Impact Optimal DG Placement Against Harmonic Distribution on Reconfiguration Distribution Network on Microgrid System

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Abstract. Increases in harmonic distortion in Radial Distribution System (RDS) will result in additional shorter insulation lifetime, higher temperature and also malfunction. These are undesirable as they cause power losses and also affect the voltage profile. In this paper the harmonic analysis is carried effect and performance placement Distributed Generation (DG) after reconfiguration distribution network in active radial distribution system or microgrid concept. The optimal size of DG is determining using K-Means Clustering method and Load Curtailment method to designing distribution network reconfiguration after restoration. The load flow analysis and harmonic flow analysis is carried out with direct approach using BBC and BCBV matrices. The proposed method is carried out on IEEE 33 bus system having the harmonic sources injected as current sources using MATLAB and ETAP software. The result show DG placement on 4 bus points using K-Means Clustering can improve voltage levels and reduce harmonic dispersion. After restoration and reconfiguration of the system, the harmonic spread is strongly influenced by the current flowing on the bus and the location of the source harmonics on the system.

1. Introduction
Radial distribution system is the simplest type of network that is commonly used. Along with the development of the radial distribution system which is getting bigger and wider it is certainly followed by several major problems in the form of greater power losses and deteriorating voltage profiles [1]. With increasing interest on power generation in an environmental friendly way, the development of renewable energy based distributed generation (DG) has received great attention in recent years as renewable energy resource are pollution free and abundant in nature [2].

Irrespective of the advantages of radial distribution, this system is very span to the spread of harmonics. The development of the age followed by technological developments will surely lead to the use of non-linear load such as semiconductor devices [3]. The source of harmonics produces a non-sinusoidal current which is flawed where each periodic wave is not a sinus form containing harmonics. Non-linear loads are the cause of high current harmonics on the system and can cause losses in the distribution of electrical energy and the destruction of existing equipment [4].

So, to reach to these targets, loss reduction and voltage profile improvement, together with THD reduction planning of the electric system with the presence of DG requires the definition of several factors such as, the best technology to be used, the number and the capacity of the units, the best location, the type of network connection and etc. the problem of DG allocation and sizing is of great importance. The installation of DG units at non-optimal places and with non-optimal sizing can result in an increase in system losses, damaging voltage state, voltage flicker, protection harmonic, stability and implying in an increase in costs and, therefore, having an effect opposite to the desired [5].

Reconfiguring a distribution network is one of the techniques of resetting network configuration by operating a switch tie or in other words changing the status of an open or closed switch on a distribution network [6, 7]. Different method have been developed to solve reconfiguration problem in
distribution network. Used of reconfiguration technique for service restoration and power loss reduction is proposed in [8].

The development of research on improving power quality especially harmonic distortion in radial distribution systems related to placement and sizing DG in the concept of microgrid by using various methods based on numerical methods, artificial intelligent, etc. Harmonic, power loss, and voltage deviation are main issue in power system quality. The installation of DG at non-optimal location and size can lead the increasing of power loss, power quality decline, protection coordination and power stability problems [9]. But for the side of the reliability of the system, when there is a disturbance where one of the buses in the system is required to undergo restoration, the action is carried out by the operator, configuring the network distribution system. In previous studies [8], research on the spread of harmonics on a passive radial distribution system after reconfiguration due to the restoration was influenced by the distance of the harmonic source to the swing bus. This paper will discuss the continuation of the previous research where the renewal of this paper is in the condition of active radial distribution system or microgrid. The effect of placement and sizing DG on harmonic distribution after restoration will be examined in this paper.

2. Basic Theory

2.1. Microgrid and type of distributed generation

Microgrid is a small-scale power system network. The generator ranges from 50kW-1kW using available energy sources such as microhydro, solar, wind, and others. By utilizing local renewable energy sources that are available in each region, microgrids can be used as a solution to realize energy independent areas for areas that are not affordable by electricity [10]. Different types of DGs include Synchronous generators, Photovoltaic generators and Asynchronous generators [11].

2.2. Harmonic, harmonic index and standard harmonic

In harmonic and interharmonic distortion, the alternating current voltage wave is not pure sinusoidal in other words distorted. Based on the fourier wave can be decomposed into several sinusoidal waves with a higher frequency of fundamental frequencies. In interharmonic distortion, wave distortion is formed from sinusoidal waves with a frequency of multiples of the fundamental wave frequency, with multiples in the form of fractions. Whereas in harmonic distortion, waveform distortion is formed from sinusoidal waves with frequency multiples of the fundamental frequency. Harmonic frequency equation can be written as follows [4, 12].

\[ f_h = h \times f_1 \]  \hspace{1cm} (1)

![Figure 1. Non-linear waves by adding harmonics of three fundamental frequencies [4]](image)

According to the IEEE, IHD is the ratio between the rms value of each harmonic current compared to the RMS value of the fundamental flow or the first harmonic. The first harmonic or fundamental flow is always worth 100%. Where the IHD equation is:

\[ IHD_n = \frac{I_n}{I_1} \times 100\% \]  \hspace{1cm} (2)
THD is the ratio between the rms value of all the harmonic components and the rms value of the fundamental expressed in percent (%):

$$I_H = \sqrt{I_2^2 + I_3^2 + I_4^2 + I_5^2 + I_6^2 + ...}$$

$$THD = \frac{I_H}{I_i} \times 100\%$$

The commonly used THD index is:

$$THD = \sqrt{\sum_{n=2}^{N} \frac{V_n^2}{V_i}}$$

Defining the ratio of the rms value of the harmonic component to the rms value of the base component is usually expressed in percent form. This index is used to measure the deviation of periodic waveforms containing harmonics of perfect sine waves. The value of THD is zero in the event of a perfect sine wave.

% VTHD is the percentage of total voltage distorted by harmonics to fundamental frequency and % ITHD is the percentage of total current distorted by harmonics to fundamental frequency. Standard voltage harmonics used according to IEEE Std. 519-1992.

2.3. K-means clustering

K-means Clustering is a method of grouping a group of data objects with a certain number based on the equation of a particular characteristic or attribute [1]. This method has proven to be reliable in solving several distribution system problems such as determining the optimal location of the Phasor Measuring Unit (PMU) and determining the optimal location of DG.

Grouping data objects by the K-means clustering method is done by calculating the closest distance of each data object to the center point of the cluster (centroid). In the initial stage of this method, the number of clusters is determined first based on the number of data objects. In addition, in the initial stage the centroids of each cluster are randomly selected from the available data objects. Then this method will test each data object and group it into one cluster based on the closest distance to each centroid. The value of the centroid will be updated repeatedly by calculating the average value of the data objects in each cluster. Then testing and grouping data objects into clusters with the new centroid is done again. The iteration will continue to be repeated until the value of the new centroid does not change from the previous centroid (converging)[1].

2.4. Reconfiguration system

Load Curtailment must have three conditions met for selecting the appropriate switch tie. This requirement is used to narrow down the optimal tie switch search solution and tie switch candidates will be selected in the use of this method. It aims to maximize the number of restored loads. This requirement is required with respect to the amount of load between sectionalizing switches [6].

- $I_{LC}^{avail}$ (available current) is the maximum amount of load that may be subtracted from the upstream bus to increase the current spare capacity. The reduced load is between the branch and $I_{LC}^{avail}$. It can provide power to each candidate tie switch.
- $I_M$ is the current spare capacity. Spare capacity is the capacity of the reserve flow that can meet the load requirements $I_M$ obtained from:

$$I_M = I_{rating \, cb} - I_{bus \, current}$$
The selected value is the largest candidate of the tie switches to be used,

- \( Z_{path} \)
  - \( Z_{path} \) is the impedance distance between buses. \( Z_{path} \) to increase the bus voltage by shortening the distance between buses in a way:

  \[
  Z_{path} = \frac{V_n}{\sum I_{L,k}}
  \]

  \( Z_{path} \) is the smallest or the shortest distance is to be selected among the candidate tie switches.

3. Methodology

3.1. FBS load flow analysis

The Forward-Backward Sweep (FBS) method is used for the power flow equation based on two matrices namely BIBC (Bus Injection to Branch Current) and BCBV (Branch Current to Bus Voltage). [BIBC] is the relation matrix between the injection current on the bus with the current at the branch, whereas [BCBV] is the relation matrix between the branch current and the bus voltage [13].

\[
[B] = [BIBC] \cdot [I] \\
[\Delta V] = [BCBV] \cdot [B]
\]

where [BCBV] is the relation matrix between the bus voltage and the branch current. Substituting equation (8) with (9) is obtained by:

\[
[\Delta V] = [BIBC] \cdot [BCBV] \cdot [I] \\
[\Delta V] = [DLV] \cdot [I]
\]

where [DLV] is the relation matrix between the voltage drop and the injection current on the bus.

The power flow solution is obtained by means of an iteration process so that it can be written as follows:

\[
I_i^k = \left( \frac{P_i^ch - jQ_i^ch}{V_i^k} \right)
\]

\[
[\Delta V_i^{k+1}] = [DLV] \cdot [I_i^k]
\]

\[
[V_i^{k+1}] = [V_0] - [\Delta V_i^{k+1}]
\]

The iteration process stops when the absolute difference between the previous iterated bus current injection and the current iteration bus current injection is less than or equal to the specified tolerance \( \varepsilon \).

\[
|I_i^{k+1} - I_i^k| \leq \varepsilon
\]

Total loss of power can be written

\[
P_{loss} = [R]^T \cdot [BIBC] \cdot [I]^2
\]
3.2. Main step K-means clustering

K-means clustering consists of several types such as Partition, Hierarchical, Density based, Model based, and Grid based. In this study, K-means clustering of Partition type is used. Grouping data objects by K-means clustering is done by calculating the closest distance of each data object to the center point of the cluster (centroid). Centroid will be updated every time iteration until convergent [14].

The stages of the K-means clustering algorithm in more detail:

- Determine the number of clusters according to the number of data objects according to the following equation.

\[ K_{group} \approx \sqrt{\frac{n}{2}} \]  

where: \( K_{group} \) is number of cluster; \( n \) is number of bus

- Initiate the centroid by randomly choosing between available data objects

- Calculate the distance of each data object to the centroid using the Euclidean distance equation as follows

\[ d\left(x_j, C_i\right) = \sqrt{\sum_{j=1}^{n} \sum_{i=1}^{m} (x_{ij} - C_{ij})^2} \]  

where: \( d \) is Euclidean distance; \( x_j \) is data object; \( C_i \) is centroid; \( n \) is number of data object; \( m \) is number of cluster.

- Group each data object into one cluster with the closest distance

- Update the centroid value of each cluster by calculating the average data object in each cluster

- Check the centroid value. If the new centroid changes from the previous centroid then the algorithm returns in step 3. But if the new centroid does not change from the previous centroid then the solution is considered convergent so the K-means clustering algorithm is complete

3.3. Modeling of DG

Grouping data objects using clustering techniques in the previous step produces candidate DG mounting buses on each cluster [1]. After getting the grouping results for each bus in the system, each data object will be sorted based on the average of the LSF normalization value and the voltage of each bus. The average normalization value of LSF and bus voltage is called the bus index. The bus index value will not exceed 1 and less than 0 because the data object is a normalization value on a scale (0.1).

Each bus will be grouped according to the value of its data object and the bus with the highest bus index value of each cluster will be the candidate for the DG installation location on the system [1]. Then each bus index for each cluster will be calculated on average to get the cluster index. Candidates for DG installation locations are on buses belonging to clusters that have high LSF values and low bus voltage [15]. Therefore, candidates for the DG installation location are on the bus with the highest bus index value in the cluster with the highest cluster index value. If bus A is a bus with the highest bus index value of a cluster X and cluster X is a cluster with the largest cluster index value, then bus A is determined to be a candidate for the DG location.

Active and reactive power capacity DG can be calculated using the following equation

\[ P_{DG} = \frac{P_{leff} + \alpha Q_{leff}}{1 + \alpha^2} \]  

\[ Q_{DG} = \frac{P_{leff} + \alpha Q_{leff}}{1 + \beta} \]
In the equation it is assumed that $\theta$ is the DG power factor angle that will be installed on the system. To calculate DG capacity considering optimal power factors, it can be stated to be [16]:

$$\alpha = \tan \theta = \frac{Q_{\text{eff}}}{P_{\text{eff}}}$$

(21)

$$\beta = \cot \theta = \frac{P_{\text{eff}}}{Q_{\text{eff}}}$$

(22)

with power factors obtained using the following equation:

$$PF_{\text{DG}} = \frac{P_{\text{eff}}}{\sqrt{P_{\text{eff}}^2 + Q_{\text{eff}}^2}}$$

(23)

3.4. Harmonic load flow

The backward sweep algorithm of HLF is used to obtain the matrix $[A]$ representing the relationship between the branch current and the bus injection current for the $h$ harmonic sequence. The forward sweep produces a $[HA]$ matrix representing the relationship between harmonic bus voltage and harmonic bus injection current. For more details, the harmonic power flow algorithm, RDS n-bus is shown on the single-line diagram as follows [17]:

![Figure 2. Single line diagram RDS 6-bus [13]](image)

It should be noted that the harmonic current vector of the filter contains one element ie the harmonic current absorbed by the filter on bus 4. If the number of filters connected to RDS is equal to $nl$ then the vector harmonic vector dimension of the filter is $(nl \times 1)$. Thus the vector of the $h$ harmonic bus current is:

$$[I^{(h)}] = [Bh]$$

(24)

To find the current flowing from the i-j branch the equation is used:

$$[B_{ij}^{(h)}] = [A_{ij}^{(h)}][I^{(h)}]$$

(25)
\[
\begin{bmatrix}
A_{ij}^{(h)}
\end{bmatrix} =
\begin{bmatrix}
\cdot \\
\cdot \\
\cdot \\
A_{ij}^{(h)}
\end{bmatrix}
\tag{26}
\]

Total loss of power can be written with vector form as follows:

\[
P_{loss}(h) = \left[ R(h) \right]^T \left[ A(h) \right] \left[ I(h) \right]^T
\tag{27}
\]

The voltage values of rms bus \( i (V_{rms_i}) \) and THD can be calculated as follows:

\[
V_{rms_i} = \sqrt{|V_i^{(1)}|^2 + \sum_{h=2}^{h_{max}} |V_i^{(h)}|^2}
\tag{28}
\]

Total Harmonic Distortion (THD) can be calculated as follows:

\[
THD_i (\%) = \frac{\sqrt{\sum_{h=2}^{h_{max}} |V_i^{(1)}|^2}}{|V_i^{(1)}|^2}
\tag{29}
\]

3.5. Main step load curtailment

Main step from load curtailment algorithm:

- Determine candidate tie switch (TS) and sectionalizing switch (SS).
- Determine candidate load bus to be restored.
- Select and operate one TS candidate and implement the load curtailment algorithm in an out-of-service restoration area.
- Select and operate the TS and SS that have been chosen and implemented load curtailment algorithm.
- Determine load with priority scale to be restored by load curtailment and open SS.
- Run load flow distribution system

3.6. Constraints

The constraints are defined in terms of bus voltage limit and the total harmonic distortion limit. Bus voltage limit: The magnitude of bus voltages should be within limit defined as:

\[
V_{\min} \leq |V_i| \leq V_{\max}
\tag{30}
\]

\( V_{\min} \) and \( V_{\max} \) is the lower and upper limit of bus voltage, \( V_i \) is the \( rms \) value of \( ith \) bus voltage

\[
|V_i| = \sqrt{|V_i|^2 + \sum_{h=2}^{h_{max}} |V_i^{(h)}|^2} \quad I = 2, 3, \ldots n
\tag{31}
\]

Total harmonics Distortion Limit: The THD of the system should be less than equal to maximum allowable limit

\[
THD_i (\%) \leq THD_{\max}
\tag{32}
\]
The maximum allowable limit for THD is 5% [18].

3.7. IEEE 33 bus and study case
In this research, the system to be tested IEEE 33 Bus Radial Distribution System consisting of 32 SS (normally close) and 5 TS (normally open).

In this research, we give harmonic source on bus 4, 21 and 29 which then in select some bus for restoration there are bus 6, 19 and 26 and placement 4 unit DG in system. In general, the flowchart of this study can be seen in the flowchart below:

![Flowchart of research](image)

4. Result and Discussion
The system IEEE 33-bus radial distribution system with 32 bus sectional switching and 5 tie switch. The base power and the base voltage taken for system are 100 MVA and 12.6 kV. Total load in terms of active power and reactive power connected is 3.72 MW and 2.30 MWAR. The total active power loss is 210 kW. After injecting harmonic source on bus 4, 21 and 29, the system will generate harmonics on the order 11, 13, 23, 25, 35, 37, 47 and 49. The result of DG placement optimization with K-Means Clustering Method can be seen in Table 1 and Figures 5 and 6.
Table 1. DG placement optimization results using K-Means Clustering

| Priority | DG in Bus | Group Cluster bus | P (kW) | Q (kVAR) | PF |
|----------|-----------|-------------------|--------|----------|----|
| 1        | 6         | 3, 6              | 2107   | 1522     | 0.810 |
| 2        | 13        | 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 26, 27, 28, 29, 30, 31, 32, 33 | 451.7  | 206.9     | 0.909 |
| 3        | 5         | 4, 5, 23, 24, 25  | 2205   | 1585     | 0.813 |
| 4        | 20        | 1, 2, 19, 20, 21, 22 | 270.1  | 120.2    | 0.913 |
|          |           |                   |        |          | 74.4 |

Losses Power (kW)

In Table 2 DG placement optimization results using K-Means Clustering with a total active power capacity of 5033.7 kW. The optimization results produce 4 clusters with a priority scale. Each cluster is placed in a DG on one of the buses that can cover the other buses in each cluster. In addition there is a decrease in losses of 135.6 kW or 64.57%.

![Comparison Voltage Bus Before and After Placement DG](image1)

**Figure 5.** Comparison voltage bus before and after placement DG

In Figure 5 Placement of 4 DG units on buses 5, 6, 13 and 20 results in improved voltage levels at all bus points. It was also seen that there were several bus points under voltage conditions that could be repaired so that all bus points were in normal conditions. In this case the biggest voltage deviation was located on bus 18 at 7.69%.

![Comparison % THD Before and After Placement DG](image2)

**Figure 6.** Comparison % THD before and after placement DG

In Figure 6, the % THD value is decrease in all bus points. This is due to the DG placement affecting the spread of harmonics which has an effect on the decline of fundamental currents in the system.
Table 2. Comparison voltage bus, % THD, active tie and losses before and after reconfiguration

| Bus | NORMAL CONDITION AFTER DG PLACEMENT | RESTORATION BUS 6 | RESTORATION BUS 19 | RESTORATION BUS 26 |
|-----|-----------------------------------|------------------|-------------------|------------------|
|     | %THD V (kV) | %THD V (kV) | %THD V (kV) | %THD V (kV) |
| 1   | 0 12.600 0.00 12.600 0.00 12.600 0.00 12.600 0.00 |
| 2   | 0.04 12.681 0.05 12.470 0.02 12.480 0.02 12.554 0.02 |
| 3   | 0.1 12.614 0.12 12.403 0.10 12.417 0.10 12.548 0.10 |
| 4   | 0.15 12.610 0.14 12.396 0.14 12.409 0.13 12.581 0.13 |
| 5   | 0.17 12.606 0.14 12.394 0.16 12.404 0.13 12.621 0.13 |
| 6   | 0.3 12.447 0.00 0.000 0.27 12.404 0.10 12.737 0.10 |
| 7   | 0.29 12.408 0.23 12.586 0.27 12.376 0.09 12.710 0.09 |
| 8   | 0.29 12.368 0.23 12.577 0.28 12.341 0.10 12.678 0.10 |
| 9   | 0.28 12.317 0.23 12.593 0.27 12.316 0.10 12.646 0.10 |
| 10  | 0.27 12.278 0.23 12.599 0.27 12.297 0.10 12.620 0.10 |
| 11  | 0.27 12.265 0.23 12.598 0.27 12.295 0.10 12.617 0.10 |
| 12  | 0.27 12.255 0.23 12.414 0.27 12.293 0.10 12.612 0.10 |
| 13  | 0.26 12.227 0.22 12.600 0.26 12.293 0.10 12.602 0.10 |
| 14  | 0.26 12.193 0.22 12.573 0.26 12.266 0.10 12.570 0.10 |
| 15  | 0.26 12.178 0.22 12.557 0.26 12.249 0.10 12.549 0.10 |
| 16  | 0.26 12.157 0.22 12.541 0.26 12.232 0.10 12.527 0.10 |
| 17  | 0.26 12.134 0.22 12.517 0.26 12.208 0.10 12.492 0.10 |
| 18  | 0.26 12.127 0.22 12.510 0.26 12.200 0.10 12.479 0.10 |
| 19  | 0.05 12.689 0.06 12.467 0.00 0.000 0.05 12.552 0.05 |
| 20  | 0.23 12.740 0.21 12.456 0.84 12.608 0.22 12.552 0.22 |
| 21  | 0.3 12.731 0.27 12.443 0.86 12.320 0.30 12.543 0.30 |
| 22  | 0.3 12.725 0.25 12.429 0.86 12.592 0.30 12.535 0.30 |
| 23  | 0.1 12.464 0.32 12.352 0.09 12.372 0.31 12.503 0.31 |
| 24  | 0.1 12.387 0.49 12.254 0.09 12.288 0.48 12.420 0.48 |
| 25  | 0.1 12.345 0.65 12.199 0.09 12.245 0.66 12.378 0.66 |
| 26  | 0.32 12.428 1.11 12.600 0.30 12.380 0.00 12.000 0.00 |
| 27  | 0.36 12.394 1.11 12.572 0.33 12.349 1.09 12.593 1.09 |
| 28  | 0.6 12.244 1.11 12.451 0.57 12.209 1.09 12.595 1.09 |
| 29  | 0.79 12.142 1.11 12.191 0.75 12.108 1.09 12.593 1.09 |
| 30  | 0.79 12.092 1.11 12.321 0.75 12.064 1.09 12.538 1.09 |
| 31  | 0.79 12.049 1.11 12.271 0.75 12.014 1.09 12.594 1.09 |
| 32  | 0.79 12.038 1.11 12.260 0.75 12.002 1.09 12.590 1.09 |
| 33  | 0.79 12.031 1.11 12.257 0.75 11.999 1.09 12.463 1.09 |

As seen in Table 2, the % THD and voltage values of buses 6, 19 and 26 are zero (in yellow highlighted cell). This is because the bus is in a condition of inactivity due to restoration action on the bus after reconfiguration using load curtailment. Reduced losses after reconfiguration is caused by the effect of restoration or release of load on the system so that the power supplied by the swing bus decreases.
The result shows that load curtailment is able to determine the correct tie switch and closed and open CB in IEEE 33-bus Radial distribution system after placement DG with K-Means Clustering Method where all voltage bus can still keep the voltage value according to standard allowed. The voltage level change after reconfiguration and varies with a minimum voltage deviation value compare the previous research [8]. In figure 6, the existence of DG placement is able to improve the voltage level in all buses on the system despite the restoration that occurs on one bus. The voltage level for each bus as a whole is close to 1 pu.

![Comparison Voltage Bus Before and After Reconfiguration](image1)

**Figure 7.** Comparison voltage bus before and after reconfiguration.

As seen in Figure 7, the % THD value varies after reconfiguration. There is a reduction of % THD on buses that are placed DG as well as buses that are around the swing bus but different from other load buses. The occurrence of an increase in the value of % THD at some load bus points around the harmonic source due to the greater current flowing on the load bus and the greater impedance value due to the distance to the swing bus or PV bus getting farther away.

![Comparison % THD Before and After Reconfiguration](image2)

**Figure 8.** Comparison % THD before and after reconfiguration

5. **Conclusion**

DG placement is a hot issue about developing power quality on radial distribution systems. The use of K-Means Clustering is considered to be able to improve the voltage level and reduce the harmonic spread in the Radial Distribution System. The reconfiguration action due to the restoration of one of the buses affects the DG that has been placed. The Load Curtailment method can determine
the status of the tie switch that will be used. Maintain voltage levels on permitted conditions and decrease power losses due to DG placement after reconfiguration but not with harmonic spreads. Harmonic injection is the source of a given bus and the amount of current flowing on the bus.

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