Investigations on Optimal Placement of Distributed Generation Units in Distribution Network Polluted with Harmonics

Thesis Submitted

By

BARNALI SANJAY MOTLING

For the Award of

Doctor of Philosophy (Engineering)

Department of Electrical Engineering
Faculty of Engineering & Technology
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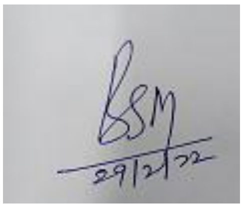
STATEMENT OF ORIGINALITY

I **Barnali Sanjay Motling** registered on **8th June, 2015,** do hereby declare that this thesis entitled "Investigations on Optimal Placement of Distributed Generation Units in Distribution Network Polluted with Harmonics**"** contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

All information in this thesis have been obtained and presented in accordance with existing academic rules and ethical conduct. I declare that, as required by these rules and conduct, I have fully cited and referred all materials and results that are not original to this work.

I also declare that I have checked this thesis as per the "Policy on Anti Plagiarism, Jadavpur University, 2019", and the level of similarity as checked by iThenticate software is 3%.



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This is to certify that the thesis entitled "Investigations on Optimal Placement of Distributed Generation Units in Distribution Network Polluted with Harmonics**"** submitted by **Barnali Sanjay Motling,** who got her name registered on **8th June, 2015** for the award of Ph.D. (Engg.) degree of Jadavpur University is absolutely based upon her own work under the supervision of **Prof. Subrata Paul and Prof. Sunita Halder nee Dey**, and that neither her thesis nor any part of the thesis has been submitted for any degree / diploma or any other academic award anywhere before.

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December, 2022

(Barnali Sanjay Motling)

Jadavpur University, Kolkata.

Dedicated to

my Father

Shri Durgashankar Chakraborty,

and

my Mother

Smt. Aparna Chakraborty

LIST OF ABBREVIATIONS AND ACRONYMS

Abbreviation	Description
kW	Kilo Watts
p.u.	Per Unit
p	Perturbation factor
k	Super scripts k is the iteration count
ε	Tolerance
R	Generator internal resistance per phase
X	Generator internal reactance per phase
i	Subscript i indicates quantities associated with i^{th}bus.
j	Subscript j indicates quantities associated with j^{th}bus.
P	Active power.
Q	Reactive power.
V	Voltage magnitude.
I	Current magnitude
DG	Distributed Generation.
PSO	Particle Swarm Optimization
P_{Loss}	Total Active power loss
P_{SS}	Real Power fed by the Substation
P_g	Real Power Generated
P_L	Real Power Demand
P_{gi}	Active power output of the DG at the i-th bus
P_{di}	Active power load at the i-th bus
P_i	Injected active power at the i-th bus
DLF	Direct Load Flow
HLF	Harmonics Load Flow
THD	Total Harmonic Distortion
THD_{VM}	Maximum total harmonic distortion in bus voltages
THD_B	Base value of total harmonic distortion
THD_L	Limiting Value of total harmonic distortion

THD_{Max}	Maximum total harmonic distortion
THD_{Min}	Minimum total harmonic distortion
S_{Max}	Maximum DG size considered
S_{Min}	Minimum DG size considered
S_{L1}	DG size in the decreasing zone
S_{L2}	DG size in the increasing zone
S_u	Unconstrained DG size
S_{opt}	Optimum DG size

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1.5 Scope of Work Undertaken in this Thesis

1.1 DISTRIBUTED GENERATION AND ITS ROLE IN ELECTRIC POWER SYSTEM

Over the last few years, penetration of distributed generation (DG) in power systems has been gradually increasing. DG, now-a-days, has become a vital and integral part of power system. DG can best be defined [1]-[3] as generating units of small capacities (typically ranging from less than a kW to tens of MW) customarily located in the distribution feeder network or at the consumers' site. Introduction of DG in distribution system can result in a number of benefits [1]-[5] which can provide solutions to the various problems the traditional power systems are facing now-a-days. In traditional power systems, bulk amount of power generated in large, centralized power stations (normally located far away from the consumers) require to be transmitted through transmission networks to suitable load centers before it can be distributed among the consumers by distribution networks. Ever increasing rise in the demand of electric power necessitates time to time expansion of generation and transmission capacity of the power systems.

This requires installation of new generating stations or capacity enhancement of the existing ones. Along with that, installation of new transmission lines is also required for transmission capacity enhancement. Majority of the large conventional power plants are fossil-fuel based plants. Enhancement of capacity of the existing fossil-fuel based generating plant or installation of a new one has been facing serious challenges due to two reasons. Firstly, the fossil reserve is alarmingly diminishing, and, secondly, these plants emits excessive amount of pollutant gases causing unacceptable level of environmental pollution. Growing public awareness on environmental pollution and demand for clean atmosphere has resulted in severe restrictions on growth of this type of power plants. Moreover, expansion of transmission network is also facing challenges due to strong public resistance against land acquisition by power sector to find proper route for installation of new lines.

The, ever-increasing demand of electric power without sufficient transmission and generation enhancement adversely affects the reliability, security and power quality of a power system, and also causes excessive power loss in the network. DG can provide answers to all these problems. As DG units are placed directly in the distribution network, and therefore close to the consumer site, their deployment results in reduction in network power loss. Additionally, it improves the voltage profile in the distribution network, enhances the system reliability and security, improves power quality, and relieves congestion in transmission and distribution network. It also allows deferral of new investments on system expansion, and thereby provides the most cost-effective measure in power industry to enhance loading capacity.

These benefits in conjunction with liberalization of electricity market have been the main driving force behind the rapid increase in DG penetration in distribution systems. Liberalization policy for the electricity market has opened up opportunities for the privately owned small generation companies to take active part in the power market. In addition to that, significant progress in renewable energy technology such as solar Photovoltaic (PV), wind turbine etc. and availability of these technologies for the development of small capacity generating units has provided tremendous impetus for these private companies to come forward to play important roles in today's power system.

1.2 DIFFERENT TYPES OF DG UNITS

Some types of DG units employ synchronous generators while wider versions used now-a-days are based on various renewable energy resources as renewable based generation are environment friendly as they do not emit pollutant gases. Diesel generator, micro-turbine and gas turbine are examples of synchronous generator based DG units. These units are directly connected to the grid. Solar PV, mini/micro hydro, wind turbine, fuel cell, geothermal and biomass are examples of renewable based DG units. Majority of the renewable based DG units are connected to the power network through power electronic inverters.

1.3 HARMONICS IN DISTRIBUTION SYSTEM AND ITS EFFECT ON DG PLACEMENT

Despite the fact that power systems are designed to run at frequencies of 50 Hz or 60 Hz worldwide, certain types of loads (non- linear loads) produce currents and voltages at integral multiples of the fundamental frequency, resulting in harmonics in the networks. Among these non linear loads, different types of power electronic loads such as adjustable speed drives (ASD), Switching Mode Power Supply (SMPS) and various other devices using power electronic converters are the most significant components injecting harmonic currents in the network and thereby producing harmonic distortions. The problem of harmonic distortion is more prominent in distribution networks. With the increasing use of Power Electronics loads in recent times, the problems associated with harmonic distortions have reached alarming stage, and therefore requires special attention in the problem of design, planning and operation of power networks, particularly the distribution networks.

Presence of harmonics in the network causes several detrimental effects [7]-[15] on power system operation such as deterioration of power factor, higher system losses, overheating of the network components, degraded voltage profile, and malfunctioning of the protection and control devices. Consideration of these factors in planning, design and operation is extremely crucial. The problem is more aggravated by the fact that the degree of distortion and the distribution of its effect along the network is quite complex and dynamic in nature in the sense that it is dependent of the harmonic nature of the non linear elements and their locations in the network.

In this context it is very important to note that majority of the DGs is now- a- days renewable based and are connected to the network through power electronic inverters which injects harmonics into the network [16], [17]. Installation of such DG units affects the harmonic distortion profile in the network and the ultimate profile depends on the size (capacity) and location of the DG unit. Giving due importance to the requirement that the maximum harmonic distortion level should be kept within some limit [18], [19] for healthy and reliable operation of the devices in the network, the size and location of the incoming DG unit must be selected with due consideration to this crucial requirement.

1.4 MOTIVATION BEHIND THE STUDIES UNDERTAKEN

It has already been mentioned in section 1.1 that introduction of DG in distribution network can provide a number of benefits. However, to get those benefits to the fullest extent, proper DG placement (appropriate location and size) is essential. Improper placement of DG units may deteriorate the system performance [3],[6] Studies are required for determination of proper location and proper size of DG unit to be installed in order to achieve specific benefits. One of the major benefits gained from DG placement is reduction in network power loss. The problem of optimal placement of DG for loss minimization in distribution network has been addressed by many researchers

[20]-[38] without considering the presence of harmonics. However, as discussed in section 1.3, the distribution networks now-a-days are affected with appreciable amount of harmonic distortion because of high degree of penetration of power electronic loads. Moreover, majority of the DG units presently are renewable based and use power electronic inverters. In such a situation, it is essential to include the effects of these harmonics sources in the study of optimal DG placement.

The aim of the studies undertaken here is to explore the problem of optimal placement of DG unit for loss minimization in radial distribution network polluted with harmonics. Relatively few researchers [39]-[48] have considered the presence of harmonics in the study of optimal DG placement. However, all these studies have employed one or other evolutionary population based method. These evolutionary computing methods are versatile optimization methods as they are capable of solving multi-objective problems and can take into account any number of constraints. But all these methods are highly computation intensive and require large amount of computation for solving DG placement problem. In this context, computationally efficient methods are always desirable so that desired solutions can be obtained with less computational effort.

1.5 SCOPE OF WORK UNDERTAKEN IN THIS THESIS

The studies undertaken in this thesis have focused on the development of computationally efficient methods for solving the problem optimal placement of DG units in radial distribution network to minimize the network power loss when harmonics generating sources are present in the network. In the context of the studies done in this thesis it is to be mentioned that harmonic load flow (HLF) is an important and essential component of the computations required in the optimization process involved in optimal DG placement problem, and has been applied in all the studies reported so far. HLF constitute the major part of computation in this problem. The methods requiring lesser number of HLF to be executed for finding the optimal solution, will, in general, be computationally more efficient than the other methods with respect to the amount of computation needed. In the studies undertaken here, backward-forward sweep method of HLF [49]-[51] has been used. A brief introduction of this load flow method has been furnished in *Appendix- D*.

The proposed methods have been tested on two benchmark distribution test networks, IEEE 33 bus network [53] and IEEE 69 bus network [54]. Necessary information on these two networks are provided in *Appendix-A* for ready reference. In reality, these two networks do not have any non-linear load. For the sake of the present studies different degree of non-linearity is inserted. Information regarding the different types of non-linearity considered has been taken from [57],[59] and has been presented in *Appendix-B*. In all the studies in this thesis, only inverter based DG units has been considered. No non-linear loads are considered in the studies in chapter 2 and chapter 3. Such loads have been taken into account in chapter 4 to chapter 6.

In chapter 2, a Particle Swarm Optimization (PSO) [55],[56] based solution to the DG placement problem has been considered where constraints on bus voltage magnitudes as well as the maximum allowable *THD* in bus voltages have been considered. PSO being a well accepted and widely used evolutionary computation method of optimization, the results obtained in this chapter have been used as the benchmark for validation of the results obtained in the later chapters. Results for both unconstrained and constrained cases have been furnished for the two test networks considered in this thesis. A brief introduction on PSO has been furnished in *Appendix-C*.

A novel, computationally efficient iterative process has been developed in chapter 3.The method utilizes the unimodal nature of variation of network power loss with DG size installed at any bus. The method proposed is, however, capable of finding the unconstrained optimal size with fairly small amount of computation. The results have shown that in comparison to the PSO technique presented in chapter 2, the proposed iterative method requires significantly less amount of computation to furnish the unconstrained solution with almost same accuracy.

Chapter 4 has presented a novel hybrid approach to determine the optimal DG size with constraint imposed on maximum allowable value of *THD* in the bus voltages. The hybrid approach is a combination of a Rule-base and some iterative computations among which the iterative method proposed in chapter 3 is also included. The Rule-base is developed based on the nature of variation of power loss and the variation of maximum *THD* with the size of the DG placed at any given bus. The results on the two test networks have shown the computational superiority of this method over the PSO based method.

A novel analytical method is presented in chapter 5, which is capable of finding the unconstrained optimal size with very little amount of computation. The method uses *B*-coefficient loss formula for expressing the network power loss as a function of the DG size with some approximation. A unique approach is proposed to determine approximate, average *B*-coefficient values. Comparative studies with the results of chapter 2 and chapter 3 have shown the superiority of this method in terms of amount of computation required. However, this method gives approximately optimal (near optimal) sizes of the DG. But, considering the fact that the DG units are commercially available in the market in discrete sizes only, the near optimal sizes appear to be quite acceptable in real situation considering the saving in computation.

When DG units are available in quite smaller discrete steps, the sizes determined by the analytical method proposed in chapter 5 may not be satisfactory in some cases. Approximate sizes nearer to the exact optimal ones are desirable in these cases. In chapter 6, some iterative steps are introduced to improve the results from the analytical method at the cost of small amount of increase in computation. The results have shown marked improvement where the difference between the analytically obtained size and the exact optimal size is quite larger. In cases when improvement was possible, only two iterations were sufficient to get the maximum possible improvement.

CHAPTER 2

Optimal siting and sizing of DG in distribution network in the presence of DG generated harmonics: A PSO based approach

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Outline of the chapter

2.1 INTRODUCTION

It has already been mentioned in chapter 1 that DG can be a viable solution to take care of many challenges the modern day power system is facing. Because of the reasons mentioned earlier, DG units are usually located in distribution network. To extract the benefits, DG units of optimal size must be placed at appropriate locations in the network. Selection of proper size and location requires the problem to be formulated as an optimization problem with appropriate objective function and necessary constraints. This chapter presents a PSO based approach to solve the optimal siting and sizing problem where objective function to minimize is the power loss in the network with suitable constraints imposed on the bus voltage magnitudes and the harmonic distortion level in the bus voltages in the network. The size of the DG unit to be installed is considered to lie within a minimum and maximum value. In this study, inverter-based DG unit is of main concern and has been considered as the only source injecting harmonics into the network. PSO has been used to solve the optimization problem as it is the most widely used among the population based evolutionary programming methods due to its simplicity, ease of implementation, and good convergence property. Moreover, as PSO is a well established and widely accepted method of optimization, the results obtained in this study has been used as reference for comparison with those obtained by the methods presented in the following chapters.

The aim is to maximize the reduction in loss within the permissible limits of bus voltage as well as PSO has been applied to solve the optimization. Only single DG unit placement is considered and the optimum size for each of the candidate buses is determined separately. It is also assumed that the only source injecting harmonics into the network is the DG unit.

2.2 MOTIVATION BEHIND THE PROPOSED STUDY

It has been shown earlier by some authors [20],[21] that when no source of harmonics is present in the network, the network power loss varies parabolically with the DG size at any given bus. That means the loss continues to decrease up to a certain size of DG, till it reaches minimum, and then goes on increasing for further increase in DG size. A rigorous study has been done by the present authors with repeated HLF, by placing harmonics injecting DG unit at different arbitrarily selected buses taken one at a time, and by varying the DG size in small steps. This study has revealed that the variation of network power loss with the size of a harmonics generating DG source placed at any given bus has almost same nature as that with a harmonics-free DG unit placed at the same bus. This variation henceforth will be termed as loss curve. Fig.2.1(a) and Fig.2.1(b) show the loss curves for some of the buses of IEEE-33 bus network and IEEE-69 bus network respectively. As these two network data (details given in *Appendix- A*) do not incorporate any non linear loads, DG unit has been used as the only harmonics injecting source to introduce the effect of harmonics in the network. To maintain clarity of the figures, the loss curves are shown for a few arbitrarily selected buses only. The total active power loss in the network including the losses due to harmonics is calculated as:

$$P_{loss} = \sum_{h=1}^{\infty} \sum_{m=1}^{B} \left| I_m^h \right|^2 R_m^h \qquad (2.1)$$

where, B *is* the total number of branches, I_m^h and R_m^h are, respectively, the r.m.s. current and resistance of the m^{th} branch for the h^{th} harmonic respectively. When no harmonic sources are present in the network the power loss is given as:

$$P_{loss_{(1)}} = \sum_{m=1}^{B} \left(\left| I_m^{(1)} \right|^2 R_m \right) \qquad (2.2)$$

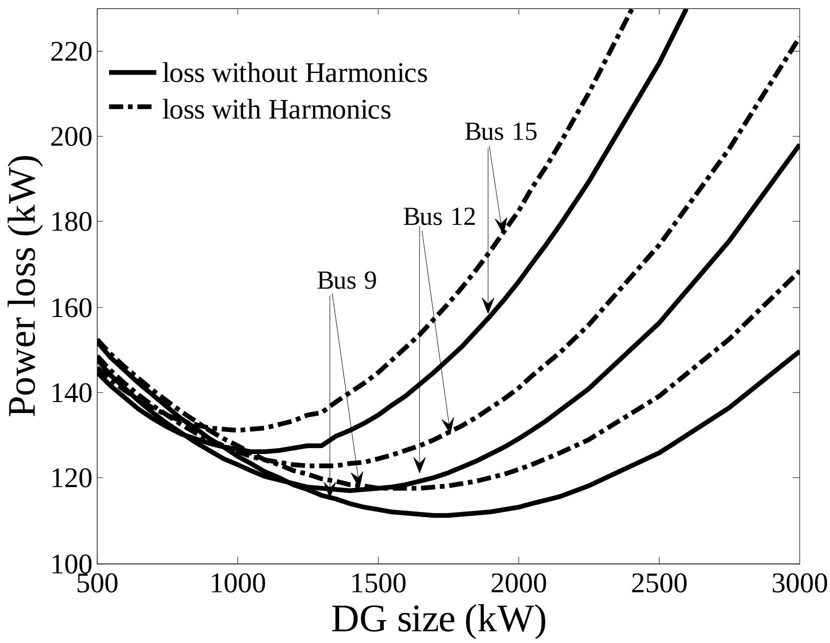

Fig. 2.1(a). Loss curves for different buses of IEEE- 33 bus network.

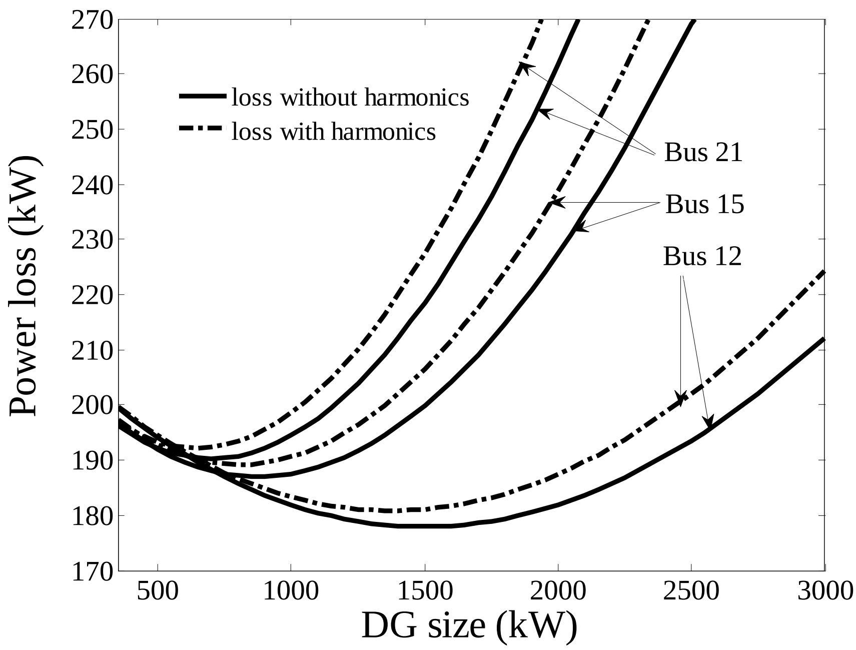

Fig. 2.1(b). Loss curves for different buses of IEEE- 69 bus network.

From the above simulation study it was also found that $max(THD_V)$ goes on increasing monotonically with increase in DG size. Fig.2.2 shows the variation of $max(THD_V)$ with DG size for different buses (only buses of the main trunk feeder are considered) of IEEE-33 network. The Figure corroborates with the fact mentioned above.

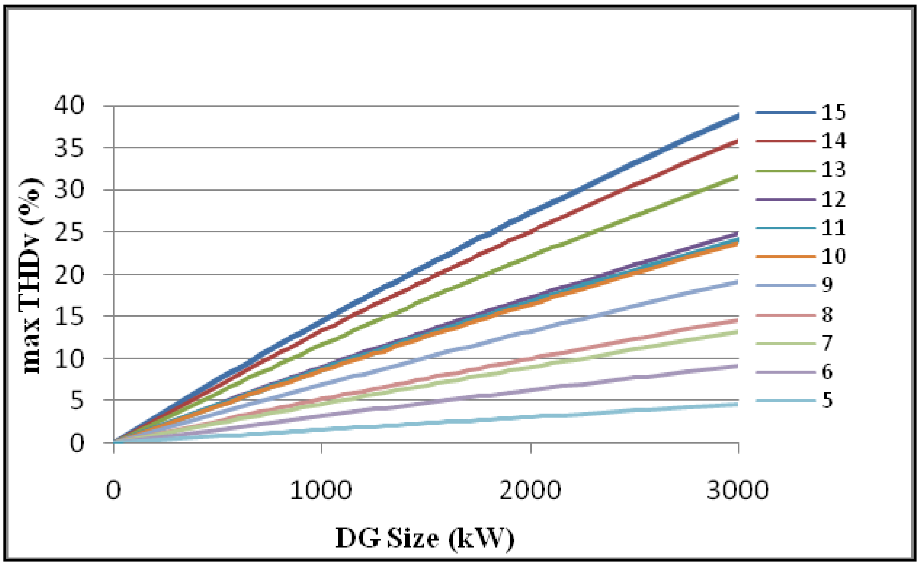

Fig. 2.2. Variation of ***max(THD$_V$)*** **with DG size for different buses of IEEE-33 bus network.**

The total harmonic distortion (in %) of any i^{th} bus voltage is given by

$$THD_{v_i} = \frac{\sqrt{\sum_{h=2}^{\infty}\left|V_i^h\right|^2}}{\left|V_i^1\right|} \times 100\% \tag{2.3}$$

where, V_i^1 and V_i^h are, respectively, the r.m.s. values of the fundamental and the h^{th} harmonic voltage of the i^{th} bus. I_m^h, R_m^h, V_i^1 and V_i^h, required for calculation of the above two quantities in (2.1) and (2.3), are obtained from HLF results. The $max(THD_V)$ is given by :

$$max(THD_V) = \max_i \{THD_V\} \tag{2.4}$$

The optimal solutions obtained in previous studies [39],[40] are based on compromise between reduction in loss and reduction in $max(THD_V)$. Degree of compromise is somewhat arbitrary and entirely depends on the experience, pragmatism and discretion of the researcher. In general it is difficult to arrive at an acceptable compromise, since no general clear-cut guide lines are available. Both these studies may generate solutions where $max(THD_V)$ is unnecessarily much below the maximum allowable limit resulting in a sacrifice in the reduction of loss. From the nature of the loss curves and the variation of $max(THD_V)$ it is obvious that only when the unconstrained minimum loss takes place for a DG size that causes a $max(THD_V)$ lower than the limiting value, the optimal solution for the DG size giving minimum loss will be associated with a $max(THD_V)$ lower than the limit. Otherwise, the optimal size will be obtained at the limiting value of $max(THD_V)$. In such cases, a lower value of $max(THD_V)$ is achieved at a lower size for which loss will be higher. However, motivation behind this additional reduction in $max(THD_V)$ at the cost of an increase in loss is not clear and such a compromise does not seem to be justified. The present work thus aims at optimizing the size of DG unit at any given bus to maximize the loss reduction permissible under the constraint imposed by the limit on $max(THD_V)$.

2.3 PROBLEM FORMULATION

In the present study, the problem is posed as a single- objective optimization problem, where the objective function to be minimized is taken as active power loss in the distribution network, while constraints are imposed on bus voltage magnitudes and $max(THD_V)$. Therefore, equation (2.1) is taken as the objective function in this problem. The optimal solution (DG size) must satisfy the following constraints:

i) Equality Constraint**:** It is given by the following real power balance equation

$$P_{ss} + P_g = \sum_{i=1}^{N} P_{d_i} + P_{loss} \tag{2.5}$$

where, P_{ss} = real power fed by the substation

P_g = real power generated by the DG

and P_{d_i} = real power demand at i^{th} bus.

ii) Inequality Constraints are:

$$\text{a) } P_{g_{min}} \le P_g \le P_{g_{max}} \tag{2.6}$$

$$\text{b) } |V|_{min} \le |V_i| \le |V|_{max} \tag{2.7}$$

$$\text{c) } max(THD_v) \le 5\% \tag{2.8}$$

where,

$P_{g_{min}}$ and $P_{g_{max}}$ = minimum & maximum limits of DG active power

$|V|_{min}$ and $|V|_{max}$ = minimum & maximum limits of bus voltages

and $max(THD_V)$ is as defined in equation (2.4).

2.4 COMPUTATIONAL STEPS FOR SOLUTION BY PSO

For the DG planning problem, the position 'y' is given by DG size (randomly selected and updated by its velocity), '*pbest*' is the DG size giving the minimum loss (*fpbest*) for a given particle and '*gbest*' is the one that gives the least value '*fgbest*' of '*fpbest*' among all the '*pbest*'. The computational steps for any selected DG location are as follows:

Step1: Set PSO parameters c_1, c_2, w and pop and maximum iteration count ($k_{\max}$).

Step2: Read line and bus data and set range of DG size, bus voltage limits, $max(THD_V)$ limit.

Step3: Initialize randomly y_i and v_i in the solution search space (range of DG size) for the entire population size pop (i.e. , $i=1,2,\ldots,pop$).

Step4: Initialize $pbest$ and $fpbest$ for the entire size pop. Also initialize $gbest$ and $fgbest$.

Step 5: Set the iteration counter k=1 & particle number i = 1.

Step 6: Find $V_{\max}$, $V_{\min}$, $max(THD_V(\%))$ and P_{loss} using HLF for y_i.

Step 7: If the bus voltage and $max(THD_V)$ are within their respective predefined limits, calculate $fpbest_i$, otherwise retain previous y_i and $fpbest_i$.

Step 8: Compare the current $fpbest_i$ with the previous $fpbest_i$. If the current $fpbest_i$ is found to be lower, set current y_i as $pbest_i$.

Step9: Check if i=pop, i.e., the search for the entire population size is over. If not, set i=i+1, (i.e., the next particle) and go back to Step 6.Otherwise go to next step.

Step10: Check whether the minimum of all the current $fpbest$ is less than the previous $fgbest$. If so, replace $gbest$ by the $pbest$ corresponding to the current minimum $fpbest$ and also replace $fgbest$ by the current minimum $fpbest$. Otherwise retain the previous $gbest$ and $fgbest$.

Step11: Update v and y, using equations (7) and (8) respectively.

Step12: If the iteration number reaches the maximum limit $(k = k_{\max})$ go to Step 13; otherwise, set iteration index $k = k + 1$, and go back to Step 6.

Step13: Print out the optimal solution $gbest$, that gives the optimal DG size, and $fgbest$, the corresponding value of objective function that represents the minimum power loss.

The variables and parameters used in presenting the above computational steps are described in *Appendix-C* which provides a brief general introduction to PSO.

2.5 CASE STUDIES AND RESULTS

Two benchmark radial distribution systems, IEEE-33 bus network and IEEE- 69 bus network have been chosen for demonstrating the efficacy of the proposed algorithm. The DG is considered to be solar PV based source injecting only active power which means a unity power factor generating source. The DG size is assumed to range between 500 to 2500 kW, which amounts to a DG penetration level of almost 15% to 80%. The maximum and minimum limits on bus voltages are set at 1.05 and 0.95purespectively. The substation bus voltage is assumed to be at 1.02 p.u. for this study. The limit on $max(THD_V)$ has been set at 5% as per IEEE standard 519 [18].

A six pulse converter is assumed to be connecting the DG to the network. The harmonic order of the 6 pulse converter is used for harmonic modeling of the DG as per data given in Table *B3* in *Appendix – B.* The optimal DG size for each of the candidate buses are obtained by running the optimization program (PSO) with the DG placed at the respective buses one at a time. Selection of candidate buses depends on number of factors such as technical, economical, geographical, social, political etc. However, in this study, this issue is not of concern, and, therefore, candidate buses are arbitrarily selected. Buses 5 to 18 of the trunk feeder and 26 to 33 on the longest lateral are taken as candidate buses for IEEE-33 bus network while buses 6 to 27 and 53 to 69 have been selected as candidate buses for IEEE-69 network. The results are furnished in Table 2.2 (a) to Table 2.3 (b).

Table 2.1(a) shows the results of base case (i.e., with no DG is installed) load flow for IEEE-33 bus network whereas that for IEEE-69 bus network is given in Table 2.1(b). Table 2.1(a) shows that under the given loading, the network power loss in the first network is 194 kW with the minimum bus voltage (V_{min}) is falling much below the specified limit of 0.95 p.u. Similarly from Table 2.1(b) it is found that under the given loading, the network power loss in this network is 215 kW and the minimum bus voltage (V_{min}) in this case too is falling much below the specified limit of 0.95 p.u.

Table 2.1(a). Base Case Load Flow Result for IEEE- 33 Bus Network.

V_S (p.u.)	P_{LOSS} (kW)	Vmax (p.u)	Vmin (p.u.)
1.02	194	1.0171	0.9351

Table 2.1(b). Base Case Load Flow Result for IEEE- 69 Bus Network.

V_S (p.u.)	P_{LOSS} (kW)	Vmax (p.u)	Vmin (p.u.)
1.02	215.08	1.0199	0.9313

Table 2.2(a) shows the minimum power loss that can be achieved along with the corresponding DG sizes for different candidate buses of IEEE-33 bus network when no constraint on $max(THD_V)$ is applied. Significant reduction in loss and no voltage limit violation for the optimal DG sizes can be observed in all cases of DG placement. Maximum loss reduction of 45% (from 194 kW to 106.72kW) takes place for a DG size of 2373 kW at bus no.6. But these improvements are associated with violation of limit on $max(THD_V)$ in all cases except for bus no.5.

Table 2.2(b) shows the corresponding results when constraint on $max(THD_V)$ is imposed. In Table 2.2(b), the effect of considering the constraint on $max(THD_V)$ is prominent. It can be observed that for bus no. 6 to 13 & 26 to 32 with the value of $max(THD_V)$ maintained marginally below the specified limit of 5%, the optimal DG sizes are much less than that obtained in case-I, with the corresponding values for minimum loss being higher, indicating less reduction in loss in each case. Maximum reduction achieved in this case is 40% (from 194 kW to 116 kW) that takes place for a DG size of 1574 kW at bus no.6. It is obvious that an attempt to reduce the $max(THD_V)$ further would require corresponding reduction in DG sizes, which would have increased the loss further. On the other hand even a small amount of increase in DG sizes will lead to the violation of constraint on $max(THD_V)$. For bus no. 14 to 18 and for bus no. 33 no solution satisfying the constraint on $max(THD_V)$ is available within the range of DG size considered. For these buses, even with a DG size of 500 kW, the $max(THD_V)$ remains above the allowable limit. However, the results obtained for bus 5 remains unaltered as minimum power loss occurs without any violation of $max(THD_V)$ constraint.

Table 2.2 (a): Optimal DG Size for Different Candidate Buses of IEEE-33 Bus Network when no Constraint on THD is imposed.

Bus No.	DG Size (kW)	P_{LOSS} (kW)	$\max(THD_V)$ (%)	V_{max} (p.u)	V_{min} (p.u.)
5	2655	128.39	4.0729	1.0187	0.9588
6	2373	106.72	7.3554	1.0185	0.9693
7	2247	107.55	10.0667	1.0184	0.9705
8	1915	111.64	9.5928	1.0183	0.9663
9	1594	117.45	10.5646	1.0181	0.9618
10	1382	120.96	11.4334	1.0179	0.9588
11	1348	121.56	11.3297	1.0179	0.9584
12	1294	122.82	11.2514	1.0179	0.9576
13	1109	127.3	12.4633	1.0178	0.955
14	1056	128.85	13.5219	1.0178	0.9542
15	999	131.17	13.9544	1.0177	0.9534
16	933	134.16	14.148	1.0177	0.9524
17	831	139.3	15.7621	1.0176	0.9509
18	784	142.06	15.8546	1.0176	0.9502
26	2242	108.35	7.4508	1.0184	0.9675
27	2086	110.42	7.619	1.0183	0.9654
28	1700	115.19	9.7333	1.0181	0.9599
29	1507	117.07	10.9901	1.0180	0.9573
30	1415	118.69	11.1269	1.0180	0.9559
31	1243	123.91	12.4418	1.0179	0.9534
32	1189	125.96	12.8655	1.0178	0.9527
33	1131	129.21	13.564	1.0177	0.9518

Table 2.2(b): Optimal DG Size for Different Candidate Buses of IEEE-33 Bus Network with THD Constraint imposed.

Bus No.	DG Size (kW)	P_{LOSS} (kW)	$\max(THD_V)$ (%)	V_{max} (p.u)	V_{min} (p.u.)
5	2655	128.39	4.0729	1.0187	0.9588
6	1574	116.07	4.9979	1.0174	0.9432
7	1076	130.14	4.9959	1.0186	0.9754
8	962	131.23	4.9969	1.0189	0.9797
9	719	139.48	4.997	1.0184	0.9694
10	573	144.47	4.9941	1.0179	0.958
11	562	145.15	4.9937	1.018	0.9606
12	544	145.21	4.9916	1.0442	0.9762
13	418	151.77	4.9942	1.0178	0.9566
14	No solution			1.0176	0.9507
15	No solution			1.0478	0.9681
16	No solution			1.0283	0.9613
17	No solution			1.0333	0.9600
18	No solution			1.0222	0.9565
26	1468	118.04	4.9982	1.0188	0.9768
27	1335	120.76	4.9974	1.0174	0.9412
28	837	134.53	4.9911	1.0183	0.9647
29	652	140.55	4.9989	1.0178	0.951
30	602	142.37	4.9937	1.0183	0.9649
31	470	149.77	4.9954	1.0178	0.9517
32	434	152.25	4.9953	1.0443	0.9726
33	No solution			1.0178	0.9528

The results for IEEE 69 bus network are shown in the following Table 2.3(a) and Table 2.3(b) which are now self- explanatory.

Table 2.3 (a): Optimal DG Size for Different Candidate Buses of IEEE-69 Bus Network when no Constraint on THD is imposed.

Bus No.	DG Size (kW)	P_{LOSS} (kW)	$\max(THD_V)$ (%)	V_{max} (p.u)	V_{min} (p.u.)
6	2835	193.99	1.4391	1.01997	0.9389
7	2778	174.38	2.6343	1.01997	0.9459
8	2763	169.86	2.9132	1.01997	0.9475
9	2749	167.66	3.054	1.01997	0.9483
10	1800	176.66	2.9812	1.01997	0.9425
11	1691	177.43	3.0303	1.01997	0.9419

12	1376	180.84	3.1754	1.01997	0.9399
13	1085	185.43	3.313	1.01997	0.9381
14	916	187.81	3.4885	1.01997	0.9371
15	807	189.17	3.6889	1.01996	0.9364
16	790	189.34	3.7233	1.01996	0.9363
17	759	189.78	3.7822	1.01996	0.9361
18	703	190.83	3.5251	1.01996	0.9358
19	680	191.39	3.5704	1.01996	0.9356
20	665	191.72	3.5922	1.01996	0.9355
21	643	192.22	3.632	1.01996	0.9354
22	642	192.25	3.6328	1.01996	0.9354
23	631	192.62	3.6431	1.01996	0.9353
24	608	193.37	3.6627	1.01996	0.9352
25	562	194.94	3.6902	1.01996	0.9349
26	545	195.52	3.7005	1.01996	0.9348
27	535	195.85	3.6999	1.01996	0.9347
53	2594	164.59	3.4007	1.01997	0.9504
54	2462	160.82	3.8008	1.01997	0.9528
55	2325	155.55	4.3442	1.01997	0.956
56	2223	150.41	4.8657	1.01997	0.9591
57	1921	121.54	6.4798	1.01997	0.9759
58	1837	107.89	7.2561	1.01997	0.9836
59	1810	102.72	7.5467	1.01997	0.9866
60	1772	97.149	7.8417	1.01997	0.9873
61	1728	89.812	8.6166	1.01997	0.9871
62	1704	91.149	8.6828	1.01997	0.9869
63	1669	93.158	8.7754	1.01997	0.9867
64	1519	101.72	9.1955	1.01996	0.9858
65	1325	115.53	9.5696	1.01996	0.9828
66	1537	180.78	2.9174	1.01997	0.9409
67	1534	180.85	2.9164	1.01997	0.9409
68	1091	187.65	3.0683	1.01997	0.9381
69	1089	187.68	3.0665	1.01997	0.9381

In this study, 50 iterations and a swarm size of 20 have been used to run the PSO program. Such values are quite common for this type of problem. With each particle of the swarm, an HLF is needed, which means 20 number of HLF requires to be executed for each iteration. Therefore, a total of (20x50) = 1000 number of HLF is required for each candidate bus.

Table 2.3 (b): Optimal DG Size for Different Candidate Buses of IEEE-69 Bus Network when Constraint on THD is imposed.

Bus No.	DG Size (kW)	P_{LOSS} (kW)	$\max(THD_V)$ (%)	V_{max} (p.u)	V_{min} (p.u.)
6	2835	193.99	1.4391	1.01997	0.9389
7	2778	174.38	2.6343	1.01997	0.9459
8	2763	169.86	2.9132	1.01997	0.9475
9	2749	167.66	3.054	1.01997	0.9483
10	1800	176.66	2.9812	1.01997	0.9425
11	1691	177.43	3.0303	1.01997	0.9419
12	1376	180.84	3.1754	1.01997	0.9399
13	1085	185.43	3.313	1.01997	0.9381
14	916	187.81	3.4485	1.01997	0.9371
15	807	189.17	3.6889	1.01996	0.9364
16	790	189.34	3.7233	1.01996	0.9363
17	759	189.78	3.7822	1.01996	0.9361
18	703	190.83	3.5251	1.01996	0.9358
19	680	191.39	3.5704	1.01996	0.9356
20	665	191.72	3.5922	1.01996	0.9355
21	643	192.22	3.632	1.01996	0.9354
22	642	192.25	3.6328	1.01996	0.9354
23	631	192.62	3.6431	1.01996	0.9353
24	608	193.37	3.6627	1.01996	0.9352
25	562	194.94	3.6902	1.01996	0.9349
26	545	195.52	3.7005	1.01996	0.9348
27	535	195.85	3.6999	1.01996	0.9347
53	2594	164.59	3.4007	1.01997	0.9504
54	2462	160.82	3.8008	1.01997	0.9528
55	2325	155.55	4.3442	1.01997	0.956
56	2223	150.41	4.8657	1.01997	0.9591
57	1451	126.77	4.9983	1.01997	0.9654
58	1223	119.04	4.9969	1.01997	0.9668
59	1151	116.56	4.9898	1.01997	0.9672
60	1080	113.83	4.9968	1.01997	0.968
61	947	113.49	4.9928	1.01997	0.9671
62	927	115.06	4.9977	1.01997	0.9669
63	897	117.38	4.9953	1.01997	0.9666
64	776	126.97	4.9983	1.01997	0.9638
65	648	139.8	4.996	1.01997	0.94997
66	1537	180.78	2.9174	1.01997	0.9409
67	1534	180.85	2.9164	1.01997	0.9409
68	1091	187.65	3.0683	1.01997	0.9381
69	1089	187.68	3.0665	1.01997	0.9381

2.6 CHAPTER SUMMARY

This chapter has presented a PSO based formulation of optimal DG placement problem for loss minimization in distribution network in presence of DG generated harmonics. The proposed formulation is capable of taking into account the constraints on bus voltage magnitudes as well as maximum allowable value of THD in bus voltage. The purpose of this study was to determine the DG size at any given bus for maximum reduction in network power loss achievable within permissible limit on voltage THD. From the simulation results obtained for two benchmark distribution test networks it has been observed that without imposition of any constraint on the maximum value of voltage THD, quite appreciable amount of loss reduction can be achieved by placing DG of proper size (optimal size) at any given bus. However, when constraint is imposed on permissible value of voltage THD, the reduction in loss is somewhat sacrificed. In other words, the power quality in terms of harmonic distortion is improved at the cost of less reduction in network power loss.

Once the solution for all the candidate buses are obtained, the ultimate optimal DG size and location for the network will be readily available from the list. Accordingly for IEEE- 33 bus network it is seen from Table 2.2 (a) and Table 2.2 (b) that, in both cases, bus 6 is the optimal location with the corresponding size being 2373 kW and 1574 kW respectively. Similarly for IEEE- 69 bus network from Table 2.3 (a) and Table 2.3 (b), it is clear that bus 61 is the optimal location for the network with corresponding DG sizes of 1728kW and 947 kW respectively.

CHAPTER 3

A computationally efficient iterative approach for optimal DG placement: An unconstrained solution

Outline of the chapter

3.1 INTRODUCTION

The PSO based method discussed in the previous chapter is highly computation intensive for optimal DG placement problem as large number of HLF is required for each candidate bus. In practical situation, a computationally faster method is always more desirable. In this chapter, a novel iterative method is proposed which requires quite small amount of computation to determine the optimal size of DG unit located at any arbitrarily selected bus for minimization of loss in distribution network. The proposed method is equally applicable for networks with or without harmonic sources. The methodology proposed is capable of finding the unconstrained optimal size of the DG with significantly less computation than is required by the evolutionary population based iterative approaches as it requires only few HLF calculations to reach the desired solution for any candidate bus.The results obtained with this method are compared with those obtained using PSO method proposed in the previous chapter to demonstrate the effectiveness of the method.

3.2 BASIS OF DEVELPOMENT OF THE PROPOSED ITERATIVE METHOD

It has already been shown in section 2.2 of chapter 2 that, irrespective of whether harmonics source is present in the network or not, the network power loss varies parabolically with the DG size at any given bus. A typical loss curve is shown in Fig.3.1 where S_{Min} and S_{Max} are the minimum and maximum DG size to be considered, and S_u is the optimal size for which the network power loss becomes minimum in the absence of any constraint. For any size S with $S_{Min} < S < S_u$, a small increment Δs in size will result in decrement of loss while a decrement Δs will increase the loss. On the other hand, if $S_{Max} > S > S_u$, an increment Δs will increase the loss whereas a decrement of same amount in size will result in reduction in loss. However, when $S = S_u$, a small perturbation Δs in either direction (increment or decrement) will result in small increase in loss. The above facts can be used as a criteria to check whether $S_u^{(old)}$ $S > S_u$ or $S < S_u$ or $S = S_u$, where, S is any arbitrary size of the DG. Based on this logic, the proposed iterative method has been developed.

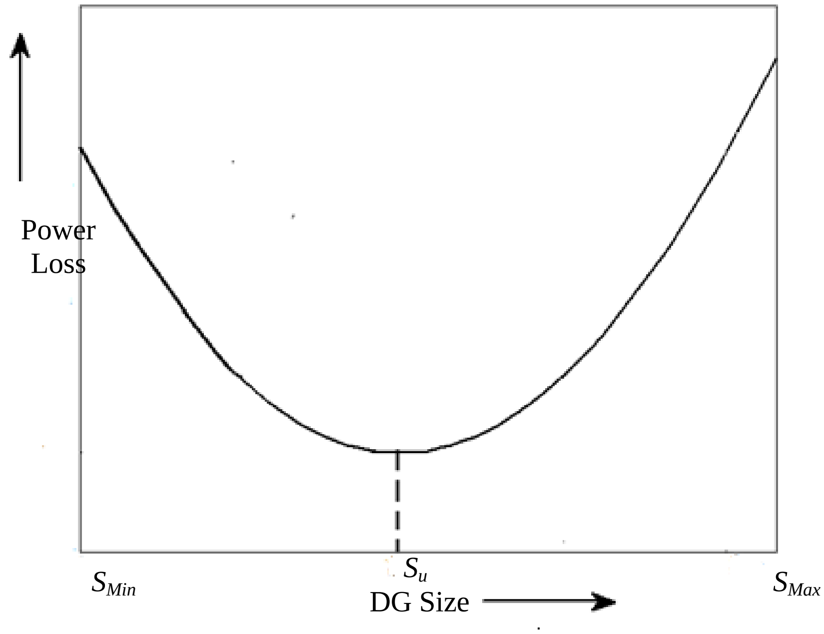

Fig. 3.1. A Typical Loss Curve.

3.3 DEMONSTRATION OF THE ITERATIVE PROCESS

In this iterative method, the solution is achieved in two stages. In stage 1, an approximate value for S_u is determined. The iterative process of stage 1 is demonstrated with the help of Fig. (3.2 a), Fig. (3.2 b) and Fig. (3.2c), where, $S_u^{(0)}$ is the initial guess for S_u with which the iteration starts, and, is given by

$$S_u^{(0)} = \frac{S_{Min} + S_{Max}}{2} \tag{3.1}$$

and $S_u^{(1)}$ and $S_u^{(2)}$,respectively, are the first and the second updated estimates obtained iteratively (using r=0 and r=1) from the following equation:

$$S_u^{(r+1)} = \frac{S_u^{(r)} + S_u^{(old)}}{2} \tag{3.2}$$

For *r=0*,

$$S_u^{(old)} = S_{Min} \text{ if } S_u^{(r)} > S_u$$
$$= S_{Max} \text{ if } S_u^{(r)} < S_u$$

and, for *r > 0*, $S_u^{(old)} = S_u^{(r-1)}$ if $S_u^{(r)}$ and $S_u^{(r-1)}$ are on the two sides of S_u (as shown in Fig.3.2(a) and Fig.3.2(b)). $S_u^{(old)}$ remains unchanged when $S_u^{(r)}$ and $S_u^{(r-1)}$ are on the same side of S_u (as shown in Fig. 3.2(c)). As example, in Fig. 3.2(a), $S_u^{(1)}$ is obtained by putting *r=0*, and $S_u^{(old)} = S_{Min}$ in equation (3.2) as $S_u^{(0)} > S_u$. Thus $S_u^{(1)}$ is given as follows:

$$S_u^{(1)} = \frac{S_u^{(0)} + S_{Min}}{2}$$

Whereas, in Fig. 3.2(b), $S_u^{(1)}$ is obtained by putting *r=0*, and $S_u^{(old)} = S_{Max}$ in equation (3.2) as $S_u^{(0)} < S_u$, and, as a result $S_u^{(1)}$ in Fig. 3.2(b) is given as

$$S_u^{(1)} = \frac{S_u^{(0)} + S_{Max}}{2}$$

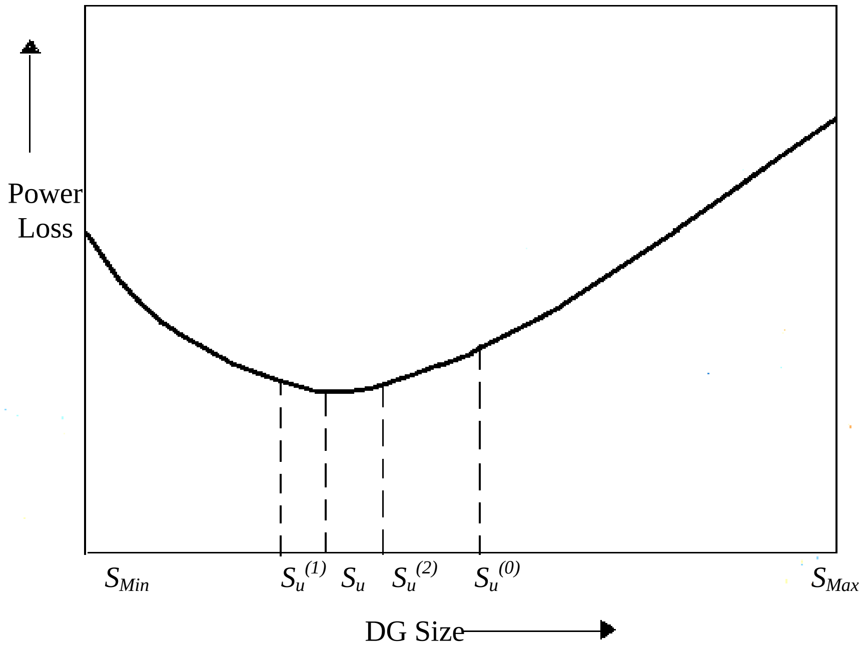

Fig. 3.2(a). Demonstration of the Proposed Iterative Process.

The second estimate $S_u^{(2)}$ in Fig. 3.2(c) is obtained from equation (3.2) by putting *r=1*, and $S_u^{(old)} = S_{Min}$ (same as the previous value) as $S_u^{(1)}$ and $S_u^{(0)}$ are on the same side of S_u.

Thus,

$$S_u^{(2)} = \frac{S_u^{(1)} + S_{Min}}{2}$$

where as, in Fig. 3.2(a) and Fig.3.2 (b), $S_u^{(old)} = S_u^{(0)}$, as $S_u^{(1)}$ and $S_u^{(0)}$ are on the two sides of S_u. In this case,

$$S_u^{(2)} = \frac{S_u^{(1)} + S_u^{(0)}}{2}$$

The estimates are updated in successive iterations with $r= 2, 3...$ and so on. The iteration continues until convergence is obtained i.e., the condition $S_u^{(r)} = S_u$ is reached. The following set of criteria is used to check whether $S_u{}^{(r)} > S_u$ or $S_u{}^{(r)} < S_u$ or $S_u{}^{(r)} = S_u$.

Criterion- 1: If $P_{Loss}^{+} > P_{Loss}^{(r)} > P_{Loss}^{-}$, then $S_u^{(r)} > S_u$

Criterion- 2: If $P_{Loss}^{+} < P_{Loss}^{(r)} < P_{Loss}^{-}$, then $S_u^{(r)} < S_u$

Criterion- 3: If $P_{Loss}^{+} > P_{Loss}^{(r)} < P_{Loss}^{-}$, then $S_u^{(r)} = S_u$

Convergence is said to have reached if criterion- 3 is satisfied.

Here, P_{Loss}^{+} and P_{Loss}^{-}, are the losses obtained for DG size S^{+} and S^{-} respectively, $P_{Loss}^{(r)}$ is the loss calculated with DG size $S_u^{(r)}$, $S^{+} = S_u^{(r)} + \Delta S$, $S^{-} = S_u^{(r)} - \Delta S$, and p is the perturbation factor.

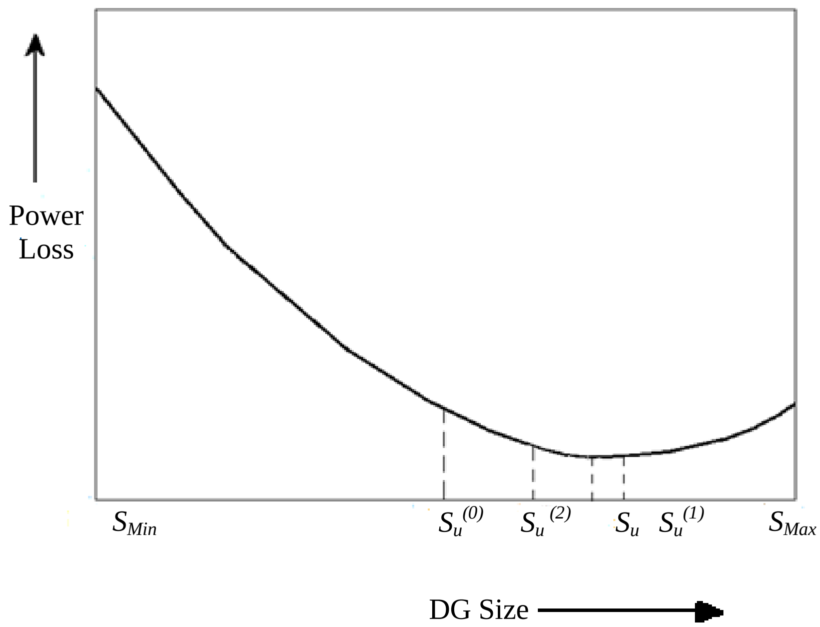

Fig. 3.2(b). Demonstration of the Proposed Iterative Process.

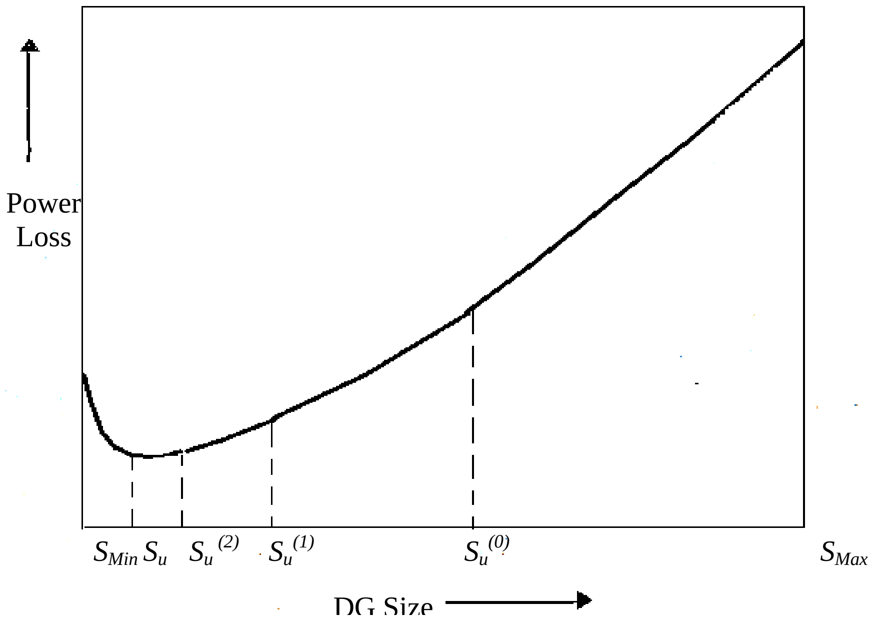

Fig. 3.2(c). Demonstration of the Proposed Iterative Process.

3.4 COMPUTATIONAL STEPS

Based on the concepts and the associated set of criteria presented in section 3.3 computational steps for finding S_u are developed. Two stages of computations are applied to obtain the final solution for S_u. The perturbation factor used in stage 1 is 5% (*i.e.* $p = 5$). As a result, the estimate of S_u obtained at this stage is approximately within $\pm 2.5\%$ of its actual value. Let it be called S_{approx}. The computational steps for stage 1 are furnished in subsection 3.4.1.

3.4.1 Computational steps for stage 1

1. Select a bus and set S_{Max}, S_{Min}, p and r_{Max}.
2. If $S_{Min} > 0$, then, check if $S_{Min} \geq S_u$. If yes, then set $S_u = S_{Min}$ and go to step 13, else go to next step.
3. Check if $S_{Max} \leq S_u$. If yes, then set $S_u = S_{Max}$ and go to step 13, else, go to next step.
4. Set r=0.
5. Calculate $S_u^{(r)} = \dfrac{S_{Min} + S_{Max}}{2}$.

6. If $S_u^{(r)} = S_u$, then set $S_u = S_u^{(r)}$ and go to step 13, else, go to next step.

7. Set $S_u^{(old)} = S_{Min}$ if $S_u^{(r)} > S_u$

$= S_{Max}$ if $S_u^{(r)} < S_u$

8. Calculate $S_u^{(r+1)} = \dfrac{S_u^{(r)} + S_u^{(old)}}{2}$

9. If $S_u^{(r+1)} = S_u$, then set $S_{opt} = S_u^{(r+1)}$, and go to step 13, else, go to next step.

10. Set $S_u^{(old)} = S_u^{(r-1)}$ if $S_u^{(r)}$ and $S_u^{(r-1)}$ are on the two sides of S_u, or, keep $S_u^{(old)}$ unchanged if $S_u^{(r)}$ and $S_u^{(r-1)}$ are on the same side of S_u.

11. Set $r = r + 1$

12. If $r > r_{Max}$, then go to step 14, else, go to step 8.

13. Print/Display the value of S_u and go to step 15.

14. Print/Display 'No convergence'.

15. Stop.

3.4.2 Computational steps for stage 2

For a more accurate solution for S_u, a second stage (stage 2) of computation is required. In stage 2, the computational steps start with S_{approx} (value of S_u obtained from stage 1) as the initial guess of $S_u^{(0)}$. The perturbation factor used in this stage is 0.5% (*i.e.* p = 0.5).Thus S_u obtained from this stage is approximately within ±0.25% of its actual value. The computational steps are as follows:

1. Set iteration count $r = 0$, $S_u^{(r)} = S_{approx}$ and $p = 0.5$.
2. If $S_u^{(r)} < S_u$ then set $S_u^{(r)} = S^+$, $m = 1$, and go to step 4, else go to next step.
3. If $S_u^{(r)} > S_u$ then set $S_u^{(r)} = S^-$, $m = -1$, and go to next step, else go to step 8.
4. Set $S_u^{(old)} = S_u^{(r)}$.
5. Set $r = r + 1$.
6. Set $S_u^{(r)} = S_u^{(old)} + m \times \Delta S$.
7. If $P_{Loss}^{(r)} < P_{Loss}^{(r-1)}$, go to step 4, else go to step 9.
8. Set $S_u^{(old)} = S_u^{(r)}$.

9. Set $S_u = S_u^{(old)}$.
10. Print and/or display S_u.
11. Stop.

3.5 SIMULATION STUDY AND RESULTS

To demonstrate its efficacy, the proposed method was applied to two benchmark radial distribution test networks, IEEE-33 bus network and IEEE-69 bus network. For the 33 bus network, bus nos. 5 to 18 and 26 to 33 are chosen as candidate buses, while bus nos. 6 to 27 and 53 to 69 are chosen for the 69 bus network. A six-pulse inverter based DG is considered, which acts as the only harmonic source in the network. The harmonic order of the 6 pulse converter used for harmonic modeling of the DG is provided in *Appendix- B* in accordance to [57],[58]. Unity power factor DG has been considered. The minimum and maximum limit on the size of DG unit to be installed has been assumed to be 500 kW and 3000kW respectively. The substation bus voltage for this study has been taken as1.02 p.u. The results obtained by the proposed method are compared with those obtained by PSO technique presented in chapter 2 [55],[56].

The results are summarized in Table 3.1(a) to Table 3.2(b). Table 3.1(a) and 3.2(a) show the results obtained for IEEE-33 and IEEE-69 bus system when harmonic sources are not present whereas Table 3.1 (b) and 3.2 (b) show the results when harmonics injected by DG are considered. From these tables it is obvious that in all cases the results obtained by the proposed method is very close to that obtained by PSO, but the amount of computation in terms of number of DLF or HLF required by the proposed method for each bus is quite small. The maximum number of load flow (DLF when harmonic source is not present and HLF when harmonic source is considered) required is 12 for both the networks. However, PSO requires large number of Load flow calculations (may be few hundred as discussed in chapter 2) for each bus. So it can be concluded that comparable results are obtained by the proposed method with significantly less computation.

Table 3.1 (a): Optimum DG Sizes for IEEE-33 Bus Network in Absence of Harmonics.

Bus No	Optimum DG size using the Proposed Approach			Optimum DG size using PSO	
	Size (kW)	P_{LOSS} (kW)	No. of DLF reqd.	Size (kW)	P_{LOSS} (kW)
5	2881	122.944	6	2882	122.944
6	2574	99.619	6	2570	99.619
7	2435	100.58	6	2437	100.58
8	2084	105.6	6	2081	105.6
9	1731	111.31	6	1728	111.31
10	1502	115.13	8	1501	115.13
11	1467	115.78	6	1465	115.78
12	1403	117.14	8	1402	117.14
13	1205	122.01	8	1206	122.01
14	1147	123.71	6	1146	123.71
15	1088	126.21	6	1084	126.21
16	1013	129.44	6	1012	129.44
17	905	135.01	6	900	135.01
18	852	144.24	6	850	144.23
26	2431	101.39	6	2431	101.39
27	2266	103.63	6	2266	103.63
28	1843	108.83	6	1843	108.83
29	1639	110.9	6	1639	110.9
30	1534	112.65	6	1534	112.65
31	1346	118.33	8	1346	118.33
32	1291	120.55	8	1291	120.55
33	1225	124.08	8	1225	124.08

Table 3.1 (b): Optimum DG sizes for IEEE-33 Bus Network in Presence of Harmonics.

Bus No.	Optimum DG size using the Proposed Approach			Optimum DG size using PSO	
	Size (kW)	P_{LOSS} (kW)	No. of HLF reqd.	Size (kW)	P_{LOSS} (kW)
5	2655	128.39	6	2655	128.39
6	2370	106.72	4	2369	106.72
7	2145	107.55	4	2247	107.55
8	1915	111.64	4	1919	111.64
9	1594	117.45	8	1592	117.45
10	1388	120.92	6	1383	120.96
11	1355	121.56	8	1352	121.56
12	1290	122.82	8	1294	122.82
13	1106	127.3	8	1111	127.3
14	1048	128.85	12	1056	128.85
15	1005	131.17	12	998	131.17
16	935	134.16	12	931	134.16
17	835	139.4	12	832	139.3
18	785	142.04	12	784	142.06
26	2243	108.35	6	2241	108.35

27	2091	110.42	8	2089	110.42
28	1700	115.19	8	1698	115.19
29	1512	117.07	4	1510	117.07
30	1416	118.69	8	1414	118.69
31	1243	123.91	8	1241	123.91
32	1192	125.96	8	1190	125.96
33	1131	129.21	8	1129	129.21

Table 3.2 (a): Optimum DG Sizes for IEEE-69 Bus Network in Absence of Harmonics.

Bus No	Optimum DG size using the Proposed Approach			Optimum DG size using PSO	
	Size (kW)	P_{LOSS} (kW)	No. of DLF reqd.	Size (kW)	P_{LOSS} (kW)
6	3085	192.17	12	3082	192.17
7	3023	170.93	12	3020	170.93
8	3012	166.04	10	3001	166.04
9	2990	163.66	10	2987	163.66
10	1959	173.41	12	1955	173.41
11	1837	174.25	12	1836	174.25
12	1500	177.95	8	1495	177.95
13	1182	182.92	12	1180	182.92
14	998	185.51	8	996	185.51
15	879	186.99	8	876	186.99
16	855	187.18	8	858	187.18
17	829	187.66	8	824	187.66
18	768	188.79	8	764	188.79
19	739	189.4	8	739	189.4
20	724	189.76	8	723	189.76
21	703	190.3	8	701	190.3
22	699	190.33	8	699	190.33
23	690	190.73	8	685	190.73
24	664	191.54	8	661	191.54
25	611	193.25	8	611	193.25
26	594	193.88	8	592	193.88
27	586	194.23	8	582	194.23
53	2816	160.35	8	2816	160.35
54	2672	156.28	8	2672	156.28
55	2523	150.61	8	2523	150.61
56	2412	145.07	8	2412	145.07
57	2080	114.01	8	2082	114.01
58	1991	99.49	8	1990	99.49
59	1962	93.96	6	1960	93.96
60	1910	88.02	6	1912	88.02
61	1868	80.12	6	1871	80.12
62	1846	81.63	6	1845	81.63
63	1807	8378	6	1807	8378
64	1643	92.96	8	1645	92.96
65	1435	107.78	8	1436	107.78

66	1672	177.87	8	1671	177.87
67	1665	177.95	8	1667	177.95
68	1186	185.32	8	1186	185.32
69	1184	185.35	8	1184	185.35

Table 3.2 (b): Optimum DG Sizes for IEEE-69 Bus Network in Presence of Harmonics.

Bus No	Optimum DG size using the Proposed Approach			Optimum DG size using PSO	
	Size (kW)	P_{LOSS}(kW)	No. of HLF reqd.	Size (kW)	P_{LOSS} (kW)
6	2840	193.99	6	2835	193.99
7	2775	174.38	6	2778	174.38
8	2765	169.86	8	2763	169.86
9	2745	167.65	10	2749	167.66
10	1800	176.66	10	1800	176.66
11	1691	177.43	10	1691	177.43
12	1376	180.84	10	1376	180.84
13	1087	185.43	10	1085	185.43
14	920	187.81	10	916	187.81
15	806	189.17	10	807	189.17
16	788	189.34	10	790	189.34
17	763	189.78	10	759	189.78
18	696	190.83	10	703	190.83
19	681	191.39	10	680	191.39
20	659	191.72	10	665	191.72
21	648	192.22	10	643	192.22
22	643	192.25	10	642	192.25
23	630	192.62	10	631	192.62
24	610	193.37	10	608	193.37
25	578	194.95	10	562	194.94
26	542	195.52	12	545	195.52
27	536	195.85	12	535	195.85
53	2594	164.59	8	2594	164.59
54	2462	160.82	8	2462	160.82
55	2325	155.55	6	2325	155.55
56	2223	150.41	6	2223	150.41
57	1918	121.54	6	1921	121.54
58	1837	107.89	6	1837	107.89
59	1811	102.72	6	1810	102.72
60	1771	97.15	6	1772	97.149
61	1725	89.81	6	1728	89.812
62	1705	91.15	6	1704	91.149
63	1669	93.15	6	1669	93.158
64	1517	101.72	8	1519	101.72
65	1324	115.52	6	1325	115.53
66	1538	180.78	6	1537	180.78
67	1532	180.85	6	1534	180.85
68	1091	187.65	6	1091	187.65
69	1089	187.68	6	1089	187.68

3.6 CHAPTER SUMMARY

This chapter has proposed a novel iterative method for calculating the optimal DG size located at any arbitrarily selected bus of a radial distribution network. It has been shown that the method requires significantly less computation than is required by the evolutionary methods. The method is a generalized one as it is equally applicable in both cases when harmonic sources are present in the network or not. The results of the study have shown that the presence of harmonics somewhat reduces the optimal size with a corresponding increase in the value of minimum loss. This corroborates with the fact which could be noticed from the loss curves (Fig.2.1 (a) and Fig. 2.1(b)) shown in section 2 of chapter 2. Though the proposed method can find only unconstrained optimal size of DG units, it is expected that it's capability of fast detection of the same can contribute significantly in reducing the amount of computation for finding the constrained optimal size.

CHAPTER 4

A Hybrid Approach for Optimal Placement of Inverter Based DG unit in distribution network in presence of harmonic distortion limit

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Outline of the chapter

4.1 Introduction

4.2 The Problem Statement

4.3 Development of Rule Base

4.4 Proposed Methodology

4.5 Simulation Studies and Test Results

4.6 Chapter Summary

4.1 INTRODUCTION

In this chapter, a hybrid method is proposed for optimal placement of inverter-based DG unit located at any given bus of a radial distribution network to minimize active power loss in the network in presence of limit on the maximum allowable harmonic distortion. A Rule-base is developed in this study which is combined with some computationally efficient iterative calculations to obtain the desired optimal solution. The solution gives the size of the DG unit that minimizes the network power loss while satisfying the constraint imposed on the allowable limit of the maximum total harmonic distortion in bus voltages (THD_{VM}). The proposed method requires only few HLF to be executed to arrive at an acceptable solution for any given bus, and thus, requires significantly less computation compared to the existing methods. To validate this claim, the results obtained using the suggested method has been benchmarked with those obtained using the PSO technique presented in chapter 2.

4.2 THE PROBLEM STATEMENT

The problem is posed as an optimization problem as already stated in chapter 2, and therefore, no more elaborated here. The objective function to be minimized is the total network power loss which is given by equation (2.1) and the equality constraint is the network power balance given by equation (2.5). The inequality constraints are given by equation (2.6) and (2.8). In this work, constraint on bus voltage magnitude has not been considered.

4.3 DEVELOPMENT OF RULE- BASE

The rule base is developed from the following observations:

Observation 1:

An extensive simulation study was done for a number of radial distribution network using repeated HLF calculations. For each network, the study was carried out by running HLF with the DG unit placed at different buses, taken one at a time, and the DG size varied in small steps. In each case, P_{Loss} and THD_{VM} were calculated from the HLF result. From the results, it was revealed that, with increase in size of the DG source placed at any given bus of a radial distribution network, the value of THD_{VM} may vary in one of the following manner:

(i) With background harmonics present in the network the value of THD_{VM} starts decreasing from THD_B (the background value of THD_{VM}), and, after attaining a minimum, starts to increase monotonically. In some cases, THD_{VM} may increase monotonically starting from THD_B.

(ii) With no background harmonics present, the value of THD_{VM} increases monotonically from zero (as $THD_B = 0$).

The variation of THD_{VM} with DG size, henceforth, will be termed as THD curve.

The above mentioned nature of THD curve can be explained as follows:
The initial decreasing nature of the THD curve is due to possible cancellation of some of the background harmonics by the DG injected harmonics. As the DG size increases, resultant magnitude of those common harmonics go on reducing causing the value of THD_{VM} to go down gradually. This trend continues up to a DG size for which the cancellation is complete, and after that, the magnitude of those common harmonics starts to increase with the DG size resulting in an increasing trend in the THD curve. However, depending on the background harmonic profile and the profile of the DG injected harmonics, the cancellation may not be appreciable or no cancellation may occur at all. In that case, the THD curve increases monotonically starting from THD_B. If $THD_B = 0$, the THD curve increases monotonically from zero as there is only DG injected harmonics which only increases with DG size.

Fig.4.1(a) and Fig.4.1(b), respectively, show the THD curves for some of the buses of IEEE-33 bus network and IEEE-69 bus network, with the load data for both the systems modified by loading condition L2 as mentioned in Table B1 and B2 of *Appendix-B* to incorporate the effects of harmonics due to non-linear loads. To maintain clarity of these figures, curves for only a few arbitrarily selected buses have been shown. To demonstrate the effect of base case loading on the THD curves, the same for bus 12 of IEEE 33 bus network with different degrees of nonlinearities in the base case loading (as given by different loading conditions L1, L2, and L3) have been presented in Fig.4. 2

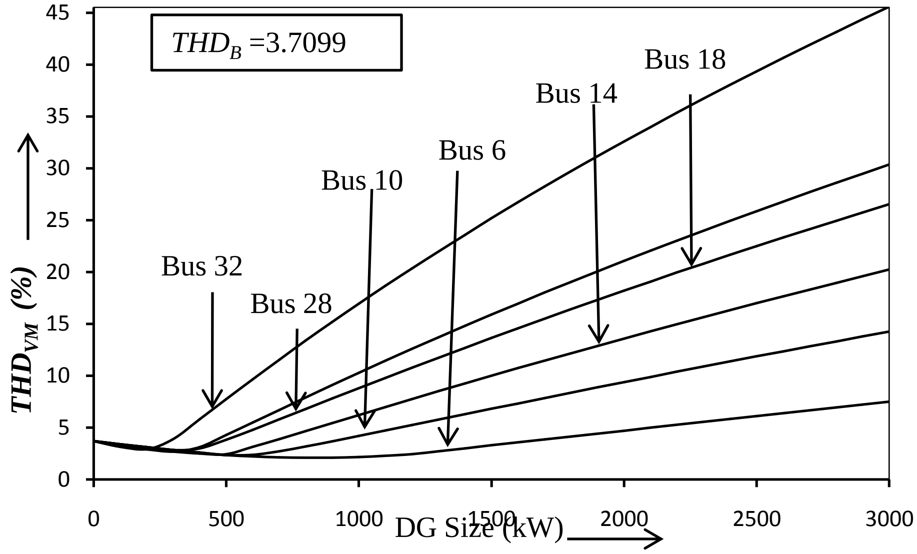


Fig. 4.1(a). *THD* Curves for Different Buses of IEEE-33 Bus Network under Loading Condition L2.

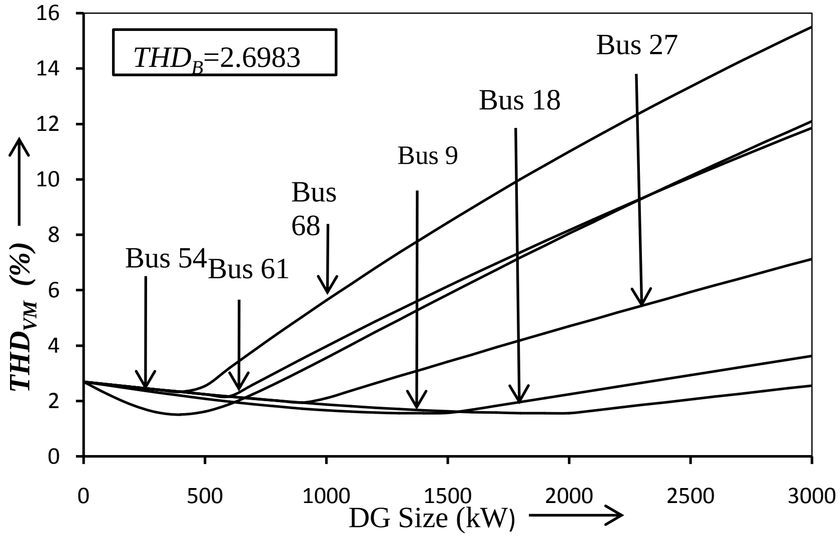


Fig. 4.1(b). *THD* Curves for Different Buses of IEEE-69 Bus Network under Loading Condition L2.

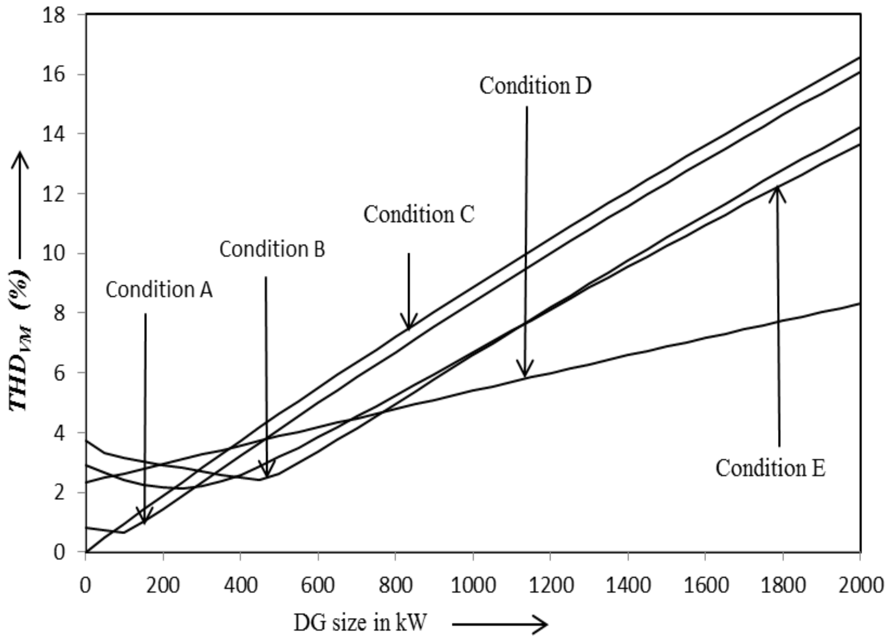


Fig. 4.2. *THD* Curves for Bus 12 of IEEE-33 Bus Network under Various Conditions.

A: Under loading condition L1 ($THD_B =$ 0.8126)
B: Under loading condition L2 ($THD_B =$ 3.7099)
C: Under loading condition L3 ($THD_B =$ 0)
D: Under loading condition L1 with 300kW DG placed at Bus 26 ($THD_B =$ 2.3309)
E: Under loading condition L2 with 200kW DG placed at Bus 30 ($THD_B =$2.9255)

Observation 2:

A typical *THD* curve is shown in Fig.4.3 in which S_{L1} and S_{L2} are the sizes for which $THD_{VM} = THD_L$, the limiting value. THD_m represents the minimum value of THD_{VM} within the range of DG size considered, and S_m is the corresponding size of the DG. S_{Max} and S_{Min} are, respectively, the maximum and minimum DG sizes considered, and THD_{Max} and THD_{Min} are the corresponding values of THD_{VM}. It is obvious from this figure that, within the range of DG size considered, a *THD* curve can intersect the THD_L line at the most for two sizes, once at S_{L1} in the decreasing zone of the *THD* curve, and, for the second time, at S_{L2} (with $S_{L2} > S_{L1}$) in the increasing zone. A decrement in size from S_{L1} will raise the value of THD_{VM} above THD_L while the same will take place for an increment in size from S_{L2} which means S_{L1} and S_{L2} are the limiting sizes as far as the constraint on maximum limit of THD_{VM} is concerned. For any size S, where $S_{L1} < S < S_{L2}$, the value of THD_{VM} will be within THD_L.This can happen only if $THD_{Min} > THD_L < THD_{Max}$ with $THD_m < THD_L$. However if $THD_{Min} < THD_L < THD_{Max}$, then, S_{L2} will be the only intersecting point. In that case, THD_{VM} will be within limit only for sizes smaller or same as S_{L2}. On the other hand, if $THD_{Min} > THD_L > THD_{Max}$, S_{L1}, will be the only intersecting point and THD_{VM} will be within limit only for sizes larger than or equal to S_{L1}, When both THD_{Max} and THD_{Min} are less than THD_L for all the sizes within the range, THD_{VM} will be within the limit. In case $THD_{Min} = THD_L$, S_{L1}, coincides with S_{Min}, while S_{L2} coincides with S_{Max} when $THD_{Max} = THD_L$. No size will be available for which $THD_{VM} \le THD_L$, if $THD_{VM} > THD_L$.

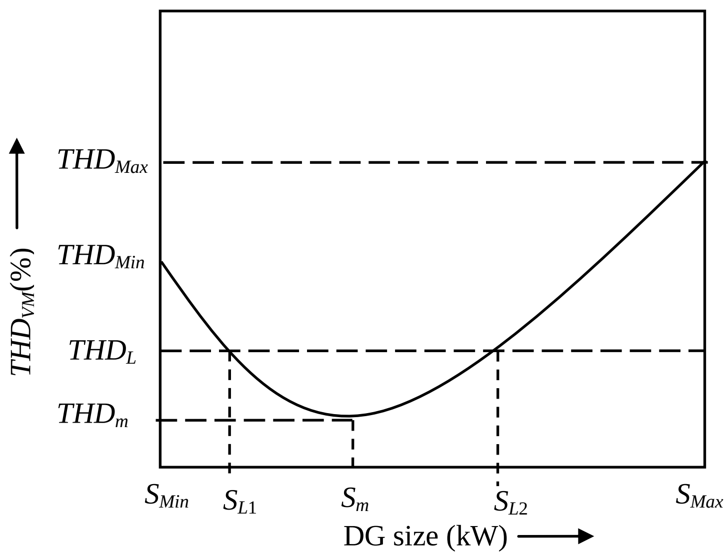


Fig. 4.3. A Typical *THD* Curve.

Observation 3:

It has been already shown in the earlier chapters that the network power loss varies in a parabolic pattern with the DG size at any given bus of a radial distribution network. Figure. 3.1 in chapter 3 shows a typical loss curve, where S_u is the unconstrained optimal size of the DG, i.e., the size that minimizes the network power loss with no constraint imposed on the maximum allowable value of THD_{VM}.

Based on the above three observations, a rule base has been developed which can identify the optimal solution S_{opt} under different situations. The rule base, along with all the necessary justifications for each situation, has been presented in Table 4.1.

Table 4.1: The Rule Base

Rule	Situations	Optimal solution S_{opt}	Justifications
1	$THD_{Min} < THD_L > THD_{Max}$	$S_{opt} = S_u$	The THD curve lies below the THD_L line for the entire range of DG sizes considered. Hence, no restriction on the optimal size is imposed by THD_L.
2	$THD_{Min} < THD_L < THD_{Max}$	a) $S_{opt} = S_{L2}$, if $S_{L2} < S_u$. b) $S_{opt} = S_u$, if $S_{L2} \geq S_u$.	S_{L2} is the determining factor as the THD curve intersects the THD_L line only once at the size S_{L2}
3	$THD_{Min} = THD_L < THD_{Max}$	a)If $THD_m < THD_L$, then i) $S_{opt} = S_{L2}$, if $S_{L2} < S_u$. ii) $S_{opt} = S_u$, if $S_{L2} \geq S_u$.	S_{L1} will coincide with S_{Min}, hence, S_{L2} will be the determining factor.
		b) $S_{opt} = S_{Min}$ if $THD_m = THD_L$	S_{Min}, is the only possible solution.
4	$THD_{Min} > THD_L > THD_{Max}$	a) $S_{opt} = S_{L1}$, if $S_{L1} > S_u$ b) $S_{opt} = S_u$, if $S_{L1} \leq S_u$.	S_{L1} is the determining factor as the THD curve intersects the THD_L line only once at the size S_{L1}
5	$THD_{Min} > THD_L = THD_{Max}$	a)If $THD_m < THD_L$, then i) $S_{opt} = S_{L1}$, if $S_{L1} > S_u$ ii) $S_{opt} = S_u$, if $S_{L1} \leq S_u$.	Both S_{L1} and S_{L2} will exist. S_{L2} will coincide with S_{Max}, so S_{L1} will be the determining factor.
6	$THD_{Min} > THD_L < THD_{Max}$	a) No solution exists, if $THD_m > THD_L$	The THD curve lies above the THD_L line for the entire range of DG size considered.
		b) $S_{opt} = S_m$, if $THD_m = THD_L$	S_m is the only possible solution.
		c)If $THD_m < THD_L$, The possible solutions are as follows : i) $S_{opt} = S_{L2}$, if $S_{L2} \leq S_u$ ii) $S_{opt} = S_{L1}$, if $S_{L1} \geq S_u$ iii) $S_{opt} = S_u$, if $S_{L1} < S_u < S_{L2}$	1) The THD curve will intersect the THD_L line at both the sizes S_{L1} and S_{L2} Therefore, i) Between S_{L1} and S_{L2}, the later size is nearer to S_u, and hence, results in less amount of loss. ii) Between S_{L1} and S_{L2}, the former size is nearer to S_u, and hence, results in less amount of loss. iii) For the entire range of DG size from S_{L1} to S_{L2}, the THD curve lies below the THD_L line.

4.4 PROPOSED METHODOLOGY

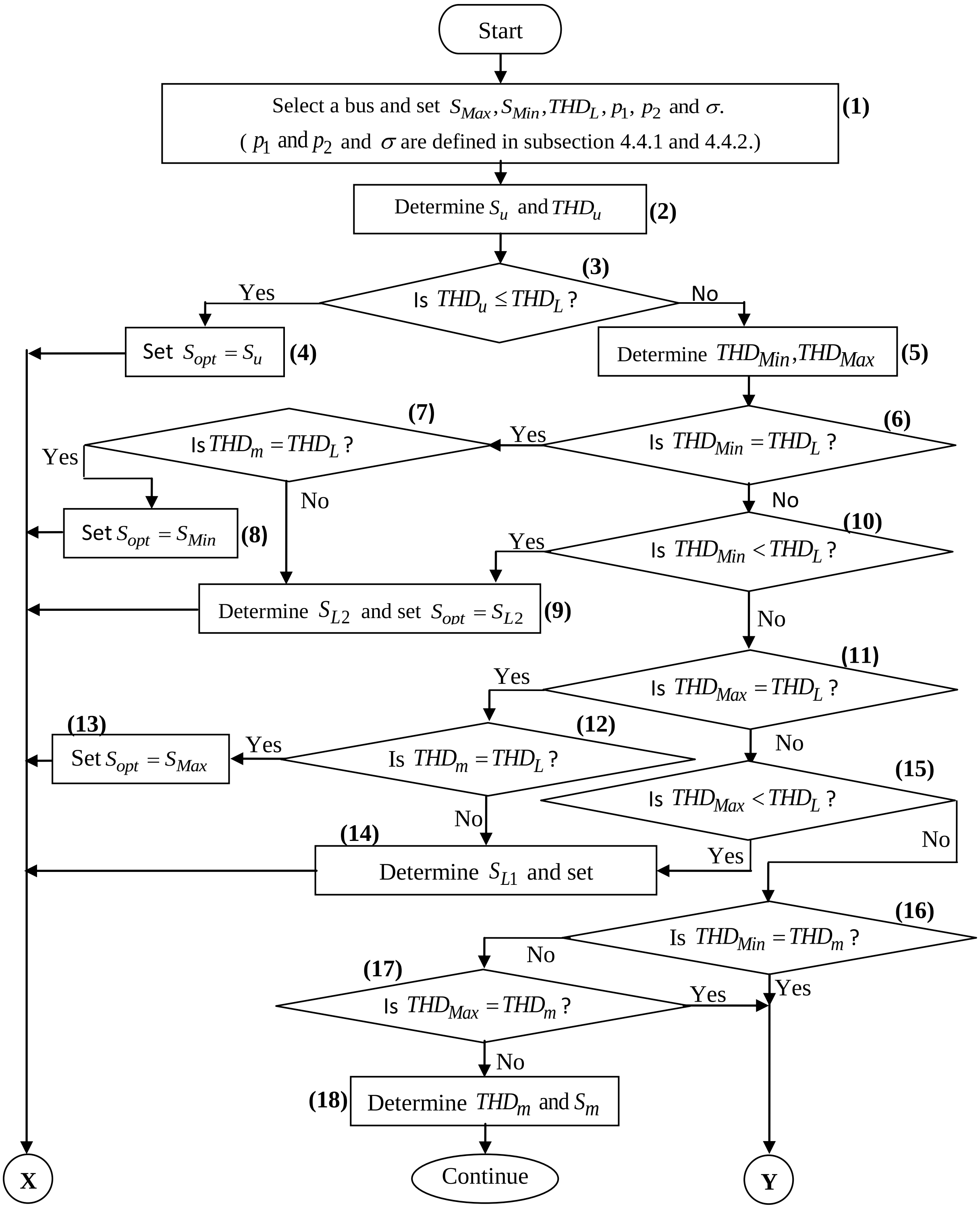
The proposed methodology is depicted in the form of a flow chart shown in Fig.4.5. The methodology is pivoted on the rule base developed in section 4.3, and on determination of appropriate quantities from the following S_u, THD_u, S_m, THD_m, THD_{Min}, THD_{Max}, S_{L1} and S_{L2}, and depending on the rule to be fired, S_u is determined using the iterative method presented in chapter 3, and THD_u is the corresponding value of THD_{VM}. THD_{Min} and THD_{Max} are obtained from the results of HLF with DG size S_{Min} and S_{Max} placed one at a time at the selected bus. The computations necessary for determination of other quantities i.e., THD_m, S_m, S_{L1} and S_{L2} are discussed in subsection 4.4.1 and subsection 4. 4.2. The followings are to be noted in the context of the flowchart:

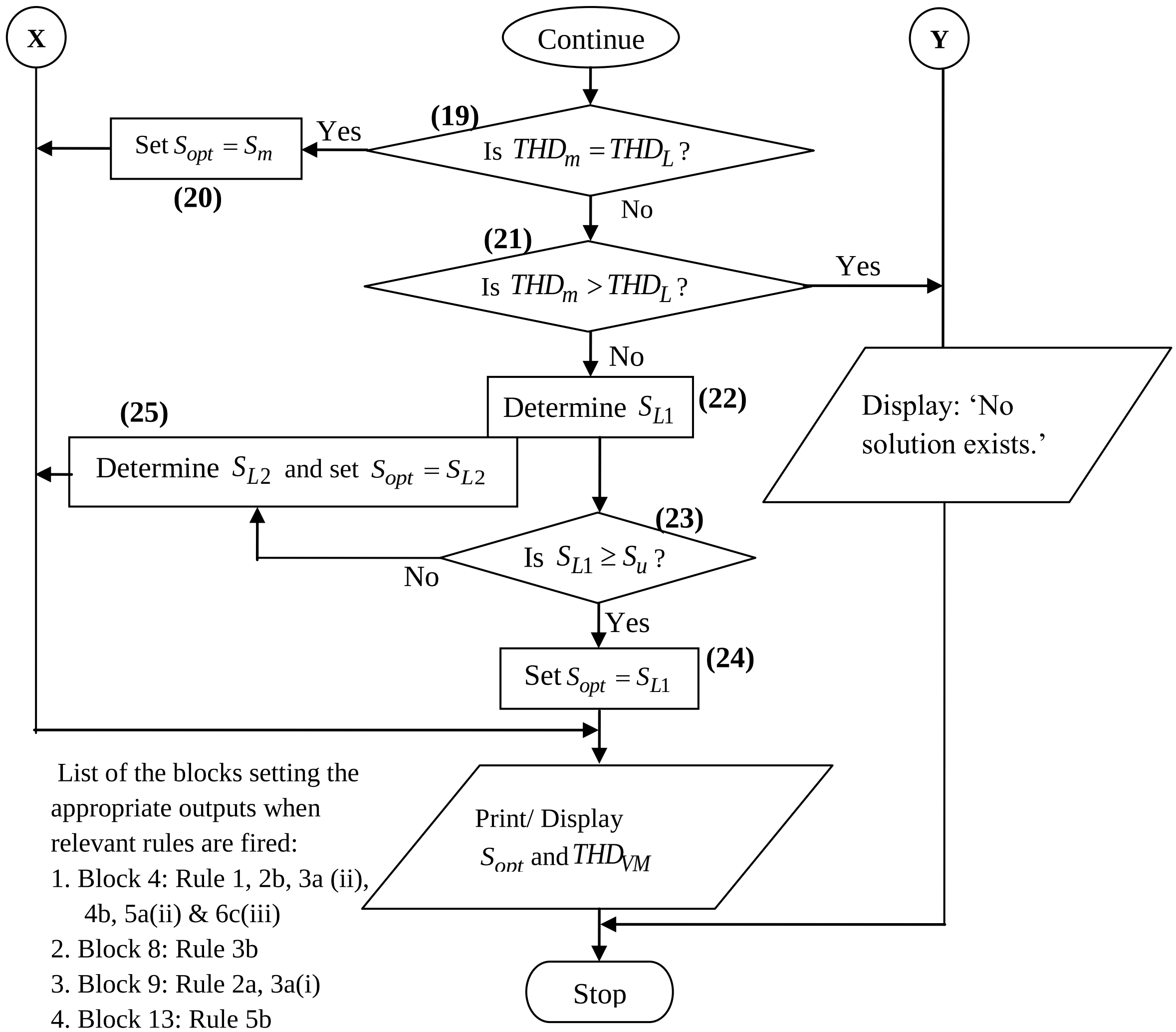
1) The condition $THD_u \leq THD_L$ is met under all of the situations leading to execution of any of the rules - 1, 2b, 3a (ii), 4b, 5a (ii) and 6c (iii) and all these rules generate same output. Hence, block 3 has been used as the first decision block in the flowchart to derive the following advantages:

   i) The number of decision blocks is reduced as multiple rules are taken care of by this single block.

   ii) No other quantities except S_u and THD_u are required to be determined to fire the appropriate rule in the above-mentioned situations. Hence, computations required under such situations will be minimum.

2) The comparison tasks done in the decision blocks 7, 12, 16 and 17 do not require determination of the value of THD_m. The value of THD_m is required only by the decision blocks 19 and 21. The reason has been explained in details in subsection 4.4.1.


Start
Select a bus and set $S_{Max}, S_{Min}, THD_L, p_1, p_2$ and σ.
(p_1 and p_2 and σ are defined in subsection 4.4.1 and 4.4.2.)
(1)
Determine S_u and THD_u
(2)
(3)
Is $THD_u \le THD_L$?
Yes
No
Set $S_{opt} = S_u$
(4)
Determine THD_{Min}, THD_{Max}
(5)
(7)
Is $THD_m = THD_L$?
Yes
Is $THD_{Min} = THD_L$?
(6)
Yes
No
No
Set $S_{opt} = S_{Min}$
(8)
(10)
Is $THD_{Min} < THD_L$?
Yes
Determine S_{L2} and set $S_{opt} = S_{L2}$
(9)
No
(11)
Is $THD_{Max} = THD_L$?
Yes
(13)
Set $S_{opt} = S_{Max}$
Yes
(12)
Is $THD_m = THD_L$?
No
(15)
Is $THD_{Max} < THD_L$?
No
(14)
Determine S_{L1} and set
Yes
No
(16)
Is $THD_{Min} = THD_m$?
No
(17)
Is $THD_{Max} = THD_m$?
Yes
Yes
No
(18)
Determine THD_m and S_m
X
Continue
Y



List of the blocks setting the appropriate outputs when relevant rules are fired:

1. Block 4: Rule 1, 2b, 3a (ii), 4b, 5a(ii) & 6c(iii)
2. Block 8: Rule 3b
3. Block 9: Rule 2a, 3a(i)
4. Block 13: Rule 5b
5. Block 14: Rule4a, 5a(i)
6. Block 26: Rule 6a
7. Block 20: Rule 6b
8. Block 24: Rule 6c(ii)
9. Block 25: Rule 6c(i)

Fig. 4.4. Computational Flowchart.

4.4.1 Determination of THD_m

It is important to note that

1. Determination of THD_m is not necessary when anyone from rules (1) to (5) is fired. The necessary comparison of THD_{Min} with THD_m required for rule 3 can be achieved by comparing THD_{Min} with THD_{VM}^{+}, where, THD_{VM}^{+} is the value of THD_{VM} for DG size S_{Min}^{+}, and $S_{Min}^{+} = S_{Min} +$ (a small positive perturbation in DG size). If $THD_{VM}^{+} < THD_{Min}$, then

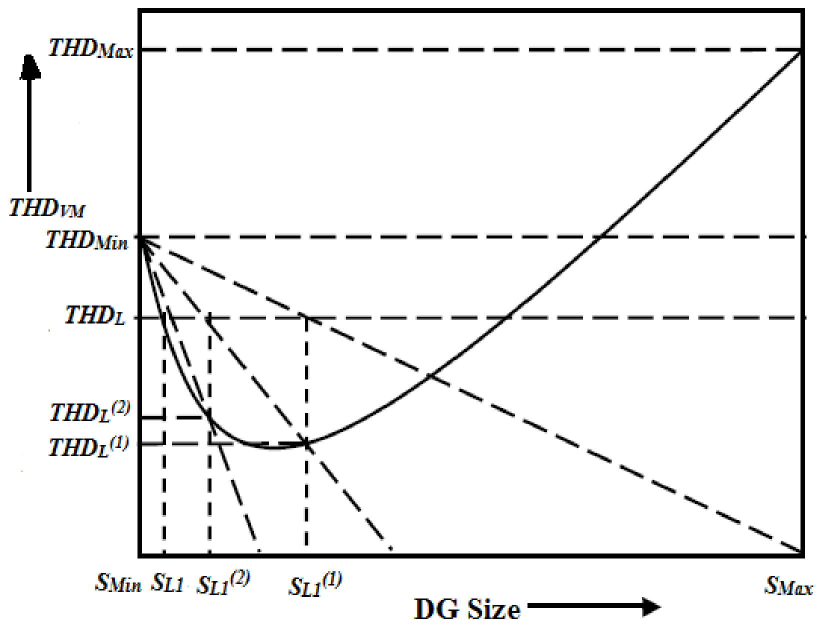
2. $THD_m < THD_{Min}$ i.e., $THD_m < THD_L$,whereas, $THD_m = THD_{Min} = THD_L$ if $THD^+_{VM} > THD_{Min}$. Similarly the comparison between THD_{Max} and THD_m required for rule 5 can be done by comparing THD_{Max} with THD^-_{VM} , where, THD^-_{VM} is the value of THD_{VM} for DG size S^-_{Max}, and $S^-_{Max} = S_{Max} +$ (a small negative perturbation in DG size). If $THD^-_{VM} < THD_{Max}$, $THD_m < THD_{Max}$ i.e., $THD_m < THD_L$,whereas, $THD_m = THD_{Max} = THD_L$ if $THD^-_{VM} > THD_{Max}$.
3. Determination of THD_m is required if rule 6 is fired. However, if $THD_m < THD_L$ then final determination of THD_m may not be necessary. In this case, if the value of THD_{VM} obtained at any step in the process of finding THD_m is found to be less than THD_L, it is then ensured that $THD_m < THD_L$, and the process is then stopped.
4. Determination of THD_m requires S_m to be determined. The nature of a *THD* curve has a similarity with that of a loss curve in the sense that both initially decreases with increase in DG size, and, after attaining a minimum, goes on increasing monotonically. Due to this similarity, S_m can be determined in the same manner as S_u is done, and hence, the same iterative scheme can be used with S_u replaced by S_m and P_{Loss} replaced by THD_{VM} . THD_m is obtained as a byproduct of this process without requiring any additional calculations.

4.4.2 Determination of S_{l1} and S_{l2}

Determination of S_{L1} is necessary if rule 4 is fired whereas S_{L2} will have to be determined when rule 2 is fired. Both S_{L1} and S_{L2} will be required if rule 6 is fired provided it is identified that $THD_m < THD_L$. An iterative method is suggested that requires only a few HLF to find out S_{L1}. The method is explained with the help of Fig.4.5a , where the first estimate $S^{(1)}_{L1}$ is obtained as the size corresponding to the point of intersection between the THD_L line and the line joining (S_{Min}, THD_{Min}) and $(S_{Max}, 0)$ using simple geometry as follows:

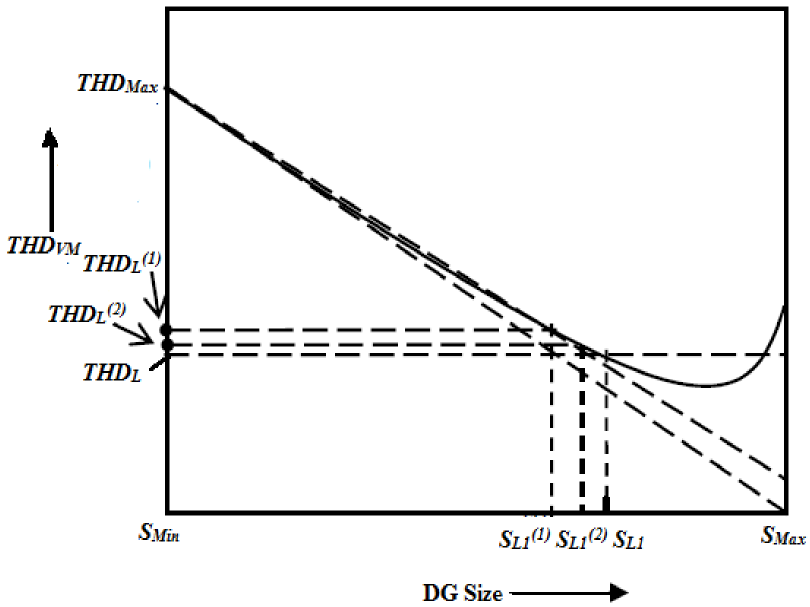
$$\frac{THD_L}{THD_{Min}} = \frac{S_{Max} - S^{(1)}_{L1}}{S_{Max} - S_{Min}} \tag{4.1}$$

$$S^{(1)}_{L1} = S_{Max} - \frac{THD_L}{THD_{Min}}(S_{Max} - S_{Min}) \tag{4.2}$$



THDMax
THDVM
THDMin
THDL
THDL(2)
THDL(1)
SMin SL1 SL1(2) SL1(1) SMax
DG Size

a



THDMax
THDVM
THDL(1)
THDL(2)
THDL
SMin SL1(1) SL1(2) SL1 SMax
DG Size

b

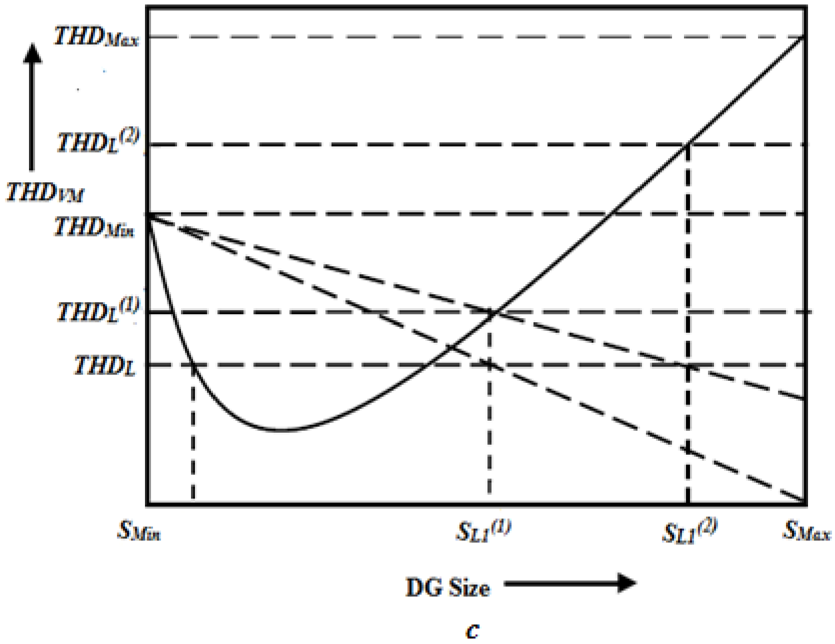


Fig. 4.5. Demonstration of the iterative method for determination of S_{L1}.

a. **Case I :when** $S_{L1} < S_{L1}^{(1)} < S_{L2}$

b. **Case II :when** $S_{L1} > S_{L1}^{(1)} < S_{L2}$

c. **Case III: when** $S_{L1} < S_{L1}^{(1)} > S_{L2}$

$THD_L^{(1)}$, the actual value of THD_{VM} on the THD curve at the size $S_{L1}^{(1)}$, is then obtained from HLF. A second estimate $S_{L1}^{(2)}$ is then obtained after joining the points (S_{Min}, THD_{Min}) and $(S_{L1}^{(1)}, THD_L^{(1)})$, and applying the same geometric approach as follows:

$$S_{L1}^{(2)} = S_{L1}^{(1)} - \frac{THD_L - THD_L^{(1)}}{THD_{Min} - THD_L^{(1)}}(S_{L1}^{(1)} - S_{Min}) \tag{4.3}$$

$THD_L^{(2)}$ corresponding to $S_{L1}^{(2)}$ is obtained from HLF. The iterative process continues with the iterative steps given by equation (4.4) until the estimated value of S_{L1} converges with the actual value as shown in Fig.4.5c.

$$S_{L1}^{(r+1)} = S_{L1}^{(r)} - \frac{THD_L - THD_L^{(r)}}{THD_{Min} - THD_L^{(r)}}(S_{L1}^{(r)} - S_{Min}) \tag{4.4}$$

where, $r = 0,1,2,\ldots$ r is the number of iteration. For r=0, $S_{L1}^{(r)} = S_{Max}$, $THD_L^{(r)}=0$.

The convergence criterion is as follows:

$$\left|THD_L^{(r+1)} - THD_L\right| \le \sigma \text{ where } \sigma \text{ is the tolerance}$$

It is to be noted that as the actual size S_{L1} is not known, the convergence is checked by the magnitude of the error between the values of THD_{VM} obtained for the estimated size and the actual value of THD_L. In the curve (shown in Fig.4.5a), $S_{L1} < S_{L1}^{(1)} < S_{L2}$, but there may be other situations where $S_{L1} > S_{L1}^{(1)} < S_{L2}$ (shown in Fig.4.5b) or $S_{L1} < S_{L1}^{(1)} > S_{L2}$ (shown in Fig.4.5c). In addition to these differences, each of the three situations has its distinguishing feature. In the first situation, $S_{L1}^{(2)}$ is always less than $S_{L1}^{(1)}$, whereas, in the second and third cases, $S_{L1}^{(2)}$ is always greater than $S_{L1}^{(1)}$. However, in the second case, $THD_L^{(2)}$ is always less than $THD_L^{(1)}$, but, $THD_L^{(2)}$ is always greater than $THD_L^{(1)}$ in the third situation. These features ensure an early detection (after second iteration only) of this difference between the two situations which is essential for proceeding with iterations. A minute observation of the figures, Fig.4.5a, Fig.4.5b and Fig.4.5c, can reveal that, in the first and second situations, the iteration will always lead to convergence, but, in the third case it will diverge. In fact, in the third case, $S_{L1}^{(r+1)} > S_{L1}^{(r)}$ for all $r > 0$. Once this diverging situation is detected after second iteration, the iterative process is repeatedly restarted with S_{Max}/n replaced by $S_{Max}/(n+1)$; $n = 1, 2, \ldots$ as the value of $S_{L1}^{(r)}$ for r= 0, until diverging condition is avoided.

The same iterative approach is also used to determine S_{L2} with the first estimate $S_{L2}^{(1)}$ obtained as the size corresponding to the point of intersection between the THD_L line and the line joining (S_{Max}, THD_{Max}) and $(S_{Min}, 0)$. The final value of S_{L2} is obtained in the same manner as S_{L1} is obtained. In this case the three different situations are given by $S_{L1} < S_{L2}^{(1)} < S_{L2}$, $S_{L1} < S_{L2}^{(1)} > S_{L2}$, and $S_{L1} > S_{L2}^{(1)} < S_{L2}$. The third situation is a diverging one, and the iteration is required to be restarted repeatedly till the diverging condition persists.

4.5 SIMULATION STUDY AND TEST RESULTS

Efficacy of the proposed approach was tested on IEEE-33 bus network and IEEE-69 bus network. The load data for the two systems were modified as given in Table B1and Table B2 of *Appendix-B* to introduce different degrees of nonlinearity in the load. A combination of different types of nonlinear loads was considered, and the harmonic spectrums of these loads are given in Table B3 of *Appendix-B.* The DG is assumed to be interfaced with the network through a six pulse converter whose harmonic spectrum is provided in Table 2.For the 33 bus network, bus nos. 6 to 18 from the main trunk and bus nos. 26 to 33 from the longest lateral were chosen for this study, while bus nos. 6 to 27 from the main trunk and bus nos. 53 to 65 from the longest lateral are chosen for the 69 bus network. Only inverter-based DG is of concern in this work. Such DG units operate at unity power factor because of their design [47], hence, unity power factor DG has been considered in this study.

Following the recommendation in IEEE-519 [18] a limit of 5% has been imposed on the maximum allowable value of THD_{VM} for both the networks, which means that, the value of THD_L is taken as 5% for this study. The minimum and maximum limit on the size of DG unit to be installed has been considered to be 400 kW and 3000 kW respectively with grid bus voltage of 1.02 p.u. The solutions are obtained with $\sigma = 0.001$. The results thus obtained with the proposed method have been compared with that obtained using PSO technique presented in chapter 2. The comparative results are summarized in Table 4.3 (a) to Table 4.4(c). Table 4.3 (a) to Table 4.3(c) show the results for IEEE-33 bus network under loading conditions L1, L2 and L3 respectively. Results for IEEE-69 bus network are shown in Table 4.4 (a) to Table 4.4(c). For brevity, results of alternate candidate buses are shown for the 69 bus network. The power losses in the two networks prior to installation of the DG are available respectively in Table 2.1 (a) and Table 2.1 (b) of chapter 2 and are reproduced here in Table 4.2 for ready reference.

Table 4.2: Network Power Loss prior to installation of DG.

Network	**Power loss (kW)**		
	Loading condition L1	**Loading condition L2**	**Loading condition L3**
IEEE-33 bus	194. 847	196.18	194.23
IEEE-69 bus	215.235	218.104	215. 0842

Table 4.3 (a): Optimum DG Sizes for IEEE-33 Bus Network under Loading Condition L1.

Bus no.	Without Constraint (By PSO)			With Constraint						
				By proposed iterative approach				By PSO		
	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	No. of HLF reqd.	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)
6	2376	106.17	6.937	1716	112.61	4.9979	18	1718	112.35	4.9988
7	2255	107.01	9.604	1188	125.69	4.9959	28	1188	125.69	4.9959
8	1926	111.12	9.1265	1064	126.94	4.9969	29	1064	126.94	4.9969
9	1600	116.99	10.1162	795	135.53	4.9970	30	795	135.53	4.9970
10	1385	120.54	10.9531	633	141.22	4.9941	25	633	141.22	4.9941
11	1356	121.15	10.9044	622	141.44	4.9937	26	622	141.44	4.9937
12	1298	122.42	10.7862	601	142.02	4.9916	30	601	142.02	4.9916
13	1111	126.94	11.9894	461	148.86	4.9942	32	461	148.86	4.9942
14	1050	128.51	12.9617	402	152.54	4.9892	24	405	151.23	4.9999
15	1000	130.84	13.4695	No solution is obtained within the range of DG size considered						
16	940	133.86	13.7504							
17	835	139.04	15.3375							
18	785	141.82	15.3868							
26	2248	107.82	7.058	1595	114.72	4.9982	27	1595	114.72	4.9982
27	1968	110.20	6.7918	1451	117. 45	4.9974	28	1451	117.44	4.9974
28	1703	114.73	9.34	908	131.18	4.9968	15	908	131.18	4.9968
29	1513	116.64	10.6234	706	137.66	4.9962	27	707	137.13	4.9995
30	1418	118.27	10.7486	653	139.24	4.9995	32	653	139.24	4.9995
31	1245	123.54	12.0524	509	147.02	4.9958	33	510	147.00	4.9995
32	1192	125.61	12.4852	470	149.61	4.9953	29	469	149.39	4.9992
33	1132	128.89	13.182	423	153.34	4.9996	29	423	153.34	4.9996

Table 4.3 (b): Optimum DG Sizes for IEEE-33 Bus Network under Loading Condition L2.

Bus no.	Without Constraint (By PSO)			With Constraint						
				By proposed iterative approach				By PSO		
	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	No. of HLF reqd.	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)
6	2409	104.58	5.8645	2101	105.95	4.9995	21	2101	105.95	4.9995
7	2281	105.45	8.2644	1488	115.74	4.9981	26	1488	115.74	4.9981
8	1953	109.68	7.7735	1347	117.33	4.9997	26	1347	117.33	4.9997
9	1619	115.68	8.5750	1032	125.44	4.9939	27	1033	125.00	4.9989
10	1402	119.31	9.2732	841	130.71	4.9937	25	841	130.70	4.9937

11	1375	119.93	9.2359	828	130.96	4.9945	21	829	130.42	4.9989
12	1313	121.23	9.0796	803	131.63	4.9943	30	803	131.63	4.9943
13	1131	125.86	10.1975	631	138.38	4.9937	29	632	138.11	4.9990
14	1072	127.47	11.1225	558	141.98	4.9953	24	558	141.98	4.9953
15	1014	129.86	11.5057	No solution is obtained within the range of DG size considered						
16	949	132.94	11.6992							
17	846	138.26	13.2653							
18	795	141.10	13.2933							
26	2280	106.27	5.9627	1960	107.88	4.9975	26	1960	107.88	4.9975
27	2127	108.41	6.1041	1793	110.35	4.9998	27	1793	110.35	4.9998
28	1725	113.35	7.9822	1154	121.73	4.9989	18	1154	121.73	4.9989
29	1537	115.30	9.1749	910	127.67	4.9982	24	910	127.67	4.9982
30	1435	116.97	9.2441	843	129.42	4.9978	30	843	129.41	4.9978
31	1259	122.36	10.4209	669	137.36	4.9999	31	669	137.35	4.9999
32	1207	124.48	10.8420	620	140.19	4.9999	25	620	140.19	4.9999
33	1148	127.84	11.5497	557	144.56	4.9986	30	557	144.56	4.9986

Table 4.3 (c): Optimum DG Sizes for IEEE-33 Bus Network under Loading Condition L3.

Bus no.	Without Constraint (By PSO)			With Constraint						
				By proposed iterative approach				By PSO		
	DG Size (kW)	P_{LOSS} (kW)	*max (THD_V)* (%)	DG Size (kW)	P_{LOSS} (kW)	*max (THD_V)* (%)	No. of HLF reqd.	DG Size (kW)	P_{LOSS} (kW)	*max (THD_V)* (%)
6	2373	106.71	7.3670	1574	116.07	4.9976	20	1574	116.07	4.9976
7	2247	107.55	10.0667	1076	130.14	4.9978	29	1076	130.14	4.9978
8	1915	111.64	9.5743	962	131.23	4.9967	30	962	131.23	4.9967
9	1594	117.45	10.5768	719	139.48	4.9994	30	719	139.48	4.9994
10	1382	120.96	11.4260	572	144.95	4.9937	24	573	144.95	4.9970
11	1348	121.56	11.3391	562	145.15	4.9938	27	562	145.15	4.9938
12	1294	122.82	11.2514	543	145.67	4.9934	29	544	145.21	4.99873
13	1109	127.30	12.4630	416	152.21	4.9894	33	418	151.77	4.9996
14	1056	128.85	13.5220	No solution is obtained within the range of DG size considered						
15	999	131.17	13.9470							
16	933	134.16	14.1451							
17	831	139.30	15.7552							
18	784	142.06	15.8546							
26	2242	108.35	7.4539	1468	118.04	4.9978	29	1468	118.04	4.9978
27	2086	110.42	7.6088	1335	120.76	4.9966	29	1335	120.76	4.9966
28	1700	115.19	9.7339	837	134.53	4.9969	15	837	134.53	4.9969
29	1507	117.07	10.9901	651	140.87	4.9945	30	652	140.55	4.9978
30	1415	118.69	11.1340	602.	142.37	4.9977	32	602.	142.37	4.9977
31	1243	123.91	12.4361	470	149.77	4.9975	31	470	149.77	4.9975
32	1189	125.96	12.8557	434	152.25	4.9954	30	434	152.25	4.9954
33	1131	129.21	13.5618	No solution is obtained within the range of DG size considered						

Table 4.4 (a): Optimum DG Sizes for IEEE-69 Bus Network under Loading Condition L1.

Bus no.	Without Constraint (By PSO)			With Constraint						
				By proposed iterative approach				By PSO		
	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	No. of HLF reqd.	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)
6	2852	193.87	1.2325	2852	193.87	1.2325	19	2852	193.87	1.2325
8	2781	169.44	2.5252	2781	169.44	2.5252	22	2781	169.44	2.5252
10	1809	176.36	2.6958	1809	176.36	2.6958	24	1809	176.36	2.6958
12	1382	180.61	2.8806	1382	180.61	2.8806	16	1382	180.61	2.8806
14	923	187.66	3.1842	923	187.66	3.1842	25	923	187.66	3.1842
16	794	189.21	3.4022	794	189.21	3.4022	24	794	189.21	3.4022
18	707	190.71	3.2015	707	190.71	3.2015	20	707	190.71	3.2015
20	668	191.61	3.2610	668	191.61	3.2610	29	668	191.61	3.2610
22	646	192.15	3.3067	646	192.15	3.3067	22	646	192.15	3.3067
24	612	193.27	3.3379	612	193.28	3.3379	27	612	193.27	3.3379
26	548	195.46	3.3719	548	195.46	3.3719	29	548	195.46	3.3719
53	2609	164.09	2.9518	2609	164.09	2.9518	20	2609	164.09	2.9518
55	2339	154.91	3.7874	2339	154.91	3.7874	13	2339	154.91	3.7874
57	1934	120.41	5.7576	1685	121.86	4.9978	28	1685	121.86	4.9978
59	1822	101.32	6.7866	1352	108.29	4.9977	28	1352	108.29	4.9977
61	1740	88.22	7.8247	1125	102.75	4.9963	20	1125	102.75	4.9963
63	1680	91.61	7.9776	1066	106.76	4.9961	17	1066	106.76	4.9961
65	1334	114.28	8.7725	772	130.82	4.9993	32	772	130.82	4.9993
67	1545	180.60	2.6792	1545	180.60	2.6792	19	1545	180.60	2.6792
69	1096	187.53	2.8139	1096	187.53	2.8139	25	1096	187.53	2.8139

Table 4.4 (b): Optimum DG Sizes for IEEE-69 Bus Network under Loading Condition L2.

Bus no.	Without Constraint (By PSO)			With Constraint						
				By proposed iterative approach				By PSO		
	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)	No. of HLF reqd.	DG Size (kW)	P_{LOSS} (kW)	*max* (THD_V) (%)
6	2881	194.05	1.7217	2881	194.05	1.7217	21	2881	194.05	1.7217
8	2809	169.14	2.2423	2809	169.14	2.2423	20	2809	169.14	2.2423
10	1826	176.15	2.3338	1826	176.15	2.3338	22	1826	176.15	2.3338
12	1396	180.47	2.4655	1396	180.47	2.4655	18	1396	180.47	2.4655

14	932	187.67	2.7041	932	187.67	2.7041	25	932	187.67	2.7041
16	802	189.25	2.8861	802	189.25	2.8861	22	802	189.25	2.8861
18	715	190.78	2.6762	715	190.78	2.6762	18	715	190.78	2.6762
20	677	191.70	2.7372	677	191.7041	2.7372	26	677	191.70	2.7372
22	653	192.25	2.7690	653	192.2547	2.7690	24	653	192.25	2.7690
24	618	193.41	2.7936	618	193.4060	2.7936	29	618	193.41	2.7936
26	554	195.63	2.8283	554	195.63	2.8283	21	554	195.63	2.8283
53	2636	163.71	2.6256	2636	163.71	2.6256	18	2636	163.71	2.6256
55	2362	154.39	3.3779	2362	154.39	3.3778	13	2362	154.39	3.3778
57	1953	119.36	5.1329	1908	119.41	4.9979	26	1908	119.41	4.9979
59	1835	99.99	6.0323	1558	102.43	4.9993	27	1558	102.43	4.9993
61	1754	86.71	6.9749	1313	94.10	4.9958	30	1313	94.10	4.9958
63	1692	90.16	7.1155	1245	98.16	4.9977	16	1245	98.16	4.9977
65	1347	113.20	7.9039	903	123.32	4.9994	25	903	123.32	4.9994
67	1560	180.48	2.3025	1560	180.48	2.3025	21	1560	180.48	2.3025
69	1108	187.53	2.3944	1108	187.53	2.3944	25	1108	187.53	2.3944

Table 4.4 (c): Optimum DG Sizes for IEEE-69 Bus Network under Loading Condition. L3.

Bus no.	**Without Constraint (By PSO)**			**With Constraint**						
				By proposed iterative approach				**By PSO**		
	DG Size (kW)	**P_{LOSS} (kW)**	***max (THD_V)* (%)**	**DG Size (kW)**	**P_{LOSS} (kW)**	***max (THD_V)* (%)**	**No. of HLF reqd.**	**DG Size (kW)**	**P_{LOSS} (kW)**	***max (THD_V)* (%)**
6	2837	193.99	1.4401	2837	193.99	1.4401	18	2837	193.99	1.4401
7	2757	169.86	2.9071	2757	169.86	2.9071	21	2757	169.86	2.9071
8	1799	176.66	2.9796	1799	176.66	2.9796	23	1799	176.66	2.9796
12	1376	180.84	3.1754	1376	180.84	3.1754	15	1376	180.84	3.1754
14	915	187.81	3.4849	915	187.81	3.4849	27	915	187.81	3.4849
16	790	189.34	3.7233	790	189.34	3.7233	25	790	189.34	3.7233
18	704	190.83	3.5298	704	190.83	3.5298	27	704	190.83	3.5298
20	665	191.72	3.5922	665	191.72	3.5922	27	665	191.72	3.5922
22	643	192.25	3.6381	643	192.25	3.6381	21	643	192.25	3.6381
24	609	193.37	3.6683	609	193.37	3.6683	26	609	193.37	3.6683
26	545	195.52	3.7005	545	195.52	3.7004	28	545	195.52	3.7005
53	2594	164.59	3.4007	2594	164.59	3.4007	21	2594	164.59	3.4007
55	2326	155.55	4.3459	2326	155.55	4.3459	14	2326	155.55	4.3459
57	1921	121.54	6.4798	1451	126.77	4.9983	29	1451	126.77	4.9983
59	1809	102.72	7.5430	1153	116.47	4.9978	30	1153	116.47	4.9978
61	1727	89.81	8.6122	948	113.49	4.9977	18	948	113.49	4.9977
63	1669	93.16	8.7754	897	117.38	4.9953	21	897	117.38	4.9953
65	1325	115.53	9.5696	648	139.80	4.9960	34	648	139.80	4.9960

67	1537	180.85	2.9219	1537	180.85	2.9219	18	1537	180.85	2.9219
69	1090	187.68	3.0692	1090	187.68	3.0692	24	1090	187.68	3.0692

From Table 4.3(a), 4.3(b), 4.3(c) it is found that, under all loading conditions, the optimum sizes for unconstrained conditions for all buses considered in this study violate the 5% limit on THD_L. From the results it is also clear that the constrained optimal sizes obtained by the proposed method corroborate with those obtained by PSO. Number of HLF required by the proposed method for each bus is also shown from which it is found that the maximum number of HLF required by the proposed method is 33, for bus number 31 and 13 under condition L1 and L3 respectively, which is significantly less than that usually required by PSO in such problems.

In this study, the PSO has been applied taking a swarm size of 10 particles with each particle represented by one DG size. Minimum number of iterations required to get the desired solution by PSO has been found to be 52 for bus 27 under loading condition L1. This means a total of (52 ×10) =520 number of HLF as one HLF is required for each particle in an iteration. For bus 15 to bus 18 in Table 4.3(a) and 4.3(b) under L1 and L2 condition, and for bus 14 to bus18 and bus 33 in Table 4.3(c), no solution is obtained as, in each of these cases, the value of THD_m ,within the range of DG size considered, is found to be above THD_L. The above results also shows that though imposition of *THD* constraint allows less reduction in loss, the reduction is still appreciable in all cases where constrained solution is available.

From Table 4.4 (a) it is found that, for the IEEE-69 bus system, the constraint on THD_{VM} is not violated for any of the buses of the main trunk, and hence, the constrained sizes for these buses coincide with the unconstrained optimal sizes. For the lateral, the unconstrained optimum size results in violation of the *THD* constraint for bus 57 to bus 65.In this case also, the results of the proposed method corroborate with those obtained from PSO. The results under loading condition L2 and L3 for IEEE-69 bus system are given in Table 4.4 (b) and Table 4.4(c) respectively. The results shown in these Tables are now self-explanatory. From Table 4.4(a), Table 4.4(b) and Table 4.4(c) it can be seen that the maximum number of HLF required for this network is 34 for bus number 65 under L3 condition, whereas, minimum number of iterations required by PSO has been found to be 93 for bus 65 under loading condition L3. It means minimum number of HLF required by PSO in this problem is (93×10)=930. Thus, the results portrayed in Table 4.3(a) to Table 4.4(c) present sufficient evidence that the number of HLF, and hence, the computation required by the suggested method is significantly less than that required by PSO. The reduction in power loss is also clear from the Tables.

It is to be noted that the computational steps mentioned in section 4.4, in general, do not yield the DG sizes in integral values. To obtain the sizes in integral values, two additional HLF are to be executed for the nearest integral sizes on the two sides, lower and higher, of the size produced by the above computational steps. Among these two sizes, the one that results in lower loss with THD_{VM} remaining within limit is chosen as the desired size. The number of HLF, shown for each bus in Table 4.3(a) to Table 4.4(c), has been counted including these two additional HLF. It may be further noted that, in reality, DGs are available in some standard sizes only. To obtain the desired standard size, the nearest standard sizes on the lower and higher side are to be considered instead of the nearest integral sizes. Between those two standard sizes, the one that produces lower amount of loss with THD_{VM} remaining within limit should be selected.

4.6 CHAPTER SUMMARY

This chapter has proposed a computationally efficient hybrid method for calculating the optimal size of inverter-based DG source placed at any selected location in a radial distribution network to minimize the network power loss in presence of limit on permissible harmonic distortion in bus voltages. The test results demonstrate the efficacy of the proposed methodology and show that the suggested approach can furnish the desired solution with significantly less computation compared to that required by PSO which is one of the most popular, efficient and widely used evolutionary computation based method. The suggested method can prove to be a very effective alternative to the evolutionary population based methods whenever any utility requires finding the optimal location and size for installation of an inverter-based DG unit in its distribution network under harmonic-constrained situation. The proposed method can be extended to the problem of optimal siting and sizing of DG. For such siting and sizing problem, the proposed algorithm is required to be repeated for all the potential candidate buses. Once the optimal DG sizes for all candidate buses are calculated, the optimal location and size for minimum network power loss is readily available from the list that can be prepared from the solutions for those buses. In that case, the total number of

HLF required will be the summation of that required for each of those buses. However, the total number of HLF calculations required by PSO, in such cases, will also increase proportionally with the number of candidate buses. So, it is needless to mention that the amount of computation required by the proposed method will be significantly less than that required by PSO.

CHAPTER 5

An Analytical Approach for Optimal DG Placement in Distribution Network contaminated with Harmonics

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Outline of the chapter

5.1 INTRODUCTION

This chapter has proposed an analytical approach to determine the optimal size and location of a distributed generation unit in a distribution network to minimize the power loss in the network. The proposed method, like the iterative method suggested in chapter 3, can determine the unconstrained optimal size. Though the proposed iterative method is computationally attractive, an analytical method is always more efficient in terms of amount of computation required, and can provide the fastest solution. The existing analytical methods [20]-[22] have a limitation that these are not equipped to take into consideration the harmonic sources present in the network. The proposed analytical approach is capable of providing fast solution for the optimal DG placement problem even when harmonic sources are connected to the network. With very little amount of computational effort, the proposed method can give near-optimal (loss minimizing) size of the DG unit placed at any given location (bus) of the network. The desired (maximum loss minimizing) size and location of the DG for the whole network can be readily available once the near-optimal sizes for all the potential candidate buses are determined. The method utilizes the concept of *B*-coefficient loss formula. The conventional method for determining the *B*-coefficients are not only computation intensive but it is also not applicable for harmonics-polluted network. An indirect method is introduced in this work which determines the approximate values of the *B*-coefficients with very small amount of computation. The test results demonstrate the efficacy of the proposed method for distribution network containing harmonic sources.

5.2 THE PROBLEM STATEMENT

The problem undertaken in this chapter requires the determination of the optimal size of the DG unit located at any given bus of a distribution network to minimize the network power loss. The problem is formulated as an optimization problem with the objective function, and the equality and inequality constraints given respectively by equation 2.1, equation 2.5 and equation 2.6 of chapter 2. The three equations are reproduced here as equation 5.1, equation 5.2 and equation 5.3 for ready reference.

$$P_{loss} = \sum_{h=1}^{\infty} \sum_{m=1}^{B} \left| I_m^h \right|^2 R_m^h \tag{5.1}$$

$$P_{ss} + P_g = \sum_{i=1}^{N} P_{d_i} + P_{loss} \tag{5.2}$$

$$P_{g_{\min}} \le P_g \le P_{g_{\max}} \tag{5.3}$$

However the solution methodology does not directly incorporate the limits on DG size. The optimal size is first determined without considering these limits. Later, if it is found that the DG size falls outside the range, then, the size is set at the limit which is violated. The solution still remains optimal because P_{Loss} is a unimodal function of P_g as shown in earlier chapters.

5.3 SOLUTION METHODOLOGY

In a power system, the power loss in the network can be expressed as a quadratic function of the active power output of the generators with the help of *B*-coefficients [60]. In a distribution network with the DG placed at any i-th bus, the network power loss can be written using *B*-coefficients as follows:

$$\begin{aligned} P_{Loss} &= B_{11}P_{SS}^2 + 2B_{12}P_{SS}(P_{gi} - P_{di}) + B_{22}(P_{gi} - P_{di})^2 \\ &= B_{11}P_{SS}^2 + 2B_{12}P_{SS}P_i + B_{22}P_i^2 \end{aligned} \tag{5.4}$$

where,

P_{gi} is the active power output of the DG at the i-th bus

P_{di} is the active power load at the i-th bus

$P_i = (P_{gi} - P_{di})$ is the injected active power at the i-th bus and B_{11}, B_{12} and B_{22}, are the *B*- coefficients.

It is to be noted that the conventional method for *B*-coefficient calculation is not only computation intensive but also not valid in case of network polluted with harmonics. So, in this work, the following indirect method is introduced for calculating these coefficients. With the loss model given by equation (5.4), the power loss in the network for three different sizes of the DG placed at any i-th bus can be written as follows:

$$P_{Loss(1)} = B_{11}P_{SS(1)}^2 + 2B_{12}P_{SS(1)}P_{i(1)} + B_{22}P_{i(1)}^2 \quad (5.5$$

$$P_{Loss(2)} = B_{11}P_{SS(2)}^2 + 2B_{12}P_{SS(2)}P_{i(2)} + B_{22}P_{i(2)}^2 \tag{5.6}$$

$$P_{Loss(3)} = B_{11}P_{SS(3)}^2 + 2B_{12}P_{SS(3)}P_{i(3)} + B_{22}P_{i(3)}^2 \tag{5.7}$$

With $P_{Loss(1)}, P_{Loss(2)}, P_{Loss(3)}$, along with $P_{SS(1)}, P_{SS(2)}, P_{SS(3)}$, known from load flow solutions (DLF in absence of harmonics and HLF in presence of harmonics) with three known sizes $P_{gi(1)}, P_{gi(2)}, P_{gi(3)}$, or equivalently $P_{i(1)}, P_{i(2)}, P_{i(3)}$, equations (5.5), (5.6) and (5.7) are three linear equations in three unknowns B_{11}, B_{12} and B_{22}, and hence, can easily be solved for B_{11}, B_{12} and B_{22}, Values of the *B*-coefficients thus obtained are somewhat average and approximate as they are derived from three different loading conditions. This is to be noted that the value of the *B*-coefficients depends on the location of the generator buses in the network. Hence, equation (5.5) to equation (5.7) are to be solved for each separate candidate bus to determine the corresponding *B*-coefficients.

With harmonic sources present in the network, three HLF calculations (DLF calculations in absence of harmonics sources) will be required to set up these three equations (5.5), (5.6) and (5.7), for each of the candidate buses. If no harmonic source is present, then three ordinary load flow calculation will be needed for each candidate bus. So, 3n numbers of HLF (or DLF depending on situations) are required for n candidate buses. Computational burden can however be reduced by deriving one of the three equations from the result of base case load flow. Once the base case load flow result is available, it will be applicable for any location of the DG unit, and need not be repeated for every candidate bus. Thus, for n candidate buses, a total of (2n+1) number of HLF (or DLF) will be required.

In the present work, the three sizes of the DG considered for the three equations (5.5), (5.6) and (5.7) for any given bus are as follows:

$$P_{gi(1)} = 0\ ;\ P_{gi(2)} = 1500\ kW;\ P_{gi(3)} = 3000\ kW;$$

It is to be noted that in distribution load flow, the grid bus is usually taken as the slack bus. While writing equation (5.4), P_{SS} is assumed as the slack generator output. However, P_{SS} is not an independent variable because, for a given value of total demand P_D, its value depends on P_{gi} in the following manner

$$P_{SS} = P_D + P_{Loss} - P_{gi} \tag{5.8}$$

$$\text{where,} \quad P_D = \sum_{i=1}^{N} P_{di}$$

Now, since P_{Loss}, is very small as compared to P_D, equation (5.8) can be approximated as follows

$$P_{SS} = P_D - P_{gi}$$
$$= P_D - (P_i + P_{di}) = (P_D - P_{di}) - P_i$$
$$= \bar{P}_D - P_i \qquad (5.9)$$

where, $\bar{P}_D = P_D - P_{di}$

Converting equation (5.4) into an equation of single independent variable P_{gi} or, equivalently, P_i, by replacing P_{SS} with equation (5.9), the following is obtained

$$P_{Loss} = aP_i^2 + bP_i + c \qquad (5.10)$$

where,

$$a = (B_{11} - 2B_{12} + B_{22})$$
$$\text{b} = 2\bar{\text{P}}_D(B_{12} - B_{11})$$
$$c = B_{11}\bar{\text{P}}_D^2$$

For minimum loss

$$\frac{\partial P_{Loss}}{\partial P_i} = 2aP_i + b = 0$$

Solving, $$P_i = \frac{-b}{2a}$$

Hence the optimal (loss minimizing) size of the DG is

$$P_{gi} = \frac{-b}{2a} + P_{di}$$

5.4 CASE STUDIES AND TEST RESULTS

Efficacy of the proposed method was tested on the IEEE-33 bus radial distribution network. Different degrees of nonlinearity in the load were introduced by modifying the load data as given by L1, L2 and L3 condition in Table B1 of the *Appendix-B.* A combination of different types of nonlinear loads was considered, and the harmonic spectrums of these loads are given in Table B3 of the *Appendix-B*. Only inverter-based DG is considered in this work. Such DG units operate at unity power factor because of their design [47], and hence, unity power factor

DG has been considered in this study. The DG is assumed to be connected to the network through a 6-pulse inverter. The harmonic spectrum of 6-pulse inverter is provided in *Appendix-B.* The DG is placed at different candidate buses, one at a time, to determine its optimal size for the respective buses. In this study, candidate buses are selected arbitrarily as the methodology is not dependent on the choice of DG location. Bus no. 6 to 18 from the main trunk and bus no. 26 to 33 from the longest lateral were chosen as candidate buses. A range of 500 kW to 3000 kW has been considered for the size of DG unit to be installed and grid bus voltage of 1.02 p.u. has been taken for this study. The results obtained with the proposed analytical method have been compared with those obtained using PSO technique presented in chapter 2, and with the iterative method suggested in chapter 3. The comparative results under loading conditions L1, L2 and L3, are summarized in Table 5.1, Table 5.2 and Table 5.3 respectively. The power losses in the test network prior to installation of the DG (the base case loss) under the three loading conditions are available in Table 4.2 of chapter 4.

Table 5.1: Results for Loading Condition L1.

Bus No.	PSO		Proposed method		Iterative method		
	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	No. of HLF reqd.
6	2376	106.17	2311	106.23	2374	106.17	14
7	2255	107.01	2197	107.06	2257	107.01	22
8	1926	111.12	1887	111.15	1925	111.12	23
9	1600	116.99	1579	117.01	1595	116.99	24
10	1385	120.54	1385	120.54	1388	120.54	17
11	1356	121.15	1355	121.15	1355	121.15	18
12	1298	122.42	1302	122.42	1300	122.42	22
13	1111	126.94	1131	126.95	1115	126.94	24
14	1050	128.51	1080	128.53	1060	128.51	14
15	1000	130.84	1021	130.87	1000	130.84	26
16	940	133.86	956	133.88	937	133.86	26
17	835	139.04	851	139.06	834	139.04	27
18	785	141.82	801	141.83	786	141.82	27
26	2248	107.82	2189	107.88	2247	107.82	23
27	1968	110.2	2044	109.96	2096	109.91	22
28	1703	114.73	1678	114.74	1701	114.73	9
29	1513	116.64	1506	116.64	1515	116.64	21
30	1418	118.27	1419	118.26	1416	118.27	24

31	1245	123.54	1256	123.55	1246	123.54	25
32	1192	125.61	1210	125.62	1194	125.61	21
33	1132	128.89	1145	128.89	1132	128.89	21

Table 5.2: Results for Loading Condition L2.

Bus No.	PSO		Proposed method		Iterative method		
	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	No. of HLF reqd.
6	2409	104.58	2340	104.65	2409	104.58	17
7	2281	105.45	2224	105.51	2281	105.45	22
8	1953	109.68	1910	109.71	1953	109.68	22
9	1619	115.68	1599	115.69	1618	115.68	21
10	1402	119.31	1402	119.31	1403	119.31	19
11	1375	119.93	1372	119.93	1375	119.93	15
12	1313	121.23	1319	121.23	1314	121.23	24
13	1131	125.86	1145	125.87	1131	125.86	21
14	1072	127.47	1094	127.49	1072	127.47	16
15	1014	129.86	1035	129.88	1014	129.86	25
16	949	132.94	969	132.97	949	132.94	25
17	846	138.26	863	138.28	846	138.26	24
18	795	141.10	812	141.12	795	141.10	24
26	2280	106.27	2217	106.33	2280	106.27	22
27	2127	108.41	2070	108.46	2127	108.41	23
28	1725	113.35	1699	113.36	1726	113.35	12
29	1537	115.3	1525	115.3	1537	115.3	18
30	1435	116.97	1437	116.97	1435	116.97	24
31	1259	122.36	1272	122.37	1260	122.36	25
32	1207	124.48	1225	124.49	1207	124.48	19
33	1148	127.84	1159	127.85	1148	127.84	24

Table 5.3: Results for Loading Condition L3.

Bus No.	PSO		Proposed method		Iterative method		
	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	DG Size (kW)	P_{LOSS} (kW)	No. of HLF reqd.
6	2373	106.72	2303	106.78	2373	106.72	14
7	2247	107.55	2189	107.6	2247	107.55	23
8	1915	111.64	1881	111.67	1915	111.64	24
9	1594	117.45	1574	117.46	1594	117.45	24
10	1382	120.96	1380	120.96	1382	120.96	16
11	1348	121.56	1350	121.56	1348	121.56	19
12	1294	122.82	1298	122.82	1294	122.82	21
13	1109	127.3	1127	127.31	1109	127.3	25
14	1056	128.85	1077	128.88	1056	128.85	13
15	999	131.17	1018	131.19	999	131.17	26
16	933	134.16	953	134.18	933	134.16	25
17	831	139.3	848	139.32	831	139.3	28
18	784	142.06	798	142.08	784	142.06	29
26	2242	108.35	2181	108.41	2242	108.35	23
27	2086	110.42	2037	110.47	2086	110.42	23
28	1700	115.19	1672	115.21	1700	115.19	9
29	1507	117.07	1501	117.08	1507	117.07	22
30	1415	118.69	1415	118.69	1415	118.69	24
31	1243	123.91	1252	123.91	1243	123.91	23
32	1189	125.96	1207	125.97	1189	125.96	22
33	1131	129.21	1141	129.22	1131	129.21	21

With the PSO results taken as the benchmark, it is found that the iterative method can provide almost exact optimal solutions whereas the DG sizes obtained by the analytical method are approximately optimal or near-optimal. However, the magnitude of the deviations in the optimal sizes obtained by the proposed method from the true optimal sizes can be considered as insignificant for all practical purpose as the corresponding increase in the value of losses are negligible. The magnitude of the maximum deviation in the optimal size is 66 kW (occurring at bus 6) in all cases, whereas, the maximum increase in the value of the minimum power loss is only (104.65 -104.58) = 0.07 kW (at bus 6 in L2 condition) which can be regarded as insignificant in practical situations. Moreover, commercially available DG units appears in discrete sizes, and rarely coincides with the theoretically obtained sizes. Therefore, in real situation, one has to settle with DG sizes which are approximately optimal. Moreover, the deviations in the sizes and the corresponding losses do not affect the optimal location. In this case, bus 6 is the optimal DG location in all situations. In addition to this, the order of the candidate buses if arranged as per the magnitudes of the corresponding losses does not get affected. In this example, it is {6,7,26,27,8,28,29,9,30,10,11,12,31,32,13,14,33,15,16,17,18}in the order of increasing value of loss under all loading conditions considered.

Among the three methods considered, the proposed analytical method requires the least amount of computation. Provided the base case HLF result is available, only two additional HLF along with some minor calculations for solving a set of three linear equations are required for each candidate bus. On the other hand, the iterative method requires much more number of HLF (as shown in the result tables) to generate exact optimal solution for each bus. Thus, for N_c number of candidate buses, a total of $(2N_c+1)$ number of HLF will be required by the suggested analytical method.In the present study, since $N_c = 21$, only a total of (2x21+1) = 43 numbers of HLF is required by the proposed method to solve the DG placement problem under any condition L1, L2 and L3. In case of the iterative method, the total number of HLF required will be equal to the summation of the HLF required for each of the candidate buses. It is obvious from the tables that, for every condition L1, L2 and L3, the total number of HLF required by the iterative method are much larger than 43.This indicates that a significant amount of reduction in computational load is achieved by the proposed method. Supriority of iterative method over the PSO technique regarding the computational requirement has already been demonstrated in chapter 3.

5.5 CHAPTER SUMMARY

An analytical method for optimal DG placement in a harmonics-polluted distribution network has been suggested in this chapter. The method has presented a novel technique for the determination of approximate B-Coefficients which are used for finding the optimal solution. Though the proposed method is applicable irrespective of whether harmonic sources are present in the network or not, its real strength lies in its capability of finding the required DG sizes with very little computational effort even when harmonic sources are present in the network. As analytical method for optimal DG placement in absence of harmonics is well established [20],[21] emphasis has been given in this study to the problem with consideration of presence of harmonics Because of the approximations in B-coefficient values and also the approximation taken in developing equation (5.9), this method gives only near optimal sizes instead of the exact optimal ones. Nevertheless, considering the practical constraint arising due to the fact that the DG units are commercially available in discrete steps only, the near optimal sizes are usually acceptable.

Test results have demonstrated the computational superiority of the proposed method over other previously presented methods. It has been observed that in finding the optimal size and location of the DG unit from a number of candidate buses, the saving in computational effort is quite appreciable. Hence, from the practical point of view, the proposed method seems to be more attractive than other available methods for the problem of DG placement in harmonics-contaminated distribution network.

Though the proposed method is capable of finding the unconstrained optimal size of the DG, its capability of fast detection of the same can be utilized while extending it for determining the constrained optimal sizes in an efficient way.

Chapter 6

An Analytical-Iterative Hybrid Approach for Optimal DG Placement

Outline of the chapter

6.1 INTRODUCTION

The analytical method presented in chapter 5 can provide fast solution for optimal DG placement problem but the sizes obtained from the method are not exactly optimal. In some cases, the deviations in the sizes from the true optimal values, are quite large and may not be desirable when DG sizes in smaller steps are available in the market. In this chapter, the work done in chapter 5 is extended by introducing iterative steps to improve the results. A comparison between the results obtained by the proposed extension and those obtained by the PSO technique and by the analytical method is presented.

6.2 THE PROPOSED EXTENSION

The method adopted in chapter 5 generates approximate solutions because of the following two reasons:

(i) Approximation in the values of *B*-coefficients.

(ii) Approximation introduced by neglecting P_{Loss}, in equation (5.9) to formulate P_{SS}.

In this chapter a stage of iteration is proposed to improve the DG size obtained by the analytical method presented in chapter 5 to get a size closer to the exact optimal one. The iterative steps to be applied for any candidate bus are as follows:

1. Solve for optimal DG size, P_g^0 as described in chapter 5 (i.e., taking $P_{Loss} = 0$)
2. Run HLF to calculate P_{Loss}^0 for the above DG size.
3. Set iteration count k=1.
4. Update P_{SS} to include P_{Loss}^{k-1}.
5. Solve (by the method applied in chapter 5) for optimal DG size, P_g^k with updated value of P_{SS}.
6. Run HLF to calculate P_{Loss}^k for the above DG size.
7. If $\left| P_{Loss}^k - P_{Loss}^{k-1} \right| < \varepsilon$, then take P_g^k as the optimal solution and go to step 10, else, go to next step.

8. If $P_{Loss}^{k} > P_{Loss}^{k-1}$ then take P_g^{k-1} as the optimal solution and go to step 10, else, go to next step.
9. Set k=k+1 and go to step 4.
10. Stop.

6.3 CASE STUDIES AND RESULTS

Study conditions identical to those considered in chapter 5 have been taken for this work also to facilitate the comparison of the results with those obtained in chapter 5. The conditions are summarized below:

- The IEEE-33 bus network for three different degrees of load non-linearity - L1, L2 and L3 has been considered.
- Only inverter-based DG operating at unity power factor is considered.
- A range of 500 kW to 3000kW has been considered for the size of DG unit to be installed.
- Grid bus voltage of 1.02 p.u. has been taken.
- Bus no. 6 to 18 on the main trunk and bus no. 26 to 33 in the longest lateral are considered as the candidate buses.

The results obtained are shown in Table 6.1, Table 6.2 and Table 6.3. The value for ε has been taken as $\varepsilon = 0.0001$

Table 6.1: Results for Loading condition L1.

Bus no.	PSO		Analytical method		Proposed Method		Deviation in DG size (kW) with PSO	
	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	Analytical method	Proposed method
6	2376	106.17	2311	106.23	2376	106.17	-65	0
7	2255	107.01	2197	107.06	2258	107.01	-58	3
8	1926	111.12	1887	111.15	1940	111.13	-39	14
9	1600	116.99	1579	117	1579	117	-21	-21
10	1385	120.54	1385	120.54	1385	120.54	0	0
11	1356	121.15	1355	121.15	1355	121.15	-1	-1
12	1298	122.42	1302	122.42	1302	122.42	4	4
13	1111	126.94	1131	126.95	1131	126.95	20	20
14	1050	128.51	1080	128.53	1080	128.53	30	30
15	1000	130.84	1021	130.87	1021	130.87	21	21

16	940	133.86	956	133.88	956	133.88	16	16
17	835	139.04	851	139.06	851	139.06	16	16
18	785	141.82	801	141.83	801	141.83	16	16
26	2248	107.82	2189	107.88	2252	107.82	-59	4
27	2095	109.91	2044	109.96	2104	109.91	-51	9
28	1703	114.73	1678	114.74	1729	114.74	-25	26
29	1513	116.64	1506	116.64	1506	116.64	-7	-7
30	1418	118.27	1419	118.26	1419	118.26	1	1
31	1245	123.54	1256	123.55	1256	123.55	11	11
32	1192	125.61	1210	125.62	1210	125.62	18	18
33	1132	128.89	1145	128.89	1145	128.89	13	13

Table 6.2: Results for Loading condition L2.

Bus no.	PSO		Analytical method		Proposed Method		Deviation in DG size (kW) with PSO	
	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	Analytical method	Proposed method
6	2409	104.58	2340	104.65	2406	104.58	-69	-3
7	2281	105.45	2224	105.51	2285	105.45	-57	4
8	1953	109.68	1910	109.71	1964	109.69	-43	11
9	1619	115.68	1599	115.69	1599	115.69	-20	-20
10	1402	119.31	1402	119.31	1402	119.31	0	0
11	1375	119.93	1372	119.93	1372	119.93	-3	-3
12	1313	121.23	1319	121.23	1319	121.23	6	6
13	1131	125.86	1145	125.87	1145	125.87	14	14
14	1072	127.47	1094	127.49	1094	127.49	22	22
15	1014	129.86	1035	129.88	1035	129.88	21	21
16	949	132.94	969	132.97	969	132.97	20	20
17	846	138.26	863	138.28	863	138.28	17	17
18	795	141.1	812	141.12	812	141.12	17	17
26	2280	106.27	2217	106.33	2279	106.27	-63	-1
27	2127	108.41	2070	108.46	2129	108.41	-57	2
28	1725	113.35	1699	113.36	1750	113.36	-26	25
29	1537	115.3	1525	115.3	1525	115.3	-12	-12
30	1435	116.97	1437	116.97	1437	116.97	2	2
31	1259	122.36	1272	122.37	1272	122.37	13	13
32	1207	124.48	1225	124.49	1225	124.49	18	18
33	1148	127.84	1159	127.85	1159	127.85	11	11

Table 6.3: Results for Loading condition L3.

Bus no.	PSO		Analytical method		Proposed Method		Deviation in DG size (kW) with PSO	
	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	DG size (kW)	P_{Loss} (kW)	Analytical method	Proposed method
6	2373	106.72	2303	106.78	2368	106.72	-70	-5
7	2247	107.55	2189	107.6	2250	107.55	-58	3
8	1915	111.64	1881	111.67	1934	111.65	-34	19
9	1594	117.45	1574	117.46	1574	117.46	-20	-20
10	1382	120.96	1380	120.96	1380	120.96	-2	-2
11	1348	121.56	1350	121.56	1350	121.56	2	2
12	1294	122.82	1298	122.82	1298	122.82	4	4
13	1109	127.3	1127	127.31	1127	127.31	18	18
14	1056	128.85	1077	128.88	1077	128.88	21	21
15	999	131.17	1018	131.19	1018	131.19	19	19
16	933	134.16	953	134.18	953	134.18	20	20
17	831	139.3	848	139.32	848	139.32	17	17
18	784	142.06	798	142.08	798	142.08	14	14
26	2242	108.35	2181	108.41	2244	108.35	-61	2
27	2086	110.42	2037	110.47	2097	110.42	-49	11
28	1700	115.19	1672	115.21	1723	115.21	-28	23
29	1507	117.07	1501	117.08	1501	117.08	-6	-6
30	1415	118.69	1415	118.69	1415	118.69	0	0
31	1243	123.91	1252	123.91	1252	123.91	9	9
32	1189	125.96	1207	125.97	1207	125.97	18	18
33	1131	129.21	1141	129.22	1141	129.22	10	10

From the results it is found that the proposed iterative steps have reduced the error in the optimal sizes obtained by the analytical method especially when the error is comparatively larger. The improved DG sizes are now nearer to the exact optimal sizes. With the improved sizes, P_{Loss} gets reduced further. It is also seen that in some cases, no improvement in the value of the sizes has taken place. In such cases, the modified value of the size obtained after the first iteration resulted in increase in the value of P_{Loss}. Therefore, in those cases the old values have been retained. In cases where improved values for DG sizes are obtained, only two steps of iteration were sufficient to get the desired result. That means very small amount of increase in the amount of computation was necessary as only two additional HLF were required.

6.4 CHAPTER SUMMARY

In this chapter some iterative steps are presented to improve the values of optimal DG sizes obtained by the analytical method suggested in chapter 5. The results obtained after the proposed corrective measures are more acceptable as the optimal values are comparatively nearer to the exact optimal values. In practical situation these values may be more acceptable than those obtained with the help of analytical method particularly when DGs are available in the market in smaller discrete steps.

CHAPTER 7

Conclusions and Further scope of studies

Outline of the chapter

7.1 CONCLUDING REMARKS

DGs are usually installed in an electrical power distribution feeder network to get several benefits. Reduction in network power loss is one of the major benefits. The studies undertaken in this thesis have focused on optimal placement of DG units in radial distribution network to minimize the network power loss when harmonics generating sources are present in the network. The main objective of these studies was to develop computationally efficient method for solving the problem. In recent years harmonics distortion in currents and voltages in distribution networks has been a major problem. Increased use of power electronic loads (non linear loads) over the last few years has increasingly given rise to harmonics pollution in the distribution networks. Moreover, one of the adverse effects of application of DGs is that it increases the problem of harmonic contamination. Majority of the DG units nowadays uses renewable energy sources. The renewable based DG units are interfaced with the network through power electronic inverters which are major sources of harmonics injecting harmonic currents into the network. Recent proliferations of such DG units in distribution system have amplified the problem. In this context, the problem of optimal DG planning has to be given proper attention to this aspect for acceptable solution. Accordingly, emphasis has been given in the present investigations on harmonics contaminated distribution networks. In all the studies in this thesis, only inverter based DG units has been considered. No non-linear load has been considered in the studies in chapter 2 and chapter 3. Such loads have been taken into account in chapter 4 to chapter 6.

In chapter 2, a PSO based solution to the problem has been presented where constraints on bus voltage magnitudes as well as the maximum allowable THD in bus voltages have been considered. PSO being a well accepted and widely used method of optimization, the results obtained in this chapter have been used as the benchmark for validation of the results obtained in the later chapters. Results for both unconstrained and constrained cases have been furnished.

Chapter 3 has presented a novel, computationally efficient iterative process which utilizes the unimodal nature of variation of network power loss with DG size installed at any bus. The method proposed is, however, capable of finding the unconstrained optimal size. The results have shown that in comparison to the PSO technique presented in chapter 2, the proposed iterative method requires significantly less amount of computation to furnish the unconstrained solution with almost same accuracy.

Chapter 4 has proposed a novel hybrid approach to consider the constraint on maximum allowable value of *THD* in the bus voltages to find the optimal DG size. The hybrid approach is a combination of a Rule-base and some iterative computations among which the iterative method proposed in chapter 3 is also included. The Rule-base is developed based on the variation of power loss and the variation of maximum *THD* with the size of the DG placed at any given bus. The results on benchmark distribution test networks have shown the computational superiority of this method over the PSO based method.

A novel analytical method is presented in chapter 5, which is capable of finding the unconstrained optimal size with very little amount of computation. Comparative studies with the results of chapter 2 and chapter 3 have shown the superiority of this method in terms of amount of computation required. However, this method gives approximately optimal (near optimal) sizes of the DG. However, considering the fact that the DG units are commercially available in the market in discrete sizes only, the near optimal sizes appear to be quite acceptable in real situation considering the computation economy of the method. However, when DG units are available in quite smaller discrete steps, the sizes determined by the analytical method proposed in chapter 5 may not be satisfactory in some cases. Approximate sizes nearer to the exact optimal ones are desirable in these cases.

In chapter 6, some iterative steps are appended with the analytical method to improve the results at the cost of small amount of increase in computation. The results have shown marked improvement where the difference between the analytically obtained size and the exact optimal size is quite larger. In cases when improvement was possible, only two iterations were sufficient to get the maximum possible improvement.

7.2 FURTHER SCOPE OF WORK

1) In all the studies, placement of single DG unit has been considered. Necessary investigations can be carried out to extend the proposed methods for simultaneous placement of multiple DG units.
2) Formulation of the proposed method methodology can be extended to incorporate more number of constraints relevant to the problem.

APPENDICES

Outline of the chapter

Appendix- A : Test Network Data

Appendix-B: Load Non-Linearity Data

Appendix-C: Particle Swarm Optimization (PSO)

Appendix-D: A brief introduction to Harmonic Load Flow (HLF)

Appendix- A : Test Network Data

Single Line Diagrams

a) IEEE-33 Bus Network [53]

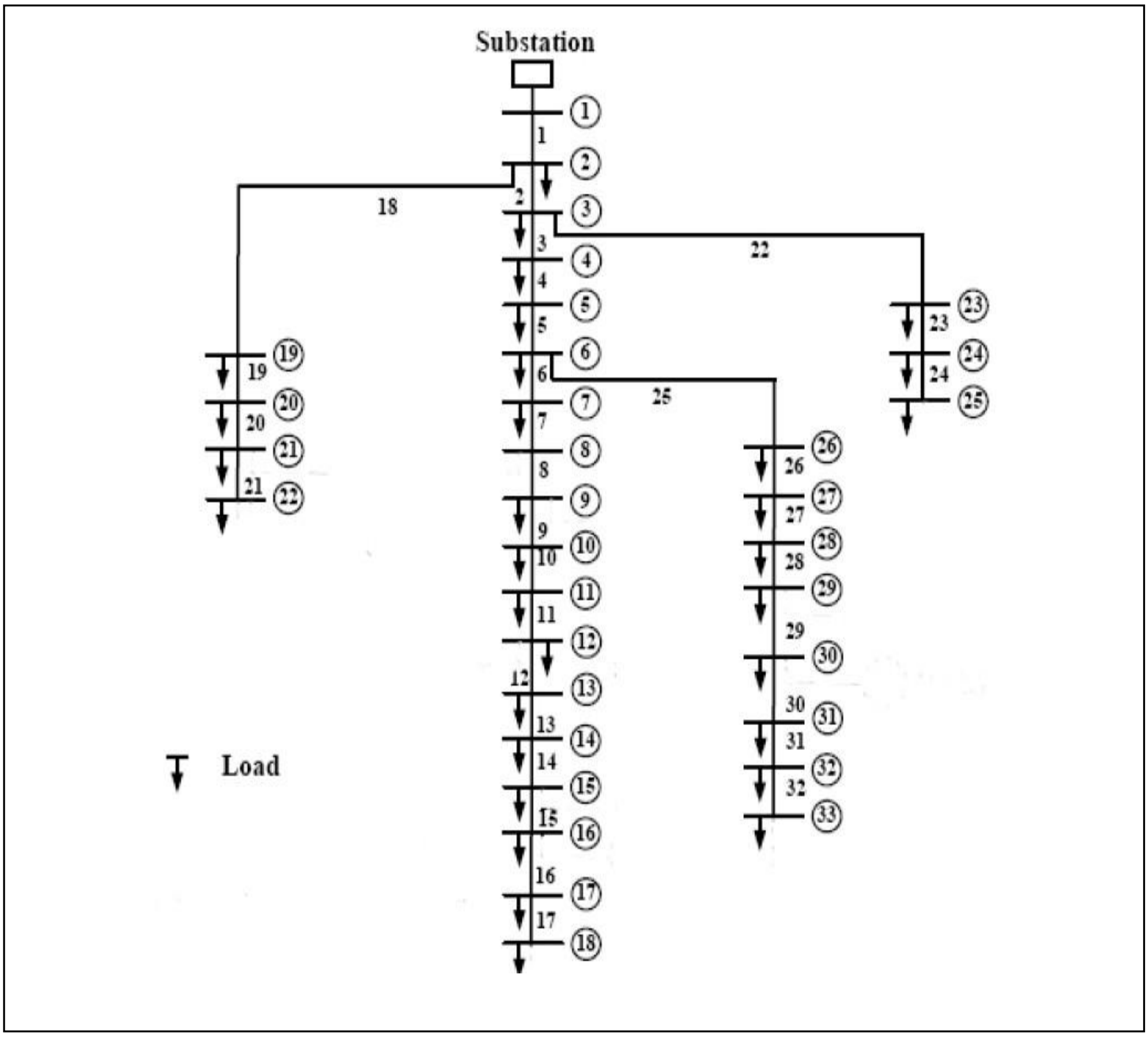

Fig. A-1(a): Single Line Diagram of IEEE-33 Bus Radial Distribution Network.

b) IEEE-69 Bus Network [54]

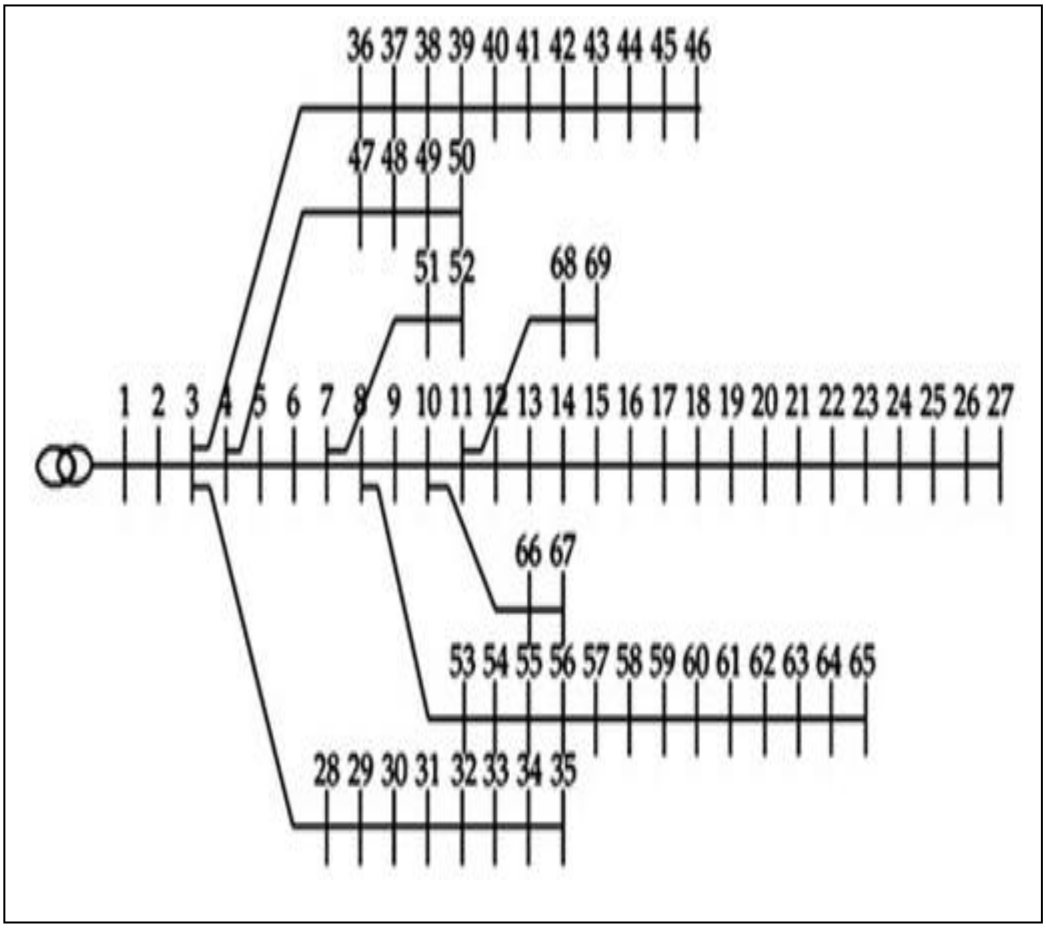

Fig. A2 (b): Single Line Diagram of IEEE- 69 Bus Radial Distribution Network.

Line Data and Load Data

a) IEEE-33 Bus Network [53]

Table A1: Line data and Load Data for IEEE- 33 Bus Radial Distribution Network.

Line no.	From bus	To bus	Line Impedance		Load at bus	
			r(ohm)	x(ohm)	P(kW)	Q(kVar)
1	1	2	0.0922	0.0470	100.0	60.0
2	2	3	0.4930	00.2512	90.0	40.0
3	3	4	0.3661	0.1864	120.0	80.0
4	4	5	0.3811	0.1941	60.0	30.0
5	5	6	0.8190	0.7070	60.0	20.0
6	6	7	0.1872	0.6188	200.0	100.0
7	7	8	0.7115	0.2351	200.0	100.0
8	8	9	1.0299	0.7400	60.0	20.0
9	9	10	1.0440	0.7400	60.0	20.0
10	10	11	0.1967	0.0651	45.0	30.0
11	11	12	0.3744	0.1298	60.0	35.0
12	12	13	1.4680	1.1549	60.0	35.0
13	13	14	0.5416	0.7129	120.0	80.0
14	14	15	0.5909	0.5260	60.0	10.0
15	15	16	0.7462	0.5449	60.0	20.0
16	16	17	1.2890	1.7210	60.0	20.0
17	17	18	0.7320	0.5739	90.0	40.0
18	2	19	0.1640	0.1565	90.0	40.0
19	19	20	1.5042	1.3555	90.0	40.0
20	20	21	0.4095	0.4784	90.0	40.0
21	21	22	0.7089	0.9373	90.0	40.0
22	3	23	0.4512	0.3083	90.0	50.0
23	23	24	0.8980	0.7091	420.0	200.0
24	24	25	0.8959	0.7071	420.0	200.0
25	6	26	0.2031	0.1034	60.0	25.0
26	26	27	0.2842	0.1447	60.0	25.0
27	27	28	1.0589	0.9338	60.0	20.0
28	28	29	0.8043	0.7006	120.0	70.0
29	29	30	0.5074	0.2585	200.0	600.0
30	30	31	0.9745	0.9629	150.0	70.0
31	31	32	0.3105	0.3619	210.0	100.0
32	32	33	0.3411	0.5302	60.0	40.0

b) IEEE-69 Bus Network [54]

Table A2: Line data and Load Data for IEEE- 69 Bus Radial Distribution Network.

Line no.	From bus	To bus	Line Impedance		Load at bus	
			r(ohm)	x(ohm)	P(kW)	Q(kVar)
1	1	2	0.0005	0.0012	0.0	0.0
2	2	3	0.0005	0.0012	0.0	0.0
3	3	4	0.0015	0.0036	0.0	0.0
4	4	5	0.0251	0.0294	0.0	0.0
5	5	6	0.366	0.1864	2.6	2.2
6	6	7	0.381	0.1941	40.4	30.0
7	7	8	0.0922	0.047	75.0	54.0
8	8	9	0.0493	0.0251	30.0	22.0
9	9	10	0.819	0.2707	28.0	19.0
10	10	11	0.1872	0.0619	145.0	104.0
11	11	12	0.7114	0.2351	145.0	104.0
12	12	13	1.03	0.34	8.0	5.0
13	13	14	1.044	0.345	8.0	5.5
14	14	15	1.058	0.3496	0.0	0.0
15	15	16	0.1966	0.065	45.5	30.0
16	16	17	0.3744	0.1238	60.0	35.0
17	17	18	0.7320	0.0016	60.0	35.0
18	18	19	0.3276	0.1083	0.0	0.0
19	19	20	0.2106	0.069	1.0	0.6
20	20	21	0.3416	0.1129	114.0	81.0
21	21	22	0.014	0.0046	5.0	3.5
22	22	23	0.1591	0.0526	0.0	0.0
23	23	24	0.3463	0.1145	28.0	20.0
24	24	25	0.7488	0.2475	0.0	0.0
25	25	26	0.3089	0.1021	14.0	10.0
26	26	27	0.1732	0.0572	14.0	10.0
27	3	28	0.0044	0.0108	26.0	18.6
28	28	29	0.064	0.1565	26.0	18.6
29	29	30	0.3978	0.1315	0.0	0.0
30	30	31	0.0702	0.0232	0.0	0.0
31	31	32	0.351	0.116	0.0	0.0
32	32	33	0.839	0.2816	14.0	10.0
33	33	34	1.708	0.5646	19.5	14.0
34	34	35	1.474	0.4873	6.0	4.0
35	3	36	0.0044	0.0108	26.0	18.55
36	36	37	0.064	0.1565	26.0	18.55
37	37	38	0.1053	0.123	0.0	0.0
38	38	39	0.0304	0.0355	24.0	17.0
39	39	40	0.0018	0.0021	24.0	17.0
40	40	41	0.7283	0.8509	1.2	1.0
41	41	42	0.31	0.3623	0.0	0.0
42	42	43	0.041	0.0478	6.0	4.3
43	43	44	0.0092	0.0116	0.0	0.0

44	44	45	0.1089	0.1373	39.22	26.3
45	45	46	0.0009	0.0012	39.22	26.3
46	4	47	0.0034	0.0084	0.0	0.0
47	47	48	0.0851	0.2083	79.0	56.4
48	48	49	0.2898	0.7091	384.7	274.5
49	49	50	0.0822	0.2011	384.7	274.5
50	8	51	0.0928	0.0473	40.5	28.3
51	51	52	0.331	0.1114	3.6	2.7
52	9	53	0.174	0.0886	4.35	3.5
53	53	54	0.203	0.1034	26.4	19.0
54	54	55	0.2842	0.1447	24.0	17.2
55	55	56	0.2813	0.1433	0.0	0.0
56	56	57	1.59	0.5337	0.0	0.0
57	57	58	0.7837	0.263	0.0	0.0
58	58	59	0.3042	0.1006	100.0	72.0
59	59	60	0.3861	0.1172	0.0	0.0
60	60	61	0.5075	0.2585	1244.0	888.0
61	61	62	0.0974	0.0496	32.0	23.0
62	62	63	0.145	0.0738	0.0	0.0
63	63	64	0.7105	0.3619	227.0	162.0
64	64	65	1.041	0.5302	59.0	59.0
65	11	66	0.2012	0.0611	18.0	13.0
66	66	67	0.0047	0.0014	18.0	13.0
67	12	68	0.7394	0.2444	28.0	20.0
68	68	69	0.0047	0.0016	28.0	20.0

Appendix-B: Load Non-Linearity Data

Table B1: Load Non- Linearity (in % of nominal Bus Loading) for IEEE-33 Bus Network.

Loading Condition	***Bus No.***	***% non-linearity***
L1	6	10
	8	15
	11	10
	14	10
	20	12
	24	20
	28	15
	30	10
L2	10% non-linearity at all the buses	10% non-linearity at all the buses
L3	No non-linear load present	No non-linear load present

Table B2: Load Non- Linearity (in % of nominal Bus Loading) for IEEE-69 Bus Network.

Loading Condition	***Bus No.***	***% non-linearity***
L1	8	12
	11	10
	17	10
	21	15
	49	20
	55	10
	61	10
	64	15
L2	10% non-linearity at all the buses	10% non-linearity at all the buses
L3	No non-linear load present	No non-linear load present

Harmonic order	**Magnitude in % of fundamental current**			
	6-pulse Converter	***12-pulse Converter***	***ASD***	***Fluorescent lamp***
1	100	100	100	100
3	0	0	0	19.2
5	19.41	1.8	18.24	10.7
7	13.09	1.6	11.9	2.1
9	0	0	0	1.4
11	7.58	6.6	5.73	0.9
13	5.86	5.4	4.01	0.6
15	0	0	0	0.5
17	3.79	0.33	1.93	0
19	3.29	0.3	1.39	0
23	2.26	1.5	0.94	0
25	2.41	1.3	0.86	0
29	1.93	0.25	0.71	0
31	0	0	0.62	0
35	0	0.2	0.44	0
37	0	0.8	0.38	0
41	0	0.4	0	0

Appendix-C: Particle Swarm Optimization (PSO)

The PSO is an evolutionary meta-heuristic method adopted that has shown effectiveness in finding out the best solutions to a variety of problems, particularly in the field of engineering when nonlinearity is present. This approach was put forth by Kennedy and Eberthart [55] and is modeled after a flock or group (swarm) of birds looking for a good environment [56]. According to the PSO technique, each member (particle) of the group (swarm) modifies its flight in accordance with two directives: its personal experience and the experience of the group. Based on their positions and the objective function, each particle or member can communicate with others. The effectiveness of the optimization procedure is directly correlated with the number of particles in a swarm, the number of swarms in the solution space, and the convergence criteria. Each particle is treated as a point in the solution space according to this method, which decides each movement in the search for the ideal point on following three parameters [55]:

1. Sociability factor - The attraction of each particle or person to the best place discovered by any member of the group is determined by this factor
2. Individuality component - The attraction of each particle or individual to the optimal position independently depends on this factor.
3. Maximum velocity- It determines the direction and size of the movement.

The PSO algorithm starts with a swarm of particles, where position '*y*' and velocity '*v*' of each particle of every swarm (say of size 'pop') are randomly initialized. The search for optimal position is carried out by updating the velocities and positions of the particles iteratively using the following expressions:

$$v_i^{k+1} = w * v_i^k + c_1 * rand_1 * \left(pbest_i^k - y_i^k \right) + c_2 * rand_2 * \left(gbest^k - y_i^k \right)$$

and $y_i^{k+1} = y_i^k + v_i^{k+1}$

where, $v_i =$ Velocity of the i^{th}particle

$y_i =$ Position of the i^{th} particle

$i = 1, 2, \ldots, pop$

$c_1 =$ Cognitive constant

$c_2 =$ Social constant

$w =$ Inertial weight of particle determining the diversification or intensification of the search

$k =$ Current iteration number.

C_1 and C_2 sums up to 4 ideally; '*rand*' is a randomly obtained number from a normal distribution with mean value = 0 and standard deviation = 1. Each particle's performance is evaluated using an aptitude function that is predetermined and is connected to the problem to be solved. The impact of the prior velocity on the current velocity is controlled by the weight of the inertia *W*. With a right choice of the inertia weight *W*, global and local exploration capacities can be balanced, which helps in finding the ideal location with overall fewer iterations. The coordinates visited throughout the optimization process are stored for each particle. As a result, every particle's displacement during each step is recorded. "*pbest*" refers to the coordinate in which each particle achieved the best fitness and the term "*gbest*" refers to the coordinate with the highest fitness that gives the final solution. The search of swarm is focused towards the particle best positions ' *pbest* ' (also called local best positions), which generates the minimum value ' *fpbest* ' of the objective function attained by each individual particle. The search continues for the entire population size. Finally, the global best position ' *gbest* ' is obtained from the best value of ' *pbest* ' positions that gives the global minimum value ' *fgbest* ' of the objective function. When compared to other optimization techniques, PSO is preferred as it requires fewer parameters to be adjusted and can do parallel computations, both of which speed up the convergence.

Appendix-D: A brief introduction to Harmonic Load Flow (HLF)

The main building block of HLF for harmonics-polluted distribution networks is the distribution load flow (DLF) calculation. A brief introduction to DLF therefore is furnished below.

The conventional Newton-Raphson (or fast decoupled) based methods exhibit excellent performance for transmission networks but these methods often fails or faces problems in case of solving DLF because of special characteristics (radial, multiphase, and high R/X ratio) of the distribution networks. Several special load flow methods [52] are available for the solution of DLF among which the backward/forward sweep (B-F-S) method is one of the most efficient and well accepted method.

Like all DLF methods, B-F-S method uses current injection model where the loads and the generators (usually DGs in distribution network) are modeled as injected currents to the respective nodes to which they are connected. Current injections are calculated from the specified P,Q values of the loads and the DGs. The DGs, in this context, are regarded as negative loads. The basic operating principle of B-F-S involves two computation steps in each iteration process. The steps are:

- *Backward sweep*, wherein, by using Kirchhoff's current law, the current at each load node, as well as the current flowing through its incoming branch is calculated starting from the end nodes and moving towards the source node.
- *Forward sweep*, wherein, by , using Ohm's law, the voltage drop on each branch, as well as the voltage at each load node, are calculated starting in the opposite direction, from the source node (whose constant voltage is taken as reference i.e., the Slack bus) and going towards the end nodes.

Each iteration step consists of a backward sweep followed by a forward sweep. The iteration process starts with a initial guess for the node voltages (usually a flat voltage starts equal to the source node voltage) and the node voltages are updated in each iteration until convergence is obtained. At the end of each iteration, the current injections are updated by the update voltages. B-F-S method is widely applied in HLF [49], [51] with necessary adaption. The network branch impedances are modified according to the harmonic frequencies. Non-linear elements (loads and DGs) are modeled as current sources injecting harmonic currents into the nodes. The fundamental and the h^{th} harmonic current injected to any i^{th} bus is modeled as :

$$I_i^{(1)} = [(P_i + jQ_i) / V_i^{(1)}]$$

$$I_i^{(h)} = C_i^{(h)}\ I^{(1)}$$

Where $C_i^{(h)}$ is ratio of the h^{th} harmonic component current to its fundamental, $I_h^{(1)}$. The $B_{ij}^{(h)}$, obtained from backward sweep is used in the forward sweep to calculate the h^{th} harmonic component of voltage drop as

$$\Delta V_{ij}^{(h)} = Z_{ij}^{(h)}\ B_{ij}^{(h)}$$

Where Z_{ij} is the impedance of branch *ij* at the h^{th} harmonic frequency. After the voltage drops are calculated for each branch, each harmonic component of bus voltages can be calculated in forward sweep.

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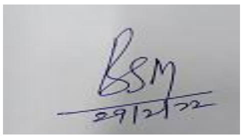

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