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Harmonic Analysis in Distribution System Planning

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Abstract: ***This thesis describes evaluating size of distribution generators in distribution systems so that voltage harmonic distortions at all the buses in a system are within IEEE 519 limits. The proposed methods are developed for two types of evaluation. One for planning stage and other for the existing distribution feeder. In the first type, typical load patterns are considered for the evaluation of DG size and in the second type, network structures of distribution systems, equivalent current injection* formulation *and the forward/backward sweep based harmonic load flow are used for evaluating the DG Size. Results show that, capacity of distribution generators will be more when they are connected near the substation. Distortion in voltage increases as the distance of DG from substation increases. Obtained results are validated with MATLAB and MiPOWER results.***

Keywords: Distributed Generator (DG), Total Harmonic Distortion (THD), Harmonic Limits, Backward/Forward Sweep

1. Introduction

Earlier days, there was only a centralized generation and from there power flowed downwards to loads. Hence, the distribution circuits were designed to operate without any generators along the feeder. But this scenario has changed now. As customers are more energy and environmental conscious, many distributed generators (DG) like photovoltaic generators, are getting connected in the radial distribution feeders. The inverters which are used in the distributed generators are the sources of harmonics as they are made up of nonlinear electronic devices such as diodes. Harmonic injection in a distribution feeder is limited by the standard IEEE 519. Hence they cannot be connected as per the individual wish.

In this paper, techniques for predicting allowable distribution generation size for a distribution feeder to keep individual and total harmonic voltage distortions within IEEE 519 limits are developed. The methods are discussed for two scenarios. One for the planning stage of evaluation and other for the existing feeder evaluation. Obtained results are checked with MAT LAB and MiPOWER results for validation.

2. Typical DG penetration pattern across feeder considering harmonic distortion limits

The approach is based on a balanced 3-phase, 4-wire radial distribution feeder. Individual linear load models are not considered. For a harmonic modeling, a DG can be treated as a nonlinear load injecting harmonics into the distribution feeder. Because feeder optimization capacitor size and location are difficult to generalize (for planning purposes), capacitor effects on harmonic voltages along the feeder are not included.

2.1 Method Proposed

The method formulated here is for generic feeder designs and typical load allocation patterns. Equations to calculate the voltage distortion levels in the presence of harmonics are given in this section for typical load allocation patterns viz. uniformly distributed, uniformly increasing and uniformly decreasing. These equations have been used in evaluating the voltage drop and allowable substation current in the presence of harmonics.

(i) Uniformly Distributed Generation

If the generation is uniform along the feeder length, i.e. if equal capacity DG's are connected along the feeder at equal intervals, such feeders are named as uniformly distributed generation feeders. Fig.1 shows a radial feeder with uniformly distributed generation.

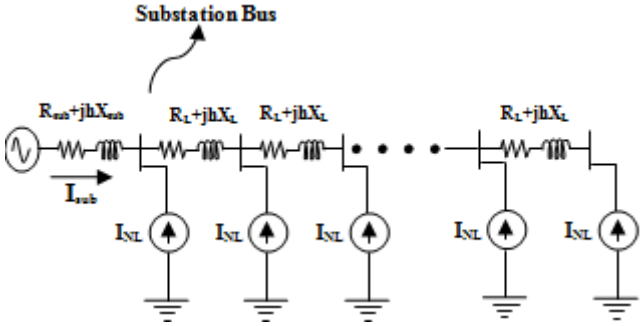

Figure 1: Uniformly distributed generation (single phase)

Harmonic voltage drop at the feeder due to the harmonic line current is,

$$V_{dist_h} = I_{sub_h} Z_{sub_h} + \left(0.5 \times Z_{line_h} \times l \times I_{sub_h}\right) \quad (1)$$

Where, V_{dist_h}, Z_{sub_h} & Z_{line_h} voltage distortion, substation impedance and line impedance in the presence of harmonics respectively. I_{sub_h} is the total allowable harmonic current at the substation.

Allowable harmonic current at the substation is given by,

$$I_{sub_h} = \frac{V_{dist_h}}{\{Z_{sub_h} + (0.5 \times Z_{line_h} \times l)\}} \quad (2)$$

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This equation gives the total allowable substation harmonic current for uniform generation case.

(ii) Linearly Increasing Generation

This is the more realistic generation. The PV penetration increases linearly as the distance increases from the substation bus. Below fig.2 shows the linearly increasing generation pattern.

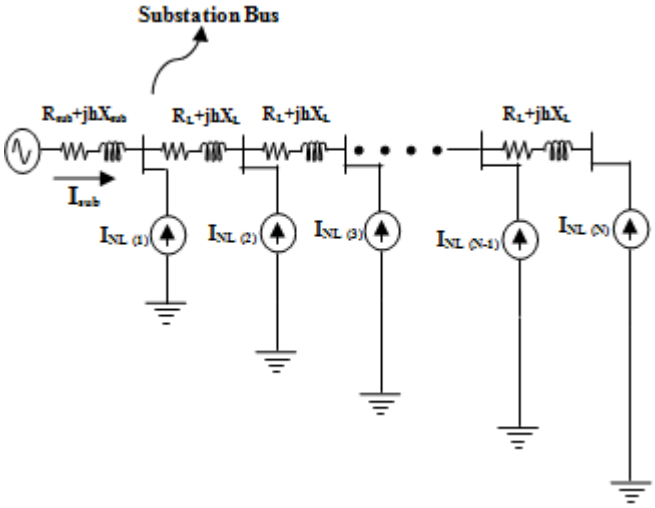

Figure 2: Linearly increasing generation (single phase)

Harmonic voltage drop at the feeder due to this harmonic line current is,

$$V_{dist_h} = I_{sub_h} Z_{sub_h} + 0.67\, Z_{line_h} \times L \times I_{sub_h} \quad (3)$$

Allowable harmonic current at the substation is given by,

$$I_{sub_h} = \frac{V_{dist_h}}{\left(Z_{sub_h} + 0.6667 Z_{line_h} L\right)} \quad (4)$$

This equation gives the total allowable substation harmonic current for uniformly increasing generation case.

(iii) Linearly Decreasing Generation

In this case the load decreases linearly as the distance increases from the substation bus as shown in fig. 3

Harmonic voltage drop at the farther end of the feeder due to this harmonic line current is,

$$V_{dist_h} = I_{sub_h} Z_{sub_h} + \int_0^L \left\{Z_{line_h} I_{line_h}(x)\right\} dx \quad (5)$$

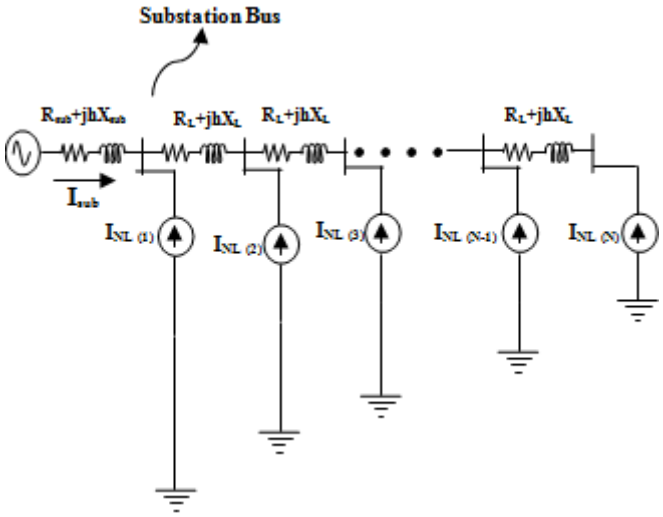

Figure 3: Linearly increasing generation (single phase)

Allowable harmonic current at the substation is given by,

$$I_{sub_h} = \frac{V_{dist_h}}{\left(Z_{sub_h} + 0.3333 Z_{line_h} L\right)} \quad (6)$$

This equation gives the total allowable substation harmonic current for uniformly decreasing generation case.

Using expressions developed above, allowable substation harmonic current I_{sub_h} at different harmonic frequencies is calculated for all three types of generation. But it is observed that, obtained I_{sub_h} meets only individual voltage harmonic distortion limit of 3% of the fundamental not the THD limit of 5%.

In order to consider for this v_{thd}, with the objective of maximizing it and to limit this to below 5% of the nominal voltage, a set of equality and inequality constraint equations are written as shown below.

Objective Function

$$v_{thd} = \frac{\sqrt{\sum_{h=2}^{n} v_h^2}}{V_1} \times 100\% \quad (7)$$

Where, v_{thd} is the voltage total harmonic distortion, h is harmonic number, n is highest order harmonic and v_1 is fundamental voltage.

Equality constraints:

$$v_h = z_h i_h \quad (8)$$

Where, v_h, z_h and i_h are h^{th} order harmonic voltage drop, impedance and current respectively.

Inequality constraints:

$$v_h \leq 3\%\ of\ fundamental \quad (9)$$

$$v_{thd} \leq 5\%\ of fundamental \quad (10)$$

It is known that, a distributed generation resource like PV panel injects harmonic currents in some percentage of fundamental current. For example,

$$i_{h_1} = p\%\ of\ i_1 \quad (11)$$

$$i_{h_2} = q\%\ of\ i_1 \quad (12)$$

$$i_{h_3} = r\%\ of\ i_1 \quad (13)$$

Where, $i_{h_1} i_{h_2}$ & i_{h_3} are first, second and third harmonic currents respectively.

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From equations (11) and (12) we can write,

$$\frac{i_{h_2}}{i_{h_1}} = \frac{q\%\ of\ i_1}{p\%\ of i_1} \quad (14)$$

Equation (14) implies,

$$i_{h_2} = \alpha_1\ i_{h_1} \quad (15)$$

From equations (11) and (13) we can write,

$$\frac{i_{h_3}}{i_{h_1}} = \frac{r\%\ of\ i_1}{p\%\ of i_1} \quad (16)$$

Equation (16) implies,

$$i_{h_3} = \alpha_2\ i_{h_1} \quad (17)$$

In general,

$$i_{h_N} = \alpha\ i_{h_1} \quad (18)$$

Then we have four unknowns (i_{h_1} i_{h_2} $i_{h_3}$and i_1) three equations. (11, 15 &17)

To solve for these equations, a code in MAT LAB is written for nonlinear programming problem. Simulation results gives value of common variable i_{h_1}.This is used to solve equation (11) to find i_1. Then DG size can be calculated using eqn.

$$P = \sqrt{3}VI \quad (19)$$

This is the approach which is followed, for evaluating the allowable sizing of a DG for a distribution feeder keeping voltage distortions within set limit of IEEE 519. It is applied to a 12.47kV distribution feeder and explained under test case.

2.2 Test Case & Results

A 12.47-kV radial distribution feeder of length 2 miles with the configuration as shown in table 1 is selected for the evaluation. Sequence impedance of line and substation are as per table 2 and 3.

Table 1: Feeder Configuration

Feeder	*Phase & Neutral Conductor*	*Feeder Capacity in A*
Feeder1	4/0 ACSR	100

Table 2: Line Sequence Impedance in ohm/mile

Impedance	*Feeder-1*
Zline(+)	0.592+j0.816
Zline(0)	0.893+j2.211

Table 3: Substation Sequence Impedance in ohm

Impedance	*Feeder-1*
Zsub(+)	0.754+j3.017
Zsub(0)	0.226+j0.905

From the equations discussed above, the calculated values I_{sub_h} are shown in table 4 for fifth, sixth, ninth and eleventh harmonics.

Table 4: Calculated I_{sub_h} for fifth, seventh, ninth and eleventh harmonics for feeder 1 of length 2 miles

Harmonic Order	I_{sub_h} *in (A) for different load patterns*		
	Uniform	*Increasing*	*Decreasing*
5	11.2422	10.4933	12.1057
7	8.0398	7.5056	8.6557
9	7.6956	6.2231	10.0809
11	5.1201	4.7804	5.5117

Since, while calculating I_{sub_h}, individual harmonic voltage distortion limit was set to 3%, obviously this limit is met. But total harmonic distortion crosses the limit of 5% as shown in equation (20).

$$v_{thd} = \frac{\sqrt{(216^2 + 216^2 + 216^2 + 216^2)}}{7199.56} \times 100 = 6\% \quad (20)$$

MAT lab results which meet THD are shown in the table 3.5.

Table 5: Simulated I_{sub_h} for fifth, seventh, ninth and eleventh harmonics for feeder 1 of length 2 miles.

Harmonic Order	***I_{sub_h} in (A) for typical generation patterns***		
	Uniform	***Increasing***	***Decreasing***
5	10.6700	9.9629	11.4912
7	8.0025	7.4722	8.6184
9	5.3350	4.9815	5.7456
11	2.6675	2.4907	2.8728

Individual and total harmonic distortion voltages obtained using simulations are shown below.

Table 6: Simulated V_{ind} for fifth, seventh, ninth and eleventh harmonics for feeder 1 of length 2 miles

Harmonic Order	V_{ind} *in (V) for typical generation patterns*		
	Uniform	*Increasing*	*Decreasing*
5	204.99	205.07	205.02
7	214.99	215.03	215.06
9	149.73	172.89	123.10
11	112.53	112.54	112.58
V_{thd}	351.17 (4.88%)	361.73 (5.02%)	340.75 (4.73%)

Size of DG for different cases, which meets the standard voltage distortion limits, is shown in table.

Table 7: Size of the DG in KW for different penetration patterns

Uniform	*Increasing*	*Decreasing*
1152.26	1075.90	1240.94

3. DG Sizing using Backward/Forward Sweep Harmonic Power Flow Method

The proposed method employs the equival**e**nt current injection transformation and the forward/backward sweep techniques to solve the harmonic load flow problem.

Equivalent current injection

For bus i, the specified complex power s_i is,

$$S_i = (P_i + jQ_i) \quad (21)$$

Where, i=1….N

And the equivalent current injection I_i^k at the k^{th} iteration is,

$$I_i^k = \left(\frac{P_i + jQ_i}{V_i^k}\right)^* \quad (22)$$

V_i^k is the voltage of bus i at the k^{th} iteration.

Backward Current Sweep

Fig. 4 shows parts of a distribution system and the harmonic currents.

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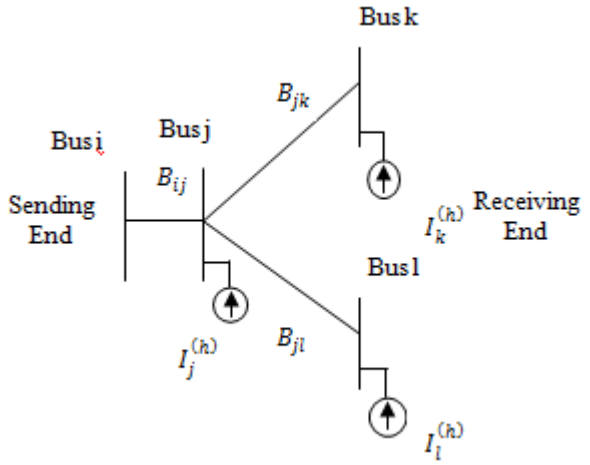

Figure 4: Parts of a Distribution System

Harmonic currents are expressed as I_j^h, I_k^h & I_l^h and B_{ij}, B_{jk} & B_{jl} are the branch currents, respectively. The relationships between branch currents and harmonic currents of Fig. 4 are,

$$B_{jk}^{(h)} = -I_k^{(h)} \quad (23)$$

$$B_{jl}^{(h)} = -I_l^{(h)} \quad (24)$$

$$B_{ij}^{(h)} = B_{jk}^{(h)} + B_{jl}^{(h)} - I_j^{(h)} \quad (25)$$

The general form can be expressed as:

$$B_{ij}^{(k)} = -I_j^{(k)} + \sum_{l \in \Omega_j} B_{jl}^k \quad (26)$$

Where I_j^k is the injection current of bus j at the k^{th} iteration and Ω_j is the set of branches connected to the bus j. Injection currents can be transformed by (22) for the fundamental load flow, and they are the harmonic currents for the harmonic load flow analysis.

Forward Voltage Sweep

From Fig. 4, if the voltage of bus i is calculated, then the relationship between branch currents and bus voltages can be expressed as,

$$V_j^{(h)} = V_i^{(h)} - B_{ij}^{(h)} * Z_{ij}^{(h)} \quad (27)$$

$$V_k^{(h)} = V_j^{(h)} - B_{jk}^{(h)} * Z_{jk}^{(h)} \quad (28)$$

$$V_l^{(h)} = V_j^{(h)} - B_{jl}^{(h)} * Z_{jl}^{(h)} \quad (29)$$

Where, $Z^{(h)}$ is the equivalent impedance of line section for the h^{th} harmonic order.

In general between bus i & j,

$$V_j^k = V_i^k - Z_{ij} * B_{ij}^k \quad (30)$$

Where Z_{ij} and B_{ij}^k are branch impedance and currents from bus i to bus j for the fundamental load flow analysis, respectively and are harmonic impedance and harmonic branch current for the harmonic load flow analysis. Fundamental load flow solution can be obtained by solving equation (22), (26), and (30) iteratively. Since the harmonic currents don't need to be transformed, the harmonic currents, branch currents and bus voltages can be solved by (26) and (30) directly. Component models are the only adjustable parts for each harmonic order in the harmonic load flow.

Calculating optimum current injection by DG

For the analysis purpose, three different locations in the distribution system viz. near substation, mid of trailing end & substation, and trailing end are considered. For each case the optimum current of the DG is calculated by writing a set of equality and inequality constraint equations and solving using nonlinear programming problem of MATLAB. Related equations will be as same as explained in previous section-2.

3.1 Test Case & Results

A 4.16kV, 11Bus three phase balanced radial distribution system as shown below is considered for the analysis.

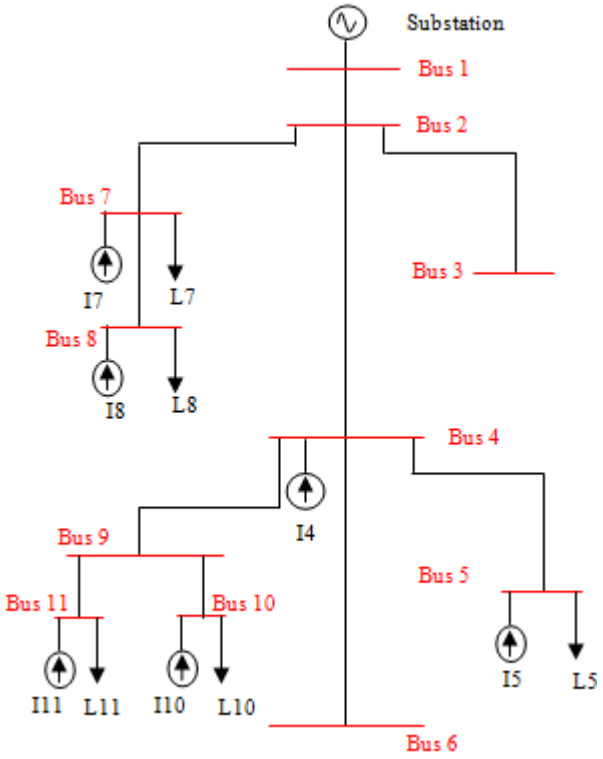

Figure 5: Three Phase, 11Bus, Balanced Distribution System

The substation sequence impedance, line impedance and load data are given in Table 8 and 9.

Table 8: Substation and line sequence impedance data

Impedance (Z)	*Zero Sequence*	*Positive Sequence*	*Negative sequence*
Line(Ω/km)	0.8768+0.289i	0.3029+0.258i	0.3029+0.258i
Substation(Ω)	0.226+0.905i	0.754+3.017i	0.754+3.017i

Table 9: Load data

Bus No.	*Real Power P in KW*	*Reactive Power Q in KVAR*
4	385	220
5	281	154
7	56.67	41.67
8	76.67	44
10	42.67	28.67
11	56.67	26.67

Load flow at fundamental frequency using forward/backward sweep and current injection techniques give the voltages at different buses of the system as tabulated in Table 10.

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Table 10: Voltage at buses from fundamental load flow

Bus No.	*Voltage in kV*	*Bus No.*	*Voltage in kV*
1	2.4017	7	2.3981
2	2.3985	8	2.3978
3	2.3985	9	2.3954
4	2.3956	10	2.3953
5	2.3944	11	2.3952
6	2.3956		

After the fundamental load flow, three different layers of DG connections are considered to check for the effect of distance of DG from the substation on the sizing and the harmonic impact on buses. The three cases are,

(i) Near substation.
(ii) At middle of substation and trailing end.
(iii) At the trailing end

For each case, size of the DG, individual and total harmonic distortion voltages at different buses are calculated and tabulated. The obtained results are compared with MiPOWER results for the correctness.

Case (i): DG's connected near substation.

In this case, injection is considered only at the buses (7&4) which are nearer to the substation.

MAT lab code gives optimum current as 10.06A. Using this current, voltage distortion limits for different harmonic frequencies and total voltage distortion limit at the buses are calculated. The calculated values at selected buses are tabulated below.

Table 11: Test Results – Case (i)

Bus No.	*Bus Voltage at different harmonic numbers in V*					THD (%)
	Fund.	*5th*	*7th*	*9th*	*11th*	
4	2395.614	68.759	72.050	24.695	37.692	4.563
2	2398.557	66.094	69.287	21.927	36.257	4.366
1	2401.777	60.763	63.762	16.390	33.386	3.981

MiPOWER simulation results are shown in table 12.

Table 12: Mi Power Results – Case (i)

Bus No.	*Bus Voltage at different harmonic numbers in V*					THD (%)
	Fund.	*5th*	*7th*	*9th*	*11th*	
4	2401.777	68.570	72.016	24.420	37.753	4.544
2	2401.777	65.959	69.280	21.722	36.321	4.355
1	2401.777	60.753	63.816	16.398	33.458	3.983

It is observed from above two tables that, MiPOWER results validate the proposed method results. Hence the optimum current of 10.06A obtained, is used to evaluate the DG size using the power equation $P = \sqrt{3}VI$. Since the voltage rating of the test feeder is 4.16kV, $P = 1.732 \times 4160 \times 10.06 = 72.47KW$

Case (ii): At the mid of substation and trailing end.

In this case, injection is considered only at the buses (5&8) which are at the middle of substation and trailing end. MAT lab code written for finding the optimum current that can be injected by DG's gives current as 9.69A. Individual and total harmonic distortion voltages at various buses calculated using this current at selected buses are tabulated in table 13.

Table 13: Test Results – Case (ii)

Bus No.	*Bus Voltage at different harmonic frequencies in V*					*THD (%)*
	Fund.	*5th*	*7th*	*9th*	*11th*	
8	2397.866	68.797	72.060	26.453	37.688	4.577
7	2398.180	66.229	69.399	23.786	36.306	4.391
2	2398.557	63.662	66.738	21.120	34.823	4.205
1	2401.848	58.527	61.416	15.787	32.158	3.834

MiPOWER simulation results are shown in table 14. Calculated DG Size is 69.8KW.

Table 14: Mi Power Results – Case (ii)

Bus No.	*Bus Voltage at different harmonic frequencies in V*					*THD (%)*
	Fund.	*5th*	*7th*	*9th*	*11th*	
8	2401.848	68.563	71.999	26.132	37.740	4.559
7	2401.848	66.046	69.365	23.521	36.363	4.376
2	2401.848	63.533	66.731	20.923	34.985	4.195
1	2401.848	58.518	61.469	15.795	32.228	3.836

Case (iii): At the trailing end.

In this case, injection is considered only at the buses (10& 11) which are at the trailing end of the system. MAT lab code gives optimum current as 8.72A. Individual and total harmonic distortion voltages at various buses calculated using this current at selected buses are tabulated in table 15.

Table 15: Test Results – Case (iii)

Bus No.	*Bus Voltage at different harmonic frequencies in V*					*THD (%)*
	Fund.	*5th*	*9th*	*11th*	*13th*	
10	2395.33	68.86	72.05	31.01	37.66	4.63
9	2395.47	66.55	69.66	28.61	36.41	4.46
4	2395.61	61.93	64.87	23.81	33.92	4.12
2	2398.55	57.31	60.08	19.01	31.43	3.78
1	2401.84	52.68	55.28	14.21	28.95	3.45

MiPOWER simulation results are shown in table 16. Calculated DG Size is 62.84KW.

Table 16: Mi Power Results – Case (iii)

Bus No.	*Bus Voltage at different harmonic freq. in V*					*THD (%)*
	Fund.	*5th*	*9th*	*11th*	*13th*	
10	2401.848	68.544	71.953	30.627	37.706	4.605
9	2401.848	66.269	69.576	28.255	36.464	4.438
4	2401.848	61.726	64.825	23.527	33.982	4.105
2	2401.848	57.197	60.080	18.836	31.499	3.777
1	2401.848	52.682	55.343	14.219	29.017	3.454

Table 17: DG Size for three cases

Location	*DG Size in KW*
Near substation	72.47
Mid of the system	69.80
Trailing end	62.84

From the above table it is observed that the size of DG is more for first case.

4. Results & Discussion

Approach explained in section two will allow utilities to predict, in the general planning stages where little specific data is known, the maximum allowable distributed resources that can be installed, thus by delivering a quality power to the customers with less distortion in the supply voltage. It is observed that, for a linearly decreasing case the size of DG obtained is more compared to other two cases. This implies

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that more capacity DG can be connected near substation. Method explained in section three can be used to analyze the distribution feeder which has already been laid and loads at each bus are known. In order to reduce the voltage distortion in the feeder, this analysis can be done and excess DG's connected can be removed. It is observed that, the size of the DG will be more when they are connected near to the substation and distortion increases with the increase in the distance of bus from the substation. The equations have been developed according to acceptable harmonic analysis assumptions wherever possible.

References

[1] Arijit Bhowmik and Arindam Maitra, "Determination of Allowable Penetration Levels of Distributed Generation Resources Based on Harmonic Limit Considerations" IEEE transactions on power delivery, Vol. 18, No. 2, April 2003.
[2] Jen-Hao Teng and Chuo Yean Chang, "Backward/Forward Sweep-Based Harmonic Analysis Method for Distribution Systems", IEEE transactions on power delivery, Vol. 22, No. 3, July 2007.
[3] Carol S. Cheng and Dariush Shlrmohammadi "A three-phase power flow method for real-time distribution system analysis" IEEE Transactions on Power Systems, Vol. 10, No. 2, May 1995.
[4] Jen-Hao Teng, IEEE Member and Chuo-Yean Chang, Department of Electrical Engineering, I-Shou University, Kaohsiung, Taiwan, R. 0. C. "A Fast Harmonic Load Flow Method for Industrial Distribution Systems" 0-7803-6338-8/00/$10.00©2000 IEEE.
[5] "Modeling and Simulation of the Propagation of Harmonics in Electric Power Network Part I: Concepts, Models and Simulation Techniques," Task Force on Harmonics Modeling and Simulation, IEEE Trans. on PWRD, Vol. 11, No. 1, Jan. 1996, pp. 452- 465.
[6] Gonen and Turan, "Electric Power Distribution System Engineering", New York: McGraw-Hill, 1986.
[7] Wakileh George J, "Power Systems Harmonics: Fundamentals, Analysis and Filter Design", New York: Springer, 2001.
[8] Roger C. Dugan, "Electrical Power Systems Quality" New York: McGraw-Hill, 2014.

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