# OPTIMAL ALLOCATION OF DISTRIBUTED GENERATION WITH HARMONICS CONSIDERATION

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***ABSTRACT***

*This paper proposes an improved analytical method with Particle Swarm Optimization (PSO) for optimal allocation of Power Electronic Based-Distribution Generation (PEB-DG) with harmonic consideration. The proposed method improved the conventional analytical method for optimal DG sizing without harmonic consideration by using a polynomial interpolating function that represents the relationship of the PEB-DG size and Total Harmonic Distortion Voltage (THDv). The interpolating function is used to estimate the appropriate DG size for buses in the IEEE 33-bus network that caused violation of the THDv limit of 5% as defined by IEEE standards. The PSO algorithm was developed and used to determine the optimal allocation for the DG with the objective to minimize the total active power loss of the network. The proposed method records the optimal size and location for the PEB-DG to be 639kW and bus 25 respectively with 19.1% reduction in active power loss and 5.46% improvement in average voltage profile when compared with the base case (without PEB-DG) system.*

***Keywords: Optimal, Allocation, Distributed Generation (DG), Harmonics***

## 1.0 INTRODUCTION

Traditional power systems networks are based on centralized structure with generation plants connected to transmission networks which consequently supply the load centres through distribution networks. However, modern power systems networks are designed as a decentralized system with smaller generating units (i.e. DGs) connected directly to distribution network located near the load centres. The benefits of DG are numerous (Chiradeja and Ramakumar, 2004; Daly and Morrison, 2001) and the reasons for implementing DGs are based on energy efficiency, deregulation or competition policy, diversification of energy sources, availability of modular generating plant, ease of finding sites for smaller generators, shorter construction times and lower capital costs of smaller plants and proximity of the generation plant to heavy loads, which reduces transmission costs/losses. Also it is accepted by many countries that the reduction in gaseous emissions (mainly $CO_2$) offered by DGs is the major legal driver for the DG implementation (Chiradeja and Ramakumar, 2004).

DG technologies can be categorized into renewable and non-renewable energy resources. The DG technologies that are based on renewable are solar, wind, small-hydro, biomass, geothermal etc. whereas the DG technologies that are based on non-renewable are combustion turbines, steam turbines, micro turbines, reciprocating engines etc. Fuel cells can be categorized into renewable (using hydrogen) and non-renewable (using natural gas or petrol) (Pepermans *et al.,* 2005; Rujula *et al.,* 2005). Among the various renewable DG types, Power Electronic Based DGs (PEB-DG) are common since the majority of the renewable resources are interconnected to the grid through power electronic converters. The penetration of PEB-DG into the distribution network of power system is a challenge for traditional electric power system operators, as it changes the network power flows, modify energy losses and has the potential of increasing the total harmonic voltage distortion of the network (Murthy *et al.,* 2013).This necessitates the need for harmonic consideration during the integration of such DGs (Ghaffarzadeh and Sadeghi, 2016).

Due to the challenges associated with the integration of PEB-DG into the distribution network, a lot of researches have been proposed for the optimal location and sizing of PEB-DGs into distribution network. Hengsritawat *et al.,* (2012) presented a probabilistic approach to obtain an optimal size of photovoltaic DG in a distributed system. Abinaya and Sasiraja (2015) presented a method for the optimal placement and sizing of DGs with harmonic consideration using Social Learning Particle Swarm Optimization (SLPSO). Kadir *et al.,* (2013) presented a method for determining the optimal sizing and placement of DG using sensitivity analysis to obtain the optimal placement and Evolutionary programming- Harmonic distribution load flow algorithm for optimal sizing. Ghaffarzadeh and Sadeghi (2016) proposed a method for simultaneous placement of inverter based DGs and capacitor bank considering harmonic pollution in distribution network. Analytical methods of DG sizing have the advantage of better accuracy compared to heuristic approach, while heuristic approach has faster convergence speed when used for the DG placement (Meena and Kumar, 2014). The use of analytical method with heuristic algorithm achieves a trade-off between accuracy and computational time. However, some of the methods in literature make use of heuristic method alone without combining it with analytical method to achieve accurate results. This paper proposes the use of improved analytical method with particle swarm optimization technique for optimal allocation of DG with harmonic consideration on a modified standard 33-bus IEEE test network. The improved analytical method is based on Polynomial Interpolation Function representing the relationship between the power output of the DG with the corresponding total harmonic voltage distortion (THDv) of the most critical bus to determine the sizing of the PEB-DG. The Particle Swarm Optimization (PSO) algorithm is used for optimal sizing and location of the PEB-DG.

## 2.0 MATERIALS AND METHODS

### *2.1 Materials*

The materials used in the work include a computer with specifications: 2.00GHz Intel(R) Core(TM) 2Duo central processing unit (CPU), 4GB installed memory (RAM) and 32-bit windows operating system (OS). Simulations were performed under the platform of MATLAB R2013a, using PSAT Toolbox for analysis.

### *2.2 Methodology*

The standard 33-bus IEEE test network shown in figure1 is modified by the introduction of adjustable speed drives (ASDs) at various buses of the network to provide background harmonics. An improved analytical method for determining the size of PEB-DG with harmonic consideration was developed through the development of the conventional analytical method for determining the size of the PEB-DG for active power loss reduction without harmonic limit consideration using MATLAB R2013a. The relationship between the sizes of each PEB-DG obtained with the corresponding Total Harmonic Voltage Distortion (THDv) at the most critical bus evaluated. A polynomial interpolation function (Lagrange basis) to represent the established relationship stated above is formulated to estimate the PEB-DG size that satisfies acceptable harmonic limits defined by IEEE 519-2014 standards.

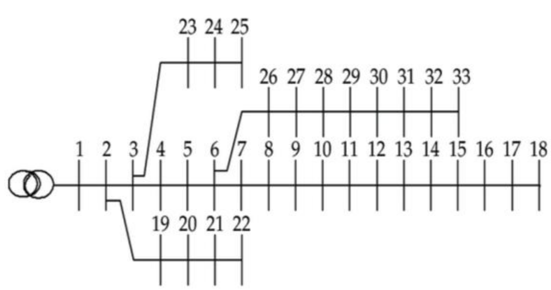


***Figure 1: Single Line Diagram of IEEE 33-Bus Distribution System***

Particle Swarm Optimization (PSO) algorithm for optimal allocation of the PEB-DG was developed by initializing the PSO particles to represent each PEB-DG size determined via the improved analytical method. The fitness function (minimization of losses) is evaluated and the constraints for each particle in each iteration step checked. The developed method is applied on the modified standard 33-bus IEEE test network to obtain optimal PEB-DG location and size. The results obtained are validated by comparing them with the base case system (33-bus IEEE network without PEB-DG using voltage profile and THDv as performance metrics)

***Modified Standard IEEE 33-Bus Network***

To modify the standard IEEE 33-bus network to include background harmonics in the network, the approach employed in Heydari *et al.* (2004) was adopted where Adjustable Speed Drives (ASDs) are placed on the most critical buses of the network so that the harmonic effect generated by them is felt by majority of the buses in the network. The ASDs were connected at buses 22 and 33 (network laterals) of the IEEE network to provide background harmonics. The ASDs employed are six-pulse converters with active and reactive power corresponding to the active and reactive power of the linear loads at buses 22 and 33 of the standard IEEE network. The locations of the ASDs were chosen such that the effect of the non sinusoidal current drawn by the ASDs is observed over majority of the buses, thus, in other words the buses selected for the placement of ASD are the most critical buses of the network. The limit on the magnitude of background harmonics generated by the ASD was assumed to be 1.5% for the network.
The active and reactive power and spectrum data for the ASD placed at buses 22 and 33 of the standard 33-bus IEEE network is depicted in Table 1.

***Table 1: Location and Size of the ASD in the 33-bus IEEE network***

| | Bus 22 | Bus 33 |
|---|---|---|
| **Active power (kW)** | 90 | 60 |
| **Reactive power (kVar)** | 40 | 40 |
| **Harmonic Component (%)** | | |
| 1st | 100 | 100 |
| 5th | 20 | 20 |
| 7th | 14 | 14 |
| 11th | 9 | 9 |
| 13th | 8 | 8 |
| 17th | 6 | 6 |

***Modeling of PEB-DG***

The DG is modeled as a Load (PQ) bus which is capable of supplying active power only (Type 1 DG). The PQ model was used so as to reduce the total active power loss, improve the voltage profile and also ensure that THDv at each bus of the network is within acceptable limit of 5%.

***Problem Formulation***

A general constrained single-objective optimization problem considering reduction in total active power loss in the distribution system considering the harmonic contribution of the DG and the background harmonics to ensure that the power quality of the system is within acceptable limits was formulated. The objective function is formulated as:

$$F = \min PL = \sum_{k}^{NL} Plossk \quad (1)$$

Subject to the power constraints: the summation of the power from the grid ($Pgrid$) and that from the distributed generation ($PDGi$) must be equal to the sum of the load ($PDi$) and the losses ($PL$) in the system.

$$\sum Pgrid + \sum_{i=1}^{N} PDGi = \sum_{i=1}^{N} PDi + PL \quad (2)$$

Voltage limits: Acceptable voltage variation in power system buses is within the range of $\pm 5\%$ (Heydari *et al.,* 2013).

$$\left|V_i\right|^{\min} \le \left|V_i\right| \le \left|V_i\right|^{\max} \quad (3)$$

Total Harmonic Voltage Distortion (THDv) Limit: according to the standard IEEE 519-2014, the

THDv of a network at the point of Common coupling (PCC) should be less than or equal to 5%.

$$\left|THDv_i\right| \le \left|THDv_i\right|^{\max} \quad (4)$$

where $F$ is the objective function, $P_L$ is the total active power loss, $Ploss_k$ is the active power loss in the kth line, $NL$ is the number of lines in the system and $N$ is the set of bus indices.

The total active power loss in power system is expressed as:

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\begin{array}{l}\alpha_{ij}\left(P_iP_j + Q_iQ_j\right)\\ +\beta_{ij}\left(Q_iP_j - P_iQ_j\right)\end{array}\right] \quad (5)$$

where

$$\alpha_{ij} = \frac{r_{ij}}{V_iV_j}\cos\left(\delta_i - \delta_j\right) \quad (6)$$

$$\beta_{ij} = \frac{r_{ij}}{V_iV_j}\sin\left(\delta_i - \delta_j\right) \quad (7)$$

$$z_{ij} = r_{ij} + x_{ij} \quad (8)$$

$V_i\angle\delta_i$ is the complex voltage at the ith bus; $P_i$ and $P_j$ are the active power injections at the ith and jth buses respectively.; $Q_i$ and $Q_j$ are the reactive power injections at the ith and jth buses respectively.

The total active power loss of the system is minimum if the partial derivative of equation (5) with respect to the active power injection from DG at bus 'i' becomes zero. Thus, the size of DG

at each bus 'i' for minimizing loss can be written as:

$$P_{DGi} = \frac{\alpha_{ii}\left(P_{Di} + aQ_{Di}\right) + \beta_{ii}\left(aP_{Di} - aQ_{Di}\right) - x_i - aY_i}{a^2\alpha_{ii} + \alpha_{ii}} \quad (9)$$

For Type 1 DG, power factor is at unity, i.e., $PF_{DG} = 1$ and $a = 0$

For Type 1 DG the size of DG at each bus 'i' for minimizing loss can be rewritten as:

$$P_{DGi} = P_{Di} - \frac{1}{\alpha_{ii}}\left[\beta_{ii}Q_{Di} + \sum_{\substack{j=1\\ j\ne i}}^{N}\left(\alpha_{ij}P_j + \beta_{ij}Q_j\right)\right] \quad (10)$$

Equation 10 was used to obtain the size of PEB-DG without harmonic consideration via the conventional analytic method. The flow chart for the conventional analytical method is shown in figure 2. The size of the DG obtained above has its objective function to be minimizing power loss but does not guarantee that the size obtained satisfies the THDv limit as stated in IEEE 519-2014 standards. This creates the need for the re-evaluation of the size of the DG so as to satisfy the THDv limit.

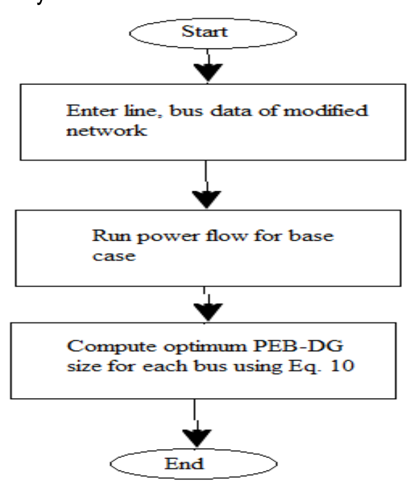


***Figure 2. Flowchart of Conventional Analytical Method for PEB-DG Sizing***

The harmonic power flow was used to determine the total harmonic distortion at bus 'i' using equation (11) (Alhaddad and El-Hawary, 2014).

$$THD_i = \frac{\sqrt{\sum_{h_o}^{h_{max}} \left|V_i^{(h)}\right|^2}}{\left|V_i^{(1)}\right|} \qquad (11)$$

where $V^{(h)}$ is the harmonic bus voltage; $h_o$ is the smallest harmonic order; $h_{max}$ is the highest harmonic order and $\left|V_i^{(1)}\right|$ is the magnitude of bus voltage at fundamental frequency.

The buses whose DG sizes violated the THDv limit were resized, by establishing a relationship between the sizes and the THDv and represented by a polynomial interpolation (Lagrange basis) function shown in equation (13).

$$P_i(x) = L_{i(x)} y_k = \sum_i \left(\prod_{j=1_{j\neq i}}^{n} \frac{x - x_j}{x_i - x_j}\right) y_k \quad \text{for} \quad i = 1 \ldots n, k = 1 \ldots n \qquad (13)$$

where $n$ = number of buses in the network, $x$ = PEB-DG size, and $y$ = THDv value

The function was used to estimate the size of the DG that satisfied the THDv limit. The flowchart for the improved analytical method for sizing of the DG is shown in Fig. 3

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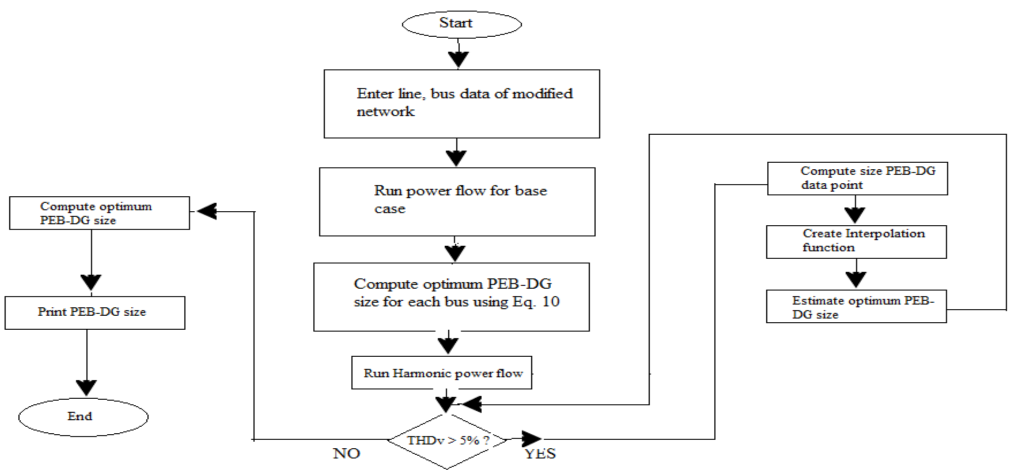


***Figure 3. Flowchart of improved Analytical Method Considering Harmonics for PEB-DG Sizing***

Note: In the computation of the optimum PEB-DG size for each bus (equation 10) takes cognizance of the active power loss minimization objective function as depicted by figure 3.

***Particle Swarm Optimization Algorithm***

Particle Swarm Optimization (PSO) algorithm is an adaptive algorithm based on a social-psychological metaphor; a population of individuals (referred to as particles). Each particle represents a potential solution. Particle Swarm has two primary operators: Velocity update and position update. During an iteration (iter) each particle is accelerated toward the particles previous best position (Pbest) and the global best (Gbest) position. At each iteration a new velocity value for each particle is calculated based on its current velocity, the distance from its previous best position, and the distance from the global best position. The new velocity value is then used to calculate the next position of the particle in the search space. This process is then iterated a number of times or until a minimum error is achieved.

In its basic form the PSO algorithm has the following procedures:

Step 1: The search space is d-dimensional

Step2: Each member of the search space is called particle and is presented by d-dimensional vector described as:

$$x_i = [x_{i1}, \; x_{i2}, \ldots \ldots \ldots \ldots x_{id}] \qquad (14)$$

where $x_i$ is the ith particle, and

$$number \;\; of \;\; particles = \max imum \;\; number \;\; of \;\; buses$$

Step 3: A set of n particles in the swarm is called population described as: $pop = [X_1, \; X_2, \ldots \ldots \ldots \ldots X_n]$ (15)

Step 4: pbest is the best previous position for each particle and described as:

$$pbest_i = [pb_{i1}, \; pb_{12}, \ldots \ldots \ldots \ldots pb_{id}] \qquad (16)$$

Step 5: gbest is the best position among all of particles position and described as:

$$gbest_i = [gb_1, \; gb_2, \ldots \ldots \ldots \ldots gb_d] \qquad (17)$$

Step 7: The rate of position change for each particle called particle velocity is described as:

$$V_i = [v_{i1}, v_{12}, \dots \dots \dots v_{id}] \quad (18)$$

Step 8: updating velocity: at iteration k the velocity for dimension of i- particle is updated by:

$$V_{id}^{k+1} = \omega V_{id}^{k} + c_1 r_1 (pb_{id}^{k} - x_{id}^{k}) + c_2 r_2 (gb_{id}^{k} - x_{id}^{k}) \quad (19)$$

Where $\omega$ is the inertia weight. $c_1$ and $c_2$ are the acceleration constants, and $r_1$ , $r_2$ are two random values in the range [0, 1]. The acceleration constants $(c_1 , c_2)$ control how far a particle will move in a single iteration. The inertia weight is used to control the convergence behavior of the PSO. In general the inertia weight is set according to equation (20):

$$\omega = \omega_{max} - \left(\frac{\omega_{max} - \omega_{min}}{iter_{max}}\right).iter \quad (20)$$

Step 9: updating position: The ith-particle position is updated by:

$$X_{id}^{k+1} = x_{id}^{k} + v_{id}^{k} \quad (21)$$

In optimization algorithms, parameters of the algorithm influence the performance and efficiency of the algorithm. Typically the acceleration constants are set to a value of 2 (i.e. $c1 = 2$, $c2 = 2$) (Heydari *et al.,* 2013). Small values of inertia weight ($\omega$) lead to more rapid convergence of the algorithm usually on suboptimal position, but large value may prevent divergence. Values of $\omega_{max} = 0.9, \omega_{min} = 0.4$ $and$ $iter_{max} = 20$, were chosen in this work based on trial and error method to achieve optimal convergence of the algorithm.

The flowchart of the improved method is shown in figure 4.

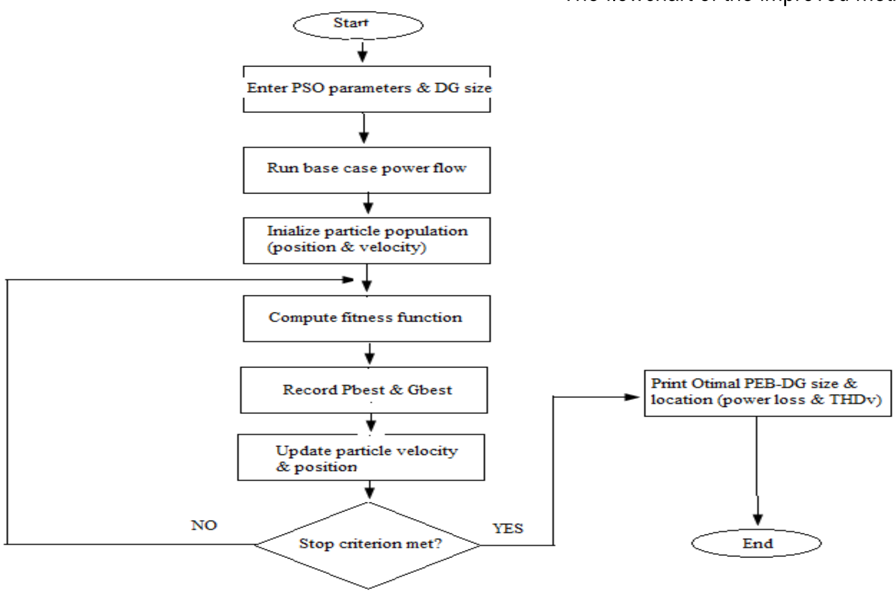


***Figure 4. Flowchart of the Improved Method for Optimal PEB-DG Allocation***

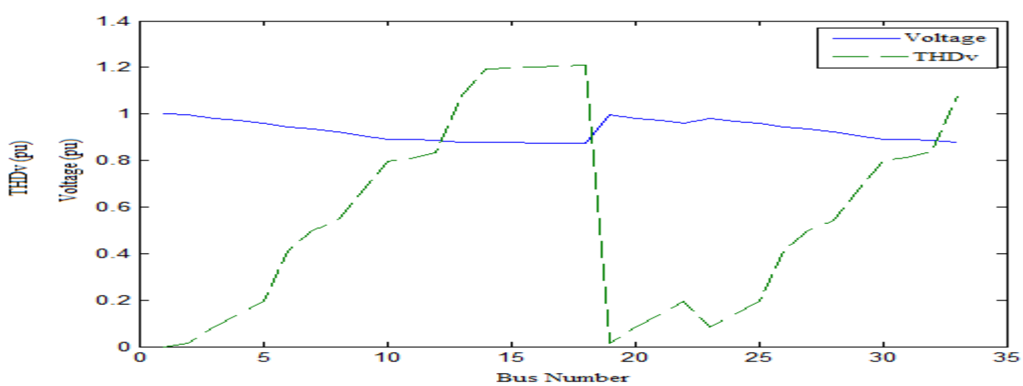


***Figure 5. Voltage and THDv Profile for the Base Case***

## 3.0 RESULTS AND DISCUSSIONS

The power flow and the harmonic power flow were run for the base case (i.e. without DG) under the platform of MATLAB R2013a, using PSAT Toolbox and the results depicted in figure 5.

From figure 5, bus 18 is observed to have the least voltage level (0.8721pu) and the highest THDv (1.2077%) in the network, because of its distance from the substation when compared with other buses in the network. In addition to bus 18 there are other buses in the network that have voltages below the acceptable limits of 0.95%, however, bus 18 is considered as the critical bus in the network for both voltage level and THDv.

The size of DG for each bus without harmonic consideration was computed using equation 10 and harmonic power flow was run to check the harmonic contribution of each DG. It was observed that bus 33 caused violation of the THDv limit of 5% if bus 18 is considered to be the critical bus. The size of each DG without harmonic consideration and the corresponding active power loss are computed and presented as in figure 6.

From the harmonic power flow the THDv of bus 33 was observed to be 5.4391% which violates the limit of 5%, this therefore disqualifies the size of bus 33 as the optimal size for the bus. The DG size of bus 33 was re-evaluated using the relationship between the DG power output for bus 33 and the corresponding THDv represented by the polynomial interpolation function given in equation 13. The function was used to estimate the PEB-DG size that satisfied the THDv limit and the result shown in figure 7.

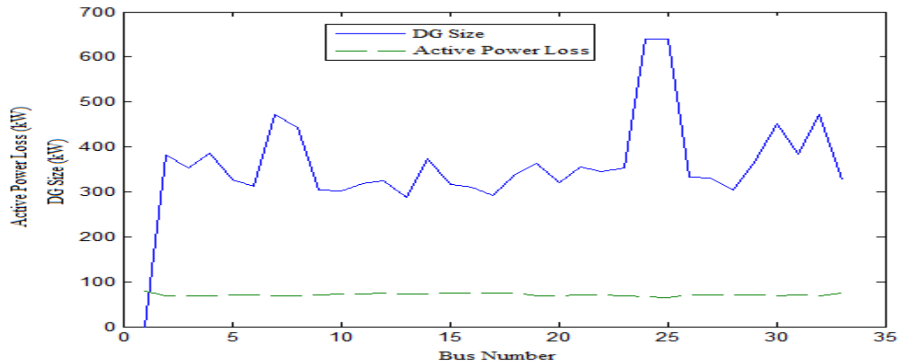


***Figure 6. PEB-DG Size and Active Power Loss without Harmonic Consideration***

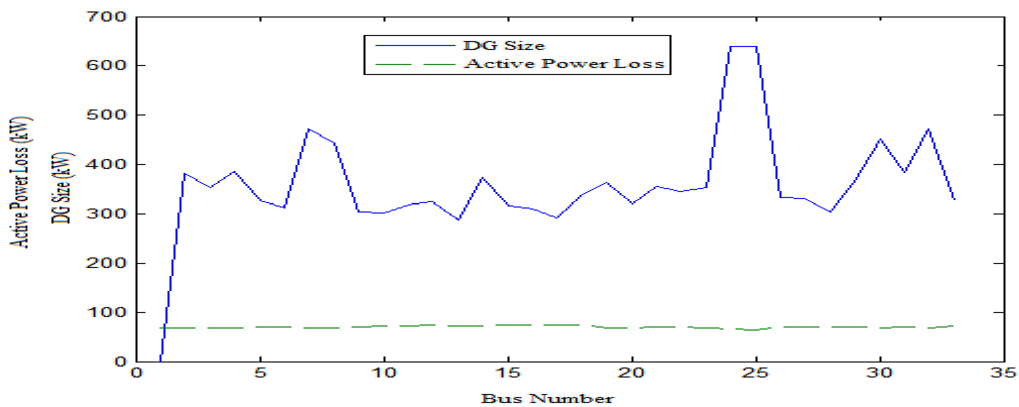


***Figure 7. PEB-DG Size and Active Power Loss with Harmonic Consideration***

**Note:** There is a difference between figures 6 and 7 in terms of the active power loss curve.

The PEB-DG sizes obtained from figure 7 are used as input parameters to the PSO algorithm to obtain the optimal size and location of the PEB-DG. The optimal size and location for the PEB-DG was found to be 639 kW and bus 25 respectively. The total active power loss after the DG allocation was found to be 639 kW.

The integration of the PEB-DG size of 639 kW at bus 25 caused significant improvement in the voltage level of the buses, as all the buses voltage are within the acceptable limit of 0.95% as shown in figure 8. At the critical bus (bus 18), the improved method records a voltage magnitude of 0.9621pu while the voltage magnitude is 0.8721pu for the base case. This indicates an improvement of 10.3% achieved by the improved method. The average voltage profile improvement in the network is 5.46%.

The THDv of the network has also improved as depicted in figure 9, despite the fact that the improved method considers a network with background harmonics and PEB-DG, the THDv value of the critical bus (bus 18) is 1.7603% which is within the acceptable IEEE THDv standard limit of 5%.

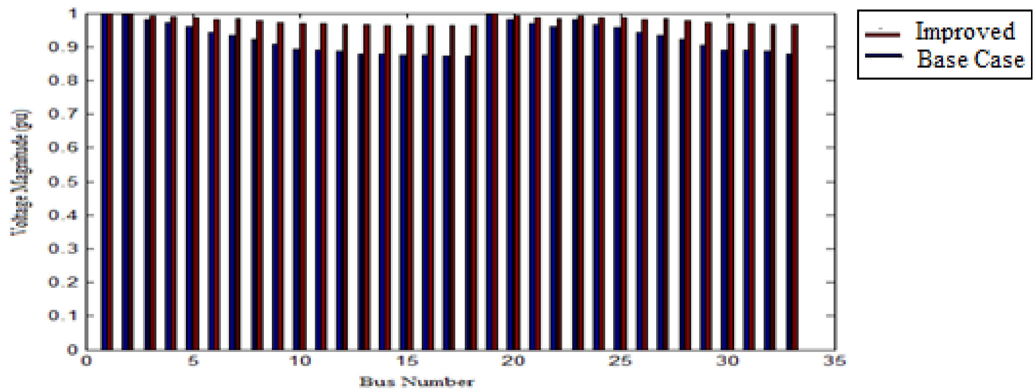


***Figure 8. Voltage Profile for the Improved Method and the Base Case***

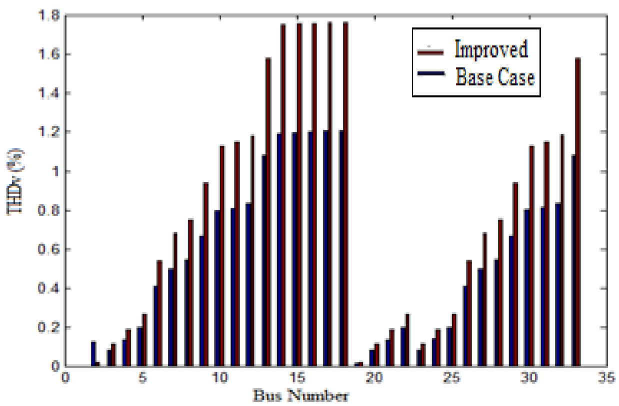


***Figure 9. THDv Profile for the Improved Method and the Base Case***

## 4.0 CONCLUSION

The paper presents an improved analytical method with PSO algorithm based technique for optimal sizing and placement of PEB-DG in IEEE 33-bus test network for total active power loss reduction with harmonic consideration. The conventional analytical method (exact loss formula) for sizing DG without harmonic consideration was developed. Power flow and harmonic power flow was employed to ascertain the harmonic contribution of each DG. A polynomial interpolation function representing the relationship of the DG size and the THDv was developed for cases where the THDv of the buses have been violated and used to estimate the appropriate DG size for those buses in the network. The PSO algorithm was employed in determining the optimal allocation for the DG.

The improved method recorded the optimal size and location for the DG to be 639kW and bus 25 respectively, with 19.1% reduction in active power loss and 5.46% improvement in average voltage profile when compared with the base case system.

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