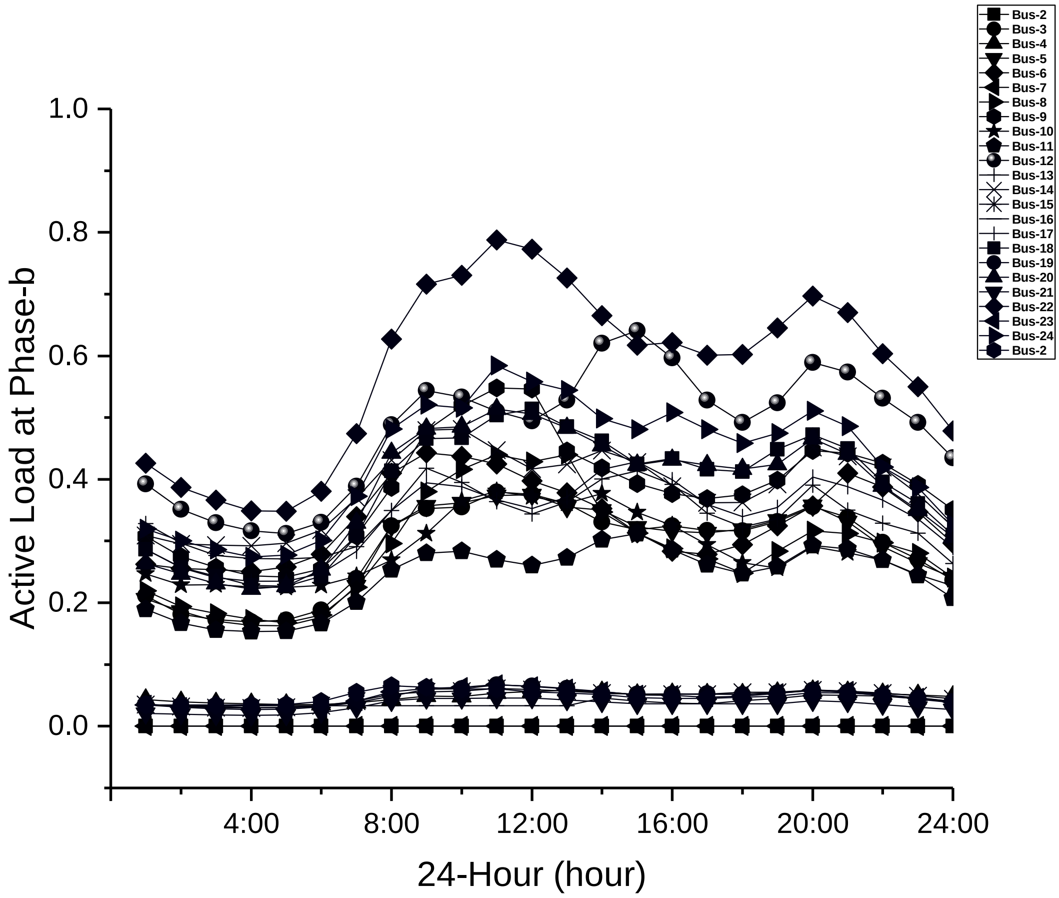

Figure 5.3: Active load for all the buses at phase-b for 24 hours.

system Phase Utilization Index (PUI) is calculated using the following expression

$$PUI = \frac{Max\{|I_a - I_{avg}|, |I_b - I_{avg}|, |I_c - I_{avg}|\} \times 100}{I_{avg}} \tag{5.5}$$

where, $I_{avg} = \frac{I_0+I_1+I_2}{3}$.

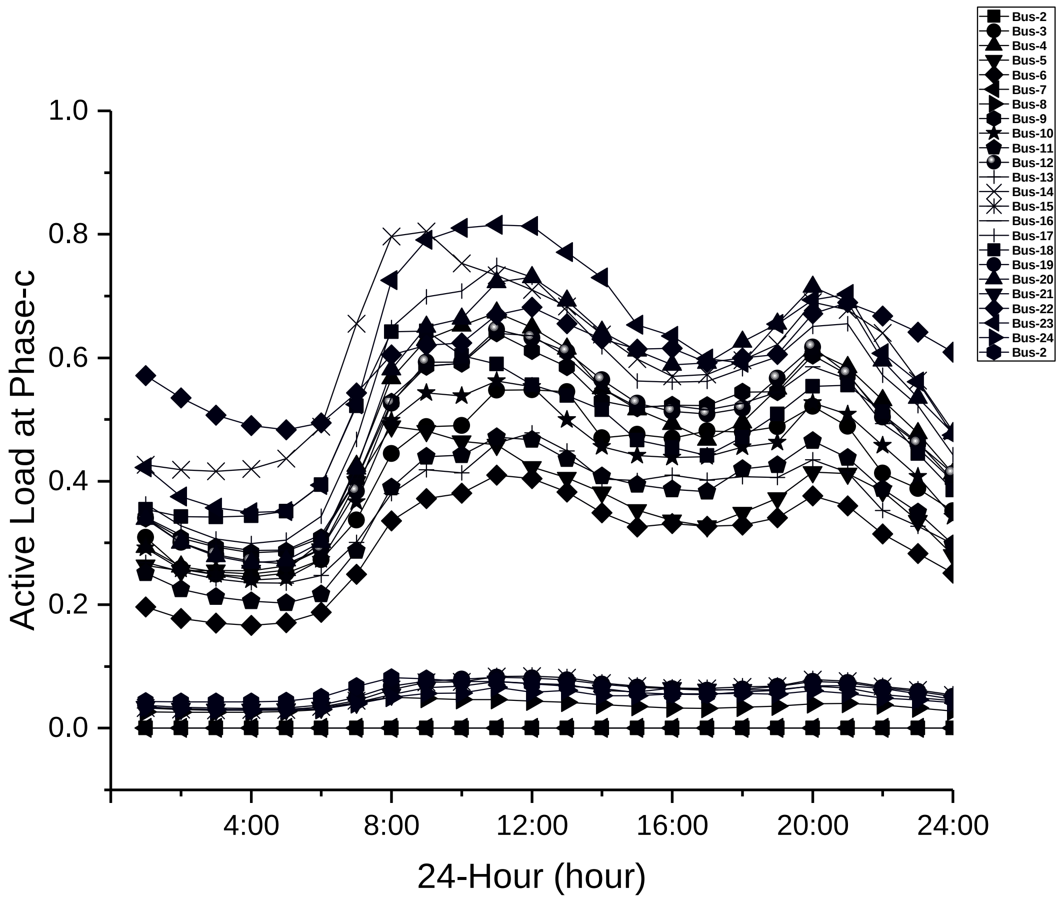

Figure 5.4: Active load for all the buses at phase-c for 24 hours.

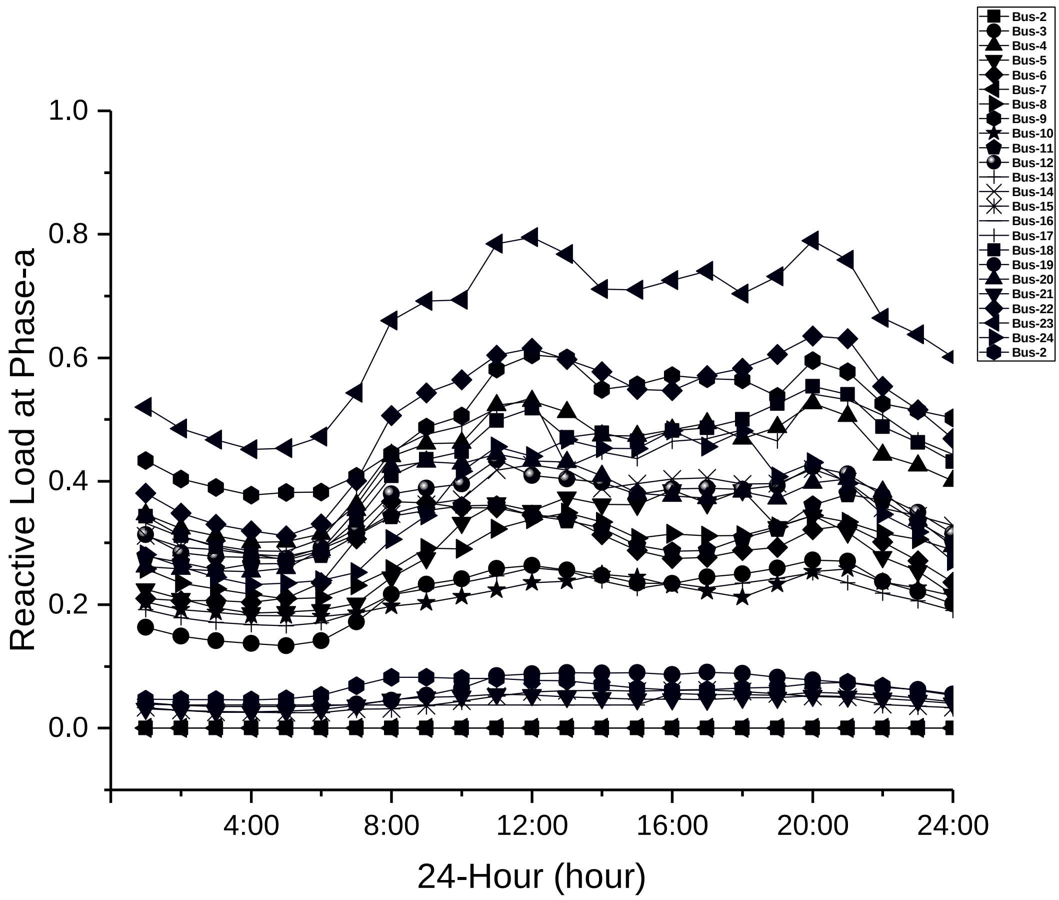

Figure 5.5: Reactive load for all the buses at phase-a for 24 hours.

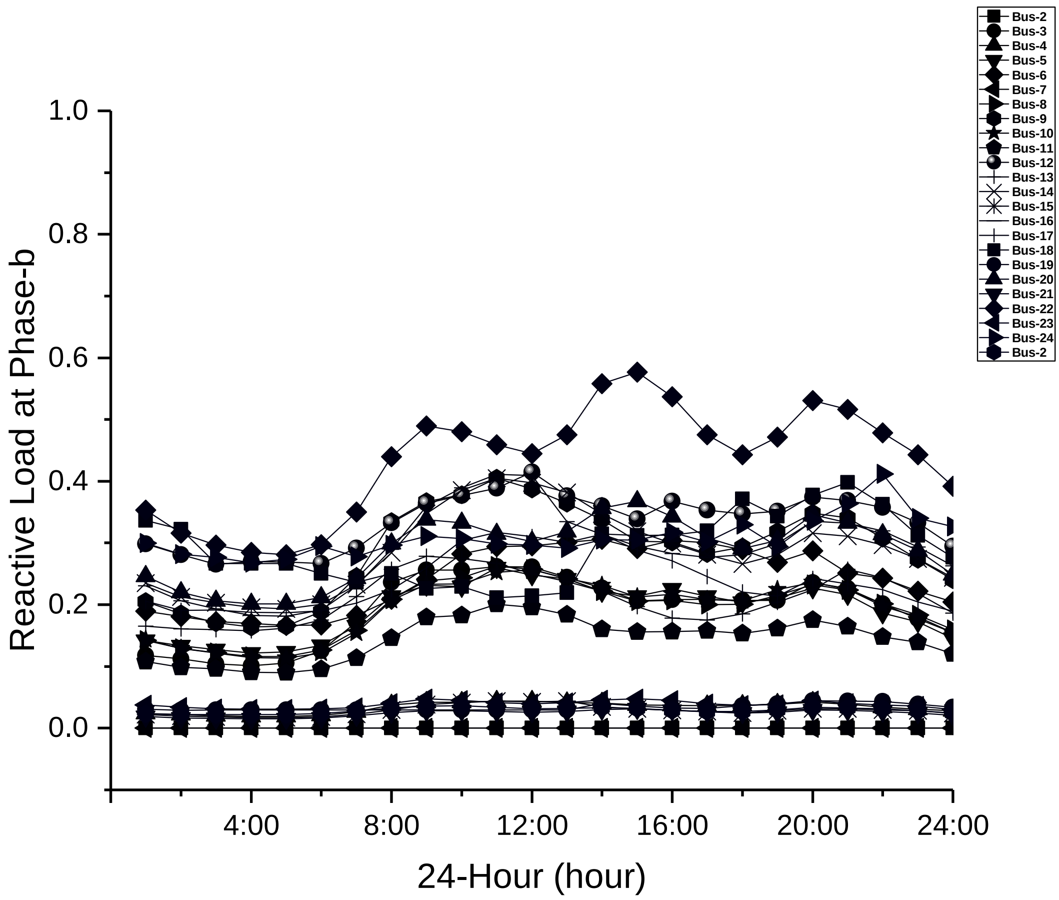

Figure 5.6: Reactive load for all the buses at phase-bfor 24 hours.

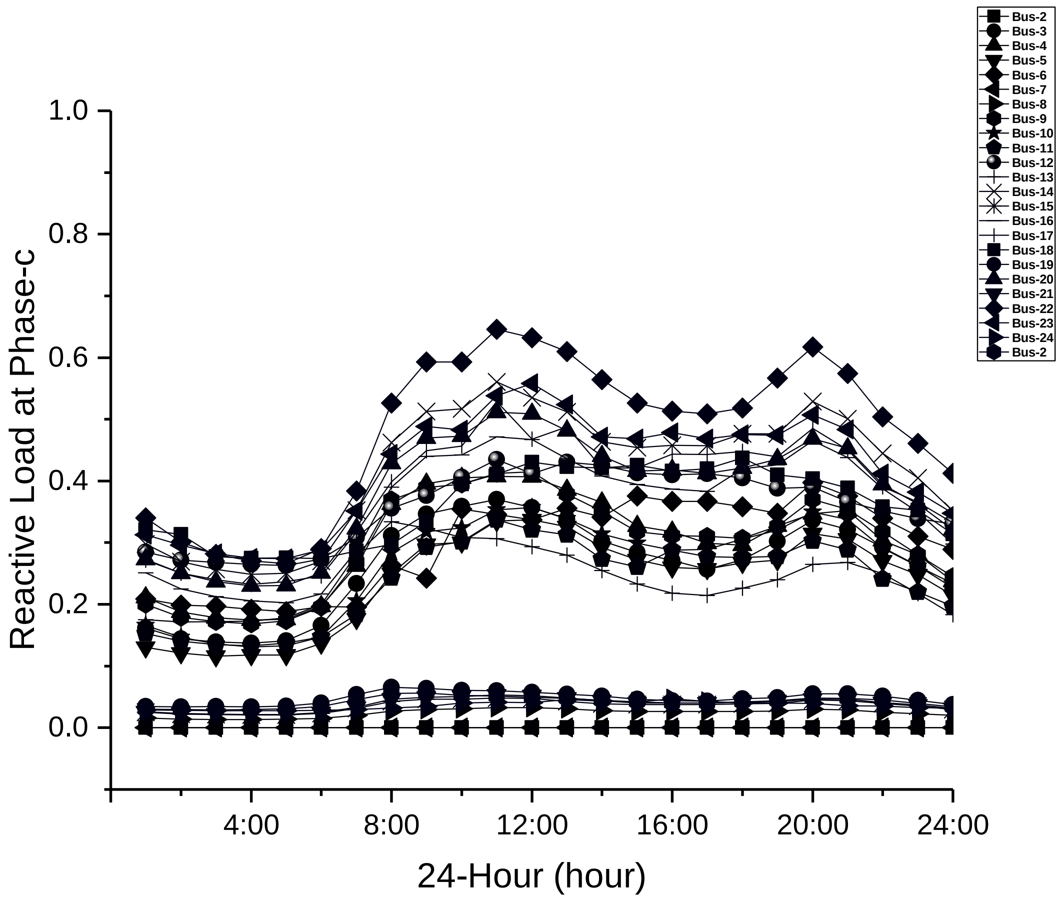

Figure 5.7: Reactive load for all the buses at phase-c for 24 hours.

Table 5.2: Comparison of load distribution of base load without DGs and with DGs

	Base Load						System with DGs					
Bus	$p_{i0}^{a,sp}$	$q_{i0}^{a,sp}$	$p_{i0}^{b,sp}$	$q_{i0}^{b,sp}$	$p_{i0}^{c,sp}$	$q_{i0}^{c,sp}$	$p_{i0}^{a,sp}$	$q_{i0}^{a,sp}$	$p_{i0}^{b,sp}$	$q_{i0}^{b,sp}$	$p_{i0}^{c,sp}$	$q_{i0}^{c,sp}$
1	9.7919	6.8930	5.8706	4.4164	8.0371	5.7971	5.8769	4.4396	5.8768	4.4395	5.8769	4.4394
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
3	-0.3600	-0.2160	-0.2880	-0.1920	-0.4200	-0.2640	**0.1384**	**0.4881**	-0.2880	-0.1920	-0.4200	-0.2640
4	-0.5760	-0.4320	-0.0480	-0.0336	-0.4800	-0.3000	-0.5760	-0.4320	-0.0480	-0.0336	-0.4800	-0.3000
5	-0.4320	-0.2880	-0.2880	-0.1920	-0.3600	-0.2400	-0.4320	-0.2880	-0.2880	-0.1920	-0.3600	-0.2400
6	-0.4320	-0.2880	-0.3360	-0.2400	-0.3000	-0.3000	-0.4320	-0.2880	-0.3360	-0.2400	-0.3000	-0.3000
7	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
8	-0.4320	-0.2880	-0.2880	-0.1920	-0.0360	-0.0240	-0.4320	-0.2880	-0.2880	-0.1920	-0.0360	-0.0240
9	-0.7200	-0.5040	-0.3840	-0.2880	-0.4800	-0.3000	-0.7200	-0.5040	-0.3840	-0.2880	-0.4800	-0.3000
10	-0.3600	-0.2160	-0.2880	-0.1920	-0.4200	-0.2640	-0.3600	-0.2160	-0.2880	-0.1920	-0.4200	-0.2640
11	-0.5040	-0.3168	-0.2400	-0.1440	-0.3600	-0.2400	**1.1463**	**-0.1341**	-0.2400	-0.1440	-0.3600	-0.2400
12	-0.5760	-0.3600	-0.4800	-0.3360	-0.4800	-0.3600	-0.5760	-0.3600	-0.4800	-0.3360	**-0.0280**	**0.2363**
13	-0.6480	-0.2160	-0.3360	-0.2112	-0.3600	-0.2400	-0.6480	-0.2160	-0.3360	-0.2112	-0.3600	-0.2400
14	-0.5760	-0.3600	-0.3840	-0.2880	-0.6000	-0.4200	-0.5760	-0.3600	-0.3840	-0.2880	-0.6000	-0.4200
15	-0.0720	-0.0432	-0.0480	-0.0288	-0.0600	-0.0360	-0.0720	-0.0432	-0.0480	-0.0288	-0.0600	-0.0360
16	-0.5760	-0.0432	-0.0384	-0.2880	-0.4800	-0.3600	-0.5760	-0.0432	-0.0384	-0.2880	-0.4800	-0.3600
17	-0.5760	-0.4320	-0.3360	-0.2400	-0.5400	-0.3840	-0.5760	-0.4320	-0.3360	-0.2400	-0.5400	-0.3840
18	-0.5760	-0.4320	-0.3840	-0.2880	-0.4800	-0.3600	-0.5760	-0.4320	-0.3840	-0.2880	-0.4800	-0.3600
19	-0.0864	-0.0648	-0.0480	-0.0336	-0.0600	-0.0480	-0.0864	-0.0648	-0.0480	-0.0336	-0.0600	-0.0480
20	-0.5040	-0.3600	-0.3840	-0.2880	-0.5400	-0.3840	**1.0853**	**0.9561**	-0.3840	-0.2880	-0.5400	-0.3840
21	-0.0576	-0.0432	-0.0336	-0.0240	-0.0540	-0.0384	-0.0576	-0.0432	-0.0336	-0.0240	-0.0540	-0.0384
22	-0.7200	-0.5040	-0.5760	-0.4320	-0.6000	-0.4800	-0.7200	-0.5040	-0.5760	-0.4320	-0.6000	-0.4800
23	-0.0864	-0.6480	-0.0480	-0.0384	-0.6000	-0.4200	-0.0864	-0.6480	-0.0480	-0.0384	-0.6000	-0.4200
24	-0.5040	-0.3600	-0.4320	-0.3072	-0.0480	-0.0360	-0.5040	-0.3600	-0.4320	-0.3072	-0.0480	-0.0360
25	-0.0864	-0.0648	-0.0480	-0.0288	-0.0600	-0.0420	-0.0864	-0.0648	-0.0480	-0.0288	**1.5567**	**0.6189**

Table 5.3: Comparison of voltages after and before Re-phasing for constant load model

	Base Case				After Re-Phasing			
Bus	$V^a(Ang)$	$V^b(Ang)$	$V^c(Ang)$	δV^{ph}_{max}	$V^a(Ang)$	$V^b(Ang)$	$V^c(Ang)$	δV^{ph}_{max}
1	1.05 (0.00)	1.05 (-120.00)	1.05 (120.00)	0.00	1.05 (0.00)	1.05 (-120.00)	1.05 (120.00)	0.00
2	1.03 (-0.59)	1.04 (-120.07)	1.03 (119.54)	0.01	1.04 (-0.26)	1.04 (-120.14)	1.04 (119.63)	0.00
3	1.02 (-0.69)	1.03 (-120.11)	1.03 (119.45)	0.01	1.03 (-0.30)	1.03 (-120.19)	1.04 (119.58)	0.00
4	1.02 (-0.72)	1.03 (-120.12)	1.03 (119.41)	0.02	1.03 (-0.34)	1.03 (-120.22)	1.04 (119.62)	0.01
5	1.02 (-0.73)	1.03 (-120.12)	1.03 (119.41)	0.02	1.03 (-0.34)	1.03 (-120.22)	1.03 (119.61)	0.01
6	1.01 (-0.70)	1.03 (-120.01)	1.02 (119.53)	0.02	1.03 (-0.26)	1.03 (-120.10)	1.03 (119.59)	0.00
7	1.00 (-0.81)	1.02 (-119.95)	1.01 (119.51)	0.02	1.02 (-0.25)	1.02 (-120.06)	1.02 (119.53)	0.00
8	1.01 (-0.71)	1.03 (-120.03)	1.02 (119.54)	0.02	1.02 (-0.27)	1.03 (-120.11)	1.03 (119.59)	0.01
9	1.00 (-0.87)	1.02 (-119.94)	1.01 (119.50)	0.02	1.01 (-0.18)	1.02 (-120.07)	1.02 (119.49)	0.01
10	0.99 (-0.92)	1.02 (-119.93)	1.00 (119.49)	0.03	1.01 (-0.11)	1.01 (-120.09)	1.02 (119.45)	0.01
11	0.99 (-0.95)	1.02 (-119.93)	1.00 (119.49)	0.03	1.01 (-0.07)	1.01 (-120.10)	1.02 (119.43)	0.01
12	0.99 (-0.95)	1.02 (-119.92)	1.00 (119.49)	0.03	1.01 (-0.07)	1.01 (-120.10)	1.02 (119.41)	0.01
13	0.99 (-0.96)	1.02 (-119.93)	1.00 (119.49)	0.03	1.01 (-0.08)	1.01 (-120.10)	1.02 (119.43)	0.01
14	1.00 (-0.82)	1.02 (-119.94)	1.01 (119.50)	0.02	1.02 (-0.26)	1.02 (-120.05)	1.02 (119.52)	0.00
15	1.00 (-0.82)	1.02 (-119.94)	1.01 (119.50)	0.02	1.02 (-0.26)	1.02 (-120.05)	1.02 (119.52)	0.00
16	1.00 (-0.85)	1.02 (-119.91)	1.01 (119.50)	0.02	1.02 (-0.29)	1.02 (-120.02)	1.02 (119.53)	0.00
17	1.00 (-0.82)	1.02 (-119.93)	1.01 (119.50)	0.02	1.01 (-0.26)	1.02 (-120.05)	1.02 (119.53)	0.01
18	1.02 (-0.70)	1.03 (-120.09)	1.02 (119.45)	0.02	1.03 (-0.30)	1.03 (-120.16)	1.03 (119.56)	0.00
19	1.01 (-0.70)	1.03 (-120.08)	1.02 (119.45)	0.02	1.03 (-0.30)	1.03 (-120.14)	1.03 (119.53)	0.01
20	1.01 (-0.70)	1.03 (-120.08)	1.02 (119.45)	0.02	1.04 (-0.30)	1.03 (-120.14)	1.03 (119.53)	0.01
21	1.01 (-0.70)	1.03 (-120.08)	1.02 (119.46)	0.02	1.03 (-0.30)	1.03 (-120.15)	1.03 (119.57)	0.00
22	1.01 (-0.70)	1.03 (-120.08)	1.02 (119.47)	0.02	1.03 (-0.30)	1.02 (-120.15)	1.03 (119.58)	0.00
23	1.02 (-0.69)	1.03 (-120.12)	1.02 (119.41)	0.02	1.03 (-0.30)	1.03 (-120.25)	1.04 (119.67)	0.01
24	1.01 (-0.69)	1.03 (-120.13)	1.02 (119.41)	0.02	1.03 (-0.30)	1.03 (-120.28)	1.04 (119.73)	0.01
25	1.01 (-0.69)	1.03 (-120.13)	1.02 (119.42)	0.02	1.03 (-0.30)	1.03 (-120.29)	1.04 (119.80)	0.02
	$Min(V^a)$	$Min(V^b)$	$Min(V^c)$	Max(δV^{ph}_{max})	$Min(V^a)$	$Min(V^b)$	$Min(V^c)$	Max(δV^{ph}_{max})
	0.99	1.02	1.00	0.03	1.01	1.01	1.02	0.02

Table 5.4: Summary of Results of important quantities

Parameter	Without DGs	BO	PSO
		With DGs	With DGs
V^a_{min}	0.98866	1.01088	1.01023
V^b_{min}	1.01502	1.01130	1.01142
V^c_{min}	1.00171	1.01659	1.01223
P_{loss}	0.02808	0.01733	0.01823
Q_{loss}	0.04364	0.02531	0.03102
$\|I_0\|$	1.27424	0.00004	0.00002
$\|I_2\|$	1.28087	0.00002	0.00123
PUI	0.24604	0.00001	0.00210

In Table 5.4, results of some important parameters found in the study are given. In each of the phases, the minimum bus voltages, V^a_{min} ,V^b_{min} and V^c_{min} for the cases with DGs and without DGs are reported in Table 5.4. It is seen from Table 5.4 that there is improvement in every parameter.

After placing DGs the zero-sequence current ($|I_0|$)), negative-sequence current ($|I_2|$), and PUI are almost negligible.

The system voltages obtained before and after considering DGs are shown in Figure 5.8. To compare the performance of widely used PSO with BO, the important parameters of the Table 5.4 have been calculated for the case of PSO also. These values indicate that in this case also BO performs better than PSO.

Conclusions

For a base case, it may be concluded that 5 single-phase DGs may be sited at buses and phases in an optimum way along with optimal sizing to achieve phase balancing. For this case, it has been shown that BO performs better than PSO. The next scenario investigates optimal allocation of phases to the DGs to achieve phase balancing for 24-hour loading scenario.

5.3.3.2 Scenario 2: 24-hour loading scenario:

In this case the optimal DG locations obtained for scenario 1 have been fixed. The real and reactive sizes obtained under scenario 1 shall be fixed as maximum capacity of DGs at respective buses. Using these sites and fixed maximum capacities for DGs along with reactive supports, the optimization for 24-hour load scenarios

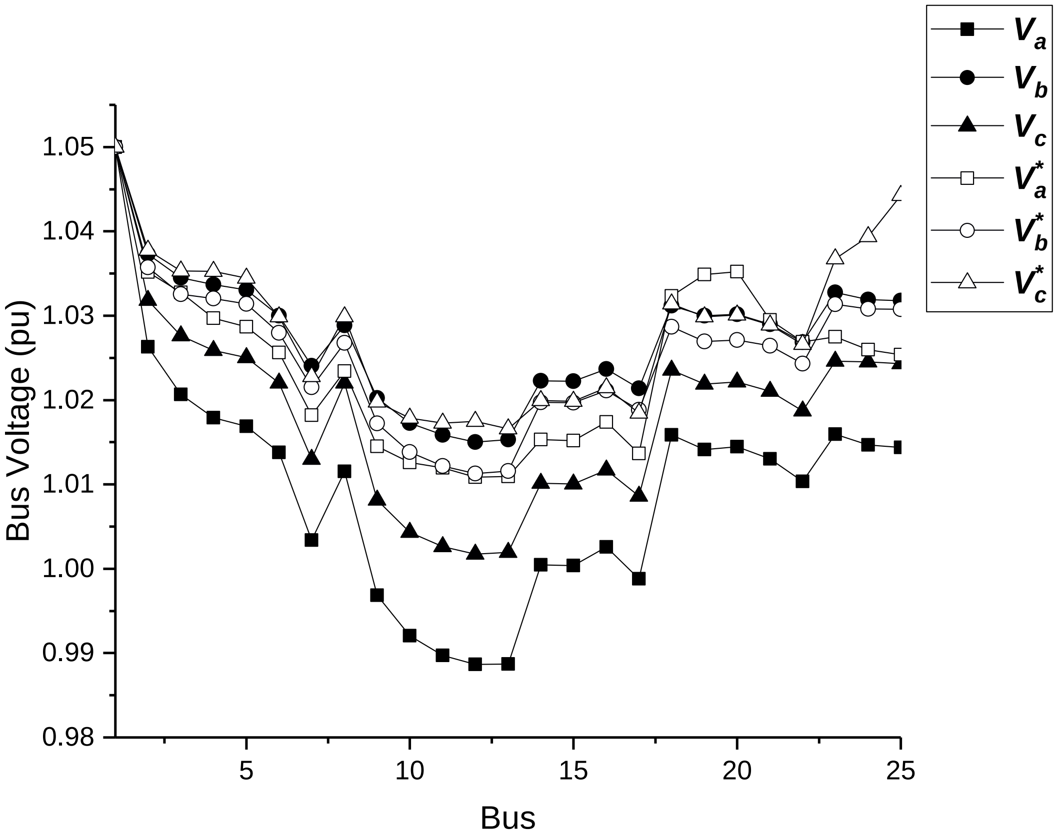

Figure 5.8: Bus voltages without and with DGs. V_a, V_b, V_c indicate bus voltages without DGs. V_a^*, V_b^*, V_c^* indicate bus voltages with DGs.

for minimizing negative- and zero-sequence currents was performed.

For each of the 24-hour loading scenario the optimal phase and sizes of the single-phase DGs (installed at their optimal buses decided under scenario 1) shall be obtained using BO algorithm. In the following paragraphs the results obtained in terms of sequence and phase currents, voltages, losses (real and reactive), and phase utilization factors are discussed.

Sequence Currents: The hourly negative- and zero-sequence currents for 24-hours without DG and with DG are shown in Fig. 5.9. It is observed from the figure that, without DG the amount of negative- and zero-sequence currents lie in the range 0.66 pu to 1.90 pu and with DG the negative- and zero-sequence currents are found to be almost negligible.

Phase currents: The effect of reduction in zero- and negative-sequence cur-

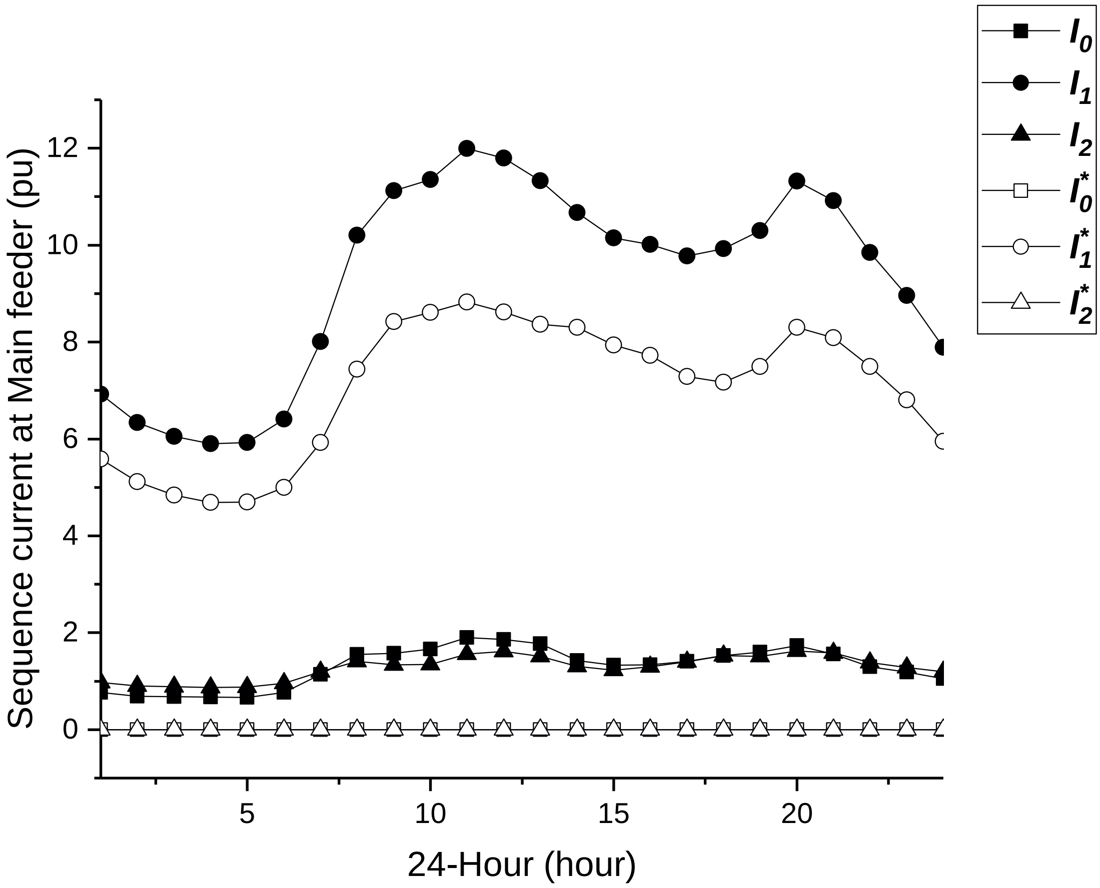

Figure 5.9: Hourly positive-, zero-, negative-sequence currents without and with DGs. I_0, I_1, and I_2 indicate sequence currents for the case when DGs are not placed. I_0^*, I_1^*, and I_2^* indicate sequence currents for the case when DGs are placed.

rents is also reflected in the phase currents at main-substation as shown in Fig. 5.10. Fig. 5.10 shows that the DGs provide currents in such a fashion that currents in three phases at the main substation get balanced. An important observation made from the figure is that the balanced phase currents of all the three phases at the main-substation are reduced to the minimum of three phase currents under unbalance (without DG). This results in increased MVA margins on the other two phases.

Voltages: The bus-wise phase voltages for the peak load condition are plotted in Fig. 5.8. From this figure, it is observed that with the use of DGs, voltage profile

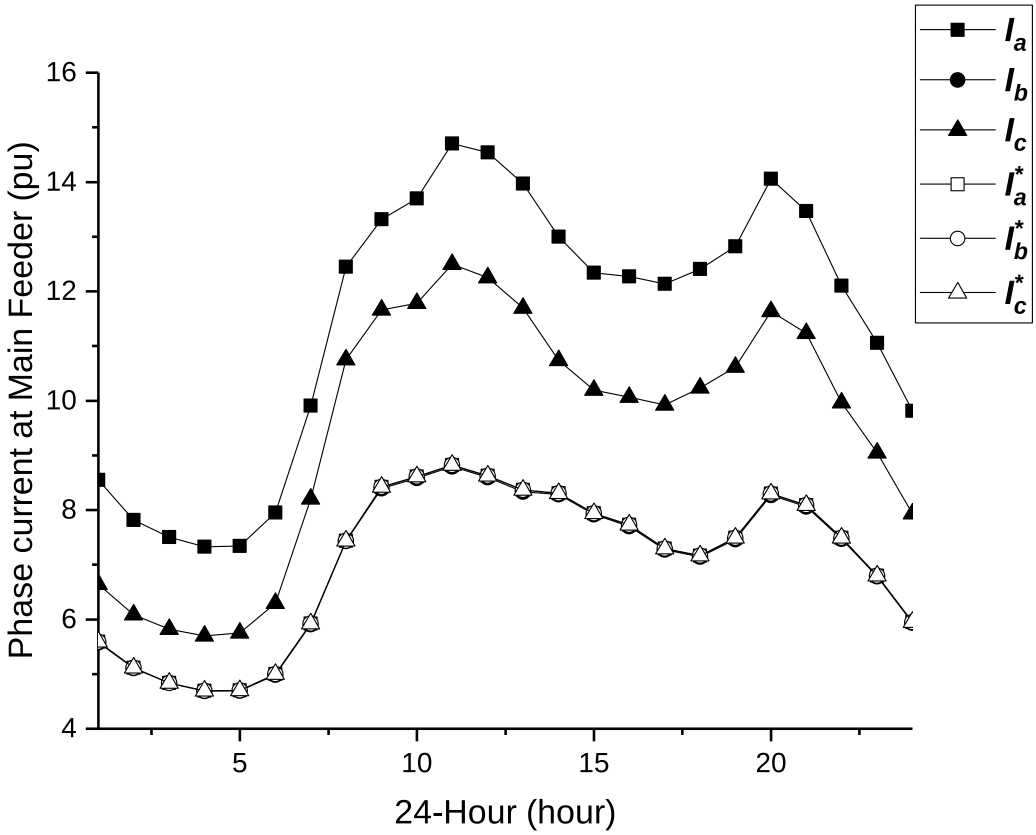

Figure 5.10: Hourly phase currents without and with DGs. I_a, I_b, and I_c indicate phase currents for the case when DGs are not placed. I_a^*, I_b^*, and I_c^* indicate phase currents for the case when DGs are placed.

improves and voltages become more balanced as compared to the case without DG. It is observed that phase voltages after scheduling DGs get pulled up towards the highest phase voltage of the case when DGs are not used. Comparison of minimum bus voltage before and after placing the DGs at every hour is shown in Fig. 5.11. From Fig. 5.11, minimum bus voltages of the system considerably improve when DGs are optimally placed in the system.

Losses: Scheduling of DGs in the system also affect the line losses. If DGs are not suitably placed, losses may increase dramatically. Effect of placement of single-phase DGs on the active and reactive line losses is also studied. Active and reactive line losses before and after placing DGs for 24-hour are shown in Fig. 5.12. It is clear from Fig. 5.12 that the active and reactive line losses also reduce. Hence,

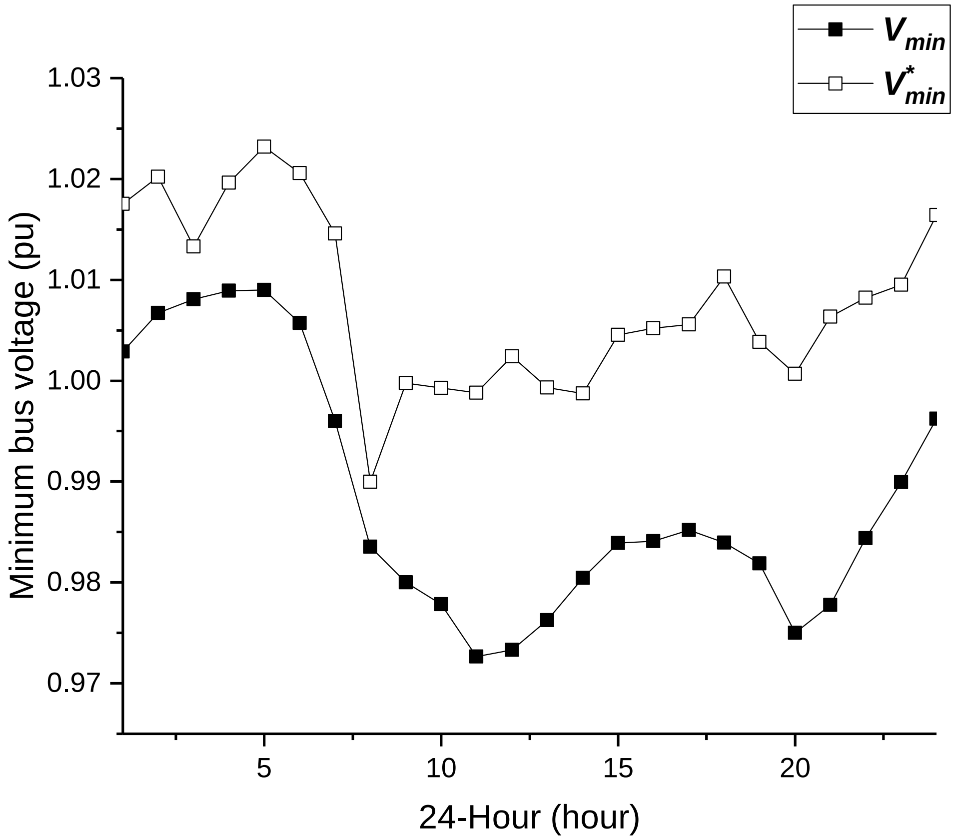

Figure 5.11: Minimum of the all bus Voltages without DGs and with DGs for 24 hour. V_{min} and V^{*}_{min} indicate the minimum bus voltage in case of Without DGs and with DGs respectively.

the placement of DGs to balance the currents at main feeder does not increase the line losses, instead losses will come down.

Phase Utilization Index (PUI): PUIs before and after placing the DGs for 24-hour are shown in Fig. 5.13. Fig. 5.13 clearly shows that the PUIs are negligible when the DGs are optimally placed.

Conclusions

The optimal phases and sizes have been obtained using BO algorithm for a 24-hour loading scenario. On the basis of results obtained, it may be concluded that (i) negative- and zero-sequence currents are negligible, (ii) all the three phase currents are reduced to the minimum of the three phase currents under unbalance, (iii) all the three phase voltages are pulled up towards the highest phase voltage of the

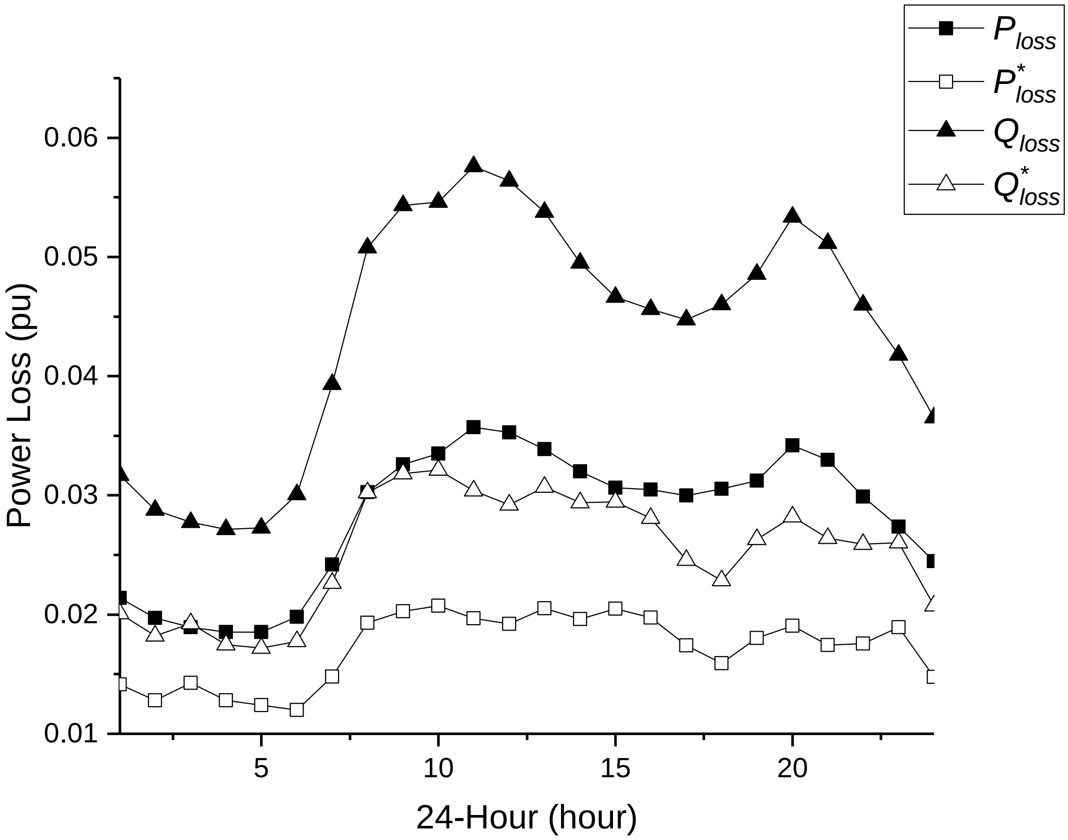

Figure 5.12: Total active and reactive power line loses for 24-hours. P_{loss} and Q_{loss} indicate total active and reactive line losses for the case when DGs are not placed. P^*_{loss} and Q^*_{loss} indicate total active and reactive power line loss for the case when DGs are placed.

case when DGs are not used, (iv) losses are reduced, and (v) phase utilization index (PUI) is negligible when DGs are phase and sized optimally.

5.3.3.3 Scenario 3: Effect of Voltage-dependency in DGs placement

Loads in a power system network are normally modelled as constant power load for simplifying the network representation and for reducing the computational complexity. This kind of simulation mostly suffices for transmission systems where due to meshed structure voltage levels at all the buses are maintained very close to the nominal voltage. But in case of distribution systems, where due to radial nature of the network, voltage levels gradually fall downstream from the root

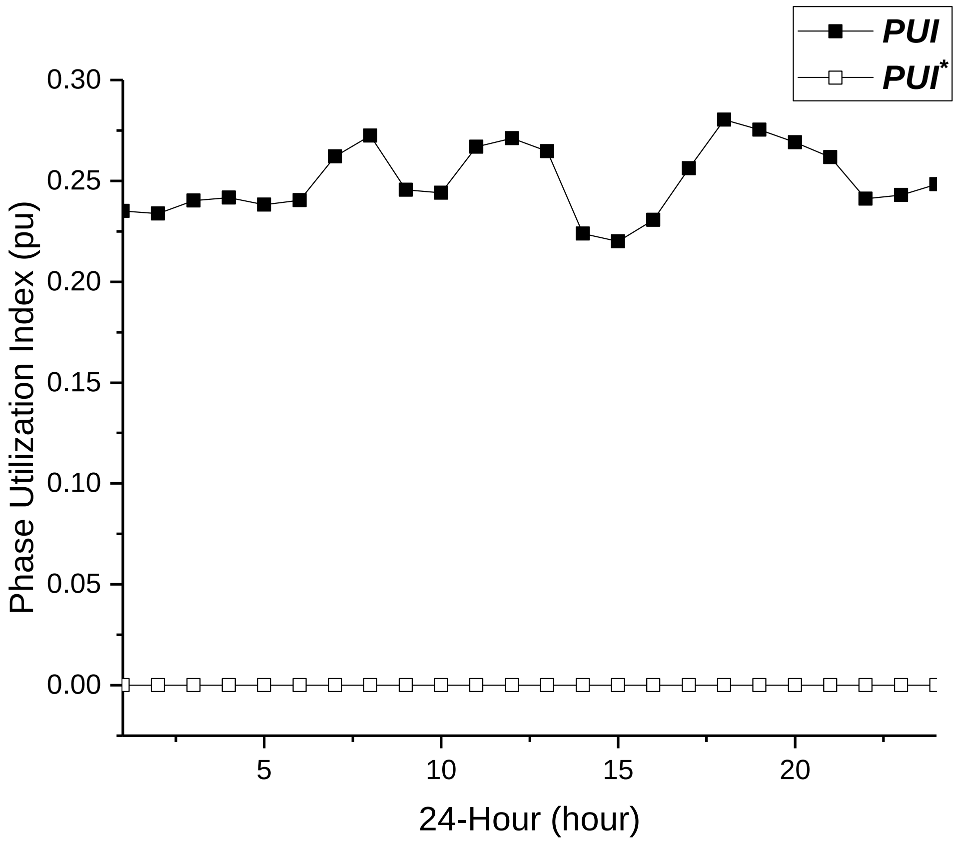

Figure 5.13: Phase Utilization Index at main feeder for 24 hours. PUI and PUI^* indicates the phase utilization index in case of without DGs and with DGs respectively.

node to the load, this assumption does not suffice and results in error in decision based on the results of load flow considering constant power load model for the system loads which are actually voltage dependent [74]. The effect of ignoring voltage dependency of load have also been investigated in this paper. Here three models (viz, commercial, agricultural, and residential) representing different types of voltage dependencies has been considered for investigation. In this investigation the optimal placement (bus and phase) and sizes of single-phase DGs obtained considering constant power load model was tested on a network comprising of dependent load.

The effect of change in load models were investigated on the basis of system's minimum phase voltages (V^a_{min} V^b_{min} V^c_{min}) power losses (P_{loss} Q_{loss}) and non-positive sequence currents. These parameters are tabulated in Table 5.5. It is observed that there is hardly much of difference in minimum system voltages and losses (P_{loss} Q_{loss}) among the different load types from the constant load model. However, the Table 5.5 shows that the difference of sequence current are quite significant among different models. This shows that the load types would have a significant impact on load balancing problem and effective optimization would only happen if load models are considered.

To further explore the effect of voltage dependent load model vis a viz constant load model, following investigations have been carried out. The optimal location (bus and phase) and size were obtained considering constant load for the system and the optimal values obtained were implemented on the system having "different load models". The mismatch in zero-sequence current are shown in Table 5.6. In the last row of Table 5.6, it is observed that the mismatch for different load models are in the range of 0.008 to 0.012 which is quite significant. However, if optimal solution is obtained using any voltage dependent load model, and is implemented on the same system having any voltage-dependent load models, the mismatches are significantly lower and are in the range 0.003 to 0.007.

A similar inference may be drawn in case of mismatch for negative-sequence currents depicted in Table 7. Thus it may be concluded that it is advisable to use a voltage dependent load model (even in an accurate one would suffice) instead of constant load for obtaining pragmatic optimal placement (bus and place) and sizes for single-phase DGs.

Table 5.5: Mismatch in results when constant power load model is considered for the voltage dependent loads

Parameters	Constant Power	Commercial Load		Agriculture Load		Residential Load	
		Value	Mismatch	Value	Mismatch	Value	Mismatch
V^a_{min}	1.01	1.01	0.00058	1.01	0.00072	1.01	0.00092
V^b_{min}	1.01	1.01	0.00033	1.01	0.00083	1.01	0.00104
V^c_{min}	1.02	1.02	0.00023	1.02	0.00084	1.02	0.00104
P_{loss}	0.01733	0.01715	0.00018	0.01817	0.00084	0.01835	0.00102
Q_{loss}	0.02531	0.02505	0.00025	0.02657	0.00126	0.02682	0.00152
I^0	0.00004	0.01118	0.01114	0.01593	0.01589	0.01733	0.01729
I^2	0.00002	0.00799	0.00797	0.00958	0.00956	0.01244	0.01242
PUI	0.00001	0.00223	0.00223	0.00306	0.00305	0.00317	0.00316

Table 5.6: Mismatch in zero-sequence currents at main feeder for different scenario of voltage dependent loads.

Load model simulated to obtain optimal solution	Zero-sequence current			
	Load model on which optimal solution is implemented			
	Agriculture	Commercial	Residential	Constant
Agriculture	0.000	0.007	0.006	0.019
Commercial	0.006	0.000	0.005	0.010
Residential	0.003	0.004	0.000	0.016
Constant	0.010	0.008	0.012	0.000

Table 5.7: Mismatch in negative-sequence currents at main feeder for different scenario of voltage dependent loads.

Load model simulated to obtain optimal solution	Negative-sequence current			
	Load model on which optimal solution is implemented			
	Agriculture	Commercial	Residential	Constant
Agriculture	0.000	0.008	0.005	0.022
Commercial	0.005	0.000	0.004	0.008
Residential	0.004	0.004	0.000	0.014
Constant	0.016	0.011	0.017	0.000

5.4 Conclusion

DG planning for the purpose of phase balancing is proposed in this work. The planning is approached in two stages. In stage 1, the optimal DG locations (phase and bus) and sizes are obtained for peak load scenario. The location are then considered to be

fixed and the sizes obtained are taken as maximum available DG real and reactive capacity at the given buses. In the stage 2, the DGs are optimally scheduled hourly (in term of phase and size) for 24-hour loading scenario to obtain the phase balancing. This whole process is combined in one and is proposed an optimisation problem. In this chapter, this optimization problem is solved using BO and PSO. From the outcome of both the algorithms, it has been established that an effective phase balancing can be achieved with help of single phase DGs scheduled in this fashion. Moreover, the reduction in losses and the improved voltage pro

file are added advantages. As compared to the performance of BO with PSO for this optimization problem, it can be concluded that the BO optimization algorithm is more robust and efficient algorithm as compared to PSO.

A detailed analysis to ascertain the effect of voltage dependency of loads on optimal scheduling of DGs establishes that for pragmatic optimal solutions, the voltages dependency of loads must be considered albeit in approximate sense rather than doing the same using constant power load model.