Techno-economic Analysis of Non-linear DG Penetration in Radial Distribution Systems

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ABSTRACT

Increasing penetration of Distributed Generation (DG) in recent years has presented new challenges for planning and optimal operation of integrated distribution systems. In this scenario, harmonic distortions caused by non-linear DG operation in the distribution networks have further added to the complexities of regulating such interconnected systems. In this article, a comprehensive analysis of unbalanced radial distribution systems (RDS) integrated with non-linear DG has been attempted. The analytical assessment has been carried out by considering various voltage harmonics in non-linear DG in the presence of shunt capacitors in the radial distribution systems. Results are obtained for Total Harmonic Distortion (THD) of voltage and current at various buses of the RDS, along with harmonic power profile. An economic assessment of annual energy loss in the presence of non-linear DG has also been attempted. The proposed method is tested on two IEEE radial distribution feeders interconnected with non-linear DG. Results show that the presence of even acceptable level of voltage harmonics in non-linear DG can cause severe harmonic amplification in the entire network, consequently leading to increased energy losses for certain harmonic orders.

Keywords: Distributed Generation, Harmonic distortion, Shunt Capacitor, Radial Distribution System, Voltage Harmonics, Total Harmonic Distortion

INTRODUCTION

Growing thrust on integrating various distributed energy resources (DER) with existing distribution systems in the recent decade has transformed the way such networks are designed and operated. Rising energy prices, deregulated electricity markets and environmental considerations have further accelerated the pace of research activity in this direction. In the last few years, many studies on DG modelling, sizing and energy losses in integrated distribution networks have been performed for sinusoidal operating conditions [1-15].

Interconnection of DERs with distribution systems is also known to cause harmonic distortions in the network due to extensive use of power electronic components in such applications. For realistic assessment of power flow and its economic impact in the interconnected distribution systems, it is therefore essential to incorporate non-linear DG operation considering its harmonic emission in the analysis.

In recent years, harmonic distortions caused by DGs in distribution systems have been discussed in some research papers. Wang et al. have investigated harmonic distortion of DG inverters by their Norton equivalent model [16]. A probabilistic approach for optimal sizing of PV-DG in a distribution system considering harmonics has been presented by Hengsritawat et al. [17]. Harmonic interaction studies of DERs with distribution networks are also crucial for getting insight into the propagation of harmonics in various buses of the distribution system. Arghandeh et al. have proposed Index of Phasor Harmonics (IPH) based upon time-domain analysis to simulate the interactions of multiple DERs in the distribution network [18]. Harmonic analysis by current-injection technique is a well-researched subject and has also been applied in harmonic studies of DG. However, limited literature is available so far on the non-linear DG operation with voltage harmonics in distribution systems. In this research paper, impact of distorted voltage of non-linear DG interconnected with distribution network has been investigated for various harmonic orders. Furthermore, shunt capacitors installed in the distribution systems are known to cause severe power quality disturbance due to possibility of harmonic resonance for a particular order. In this article, a multi-frequency power flow analysis for unbalanced radial distribution systems has been proposed by considering harmonic currents absorbed by shunt capacitors due to voltage distortion in non-linear DG. Levels of voltage harmonics in the DG are considered as per IEEE Standard 1547-2003 and 1547a-2014 (amended), which describe harmonic distortion limits of DGs for interconnection with the grid [19-20]. Harmonic power profile and bus *THDs* of voltage and current are obtained by considering both harmonic magnitude and harmonic phase angles in the proposed algorithm. This analysis is followed by economic assessment of annual energy consumption for various voltage harmonics in non-linear DG. Next we discuss total harmonic current phasor in the presence of non-linear DG. Then we present the mathematical background for distortion power and energy profile. Numerical results are shown next, followed by the conclusion.

Nomenclature

$\left[\overline{V}_{NLDG}^{(h)}\right]_{abc}$	*Non*-linear *DG Voltage of harmonic order* '*h*' (*three*-phase)
$\left[\overline{I}_{C_1}^{(h)}\right]_{abc}, \left[\overline{I}_{C_2}^{(h)}\right]_{abc}$	*Harmonic currents absorbed by capacitors* C_1 *and* C_2
$\left[\overline{Z}_{12}^{(h)}\right]_{abc}, \left[\overline{Z}_{23}^{(h)}\right]_{abc}, \ldots$	*Harmonic line impedance phasors*
$\left[\overline{Z}_{C_1}^{(h)}\right]_{abc}, \left[\overline{Z}_{C_2}^{(h)}\right]_{abc}$	*Harmonic impedances of capacitors* C_1 *and* C_2
$\left[Z_{Load(i)}^{(h)}\right]_{abc}$	*Frequency-dependent load impedance*
$\left[P_{(i)}^{(1)}\right]_{abc}$	*Three-phase fundamental real power of bus* '*i*'
$\left[Q_{(i)}^{(1)}\right]_{abc}$	*Three-phase fundamental reactive power of bus* '*i*'
$\left[\overline{V}_{(i)}^{(1)}\right]_{abc}$	*Three-phase fundamental voltage of bus* '*i*'
$\left[I_{Line(l)}^{(h)}\right]_{abc}$	*Three-phase harmonic current in line* '*l*'
$\left[P_{Loss(l)}^{(h)}\right]_{abc}$	*Harmonic real power loss in line* '*l*'
$\left[Q_{Loss(l)}^{(h)}\right]_{abc}$	*Harmonic reactive power loss in line* '*l*'

MATHEMATICAL FRAMEWORK FOR TOTAL HARMONIC CURRENT IN THE PRESENCE OF NON-LINEAR DG

Voltage distortion of non-linear DG is propagated to the interconnected distribution network, consequently leading to current distortion in various buses. In the proposed algorithm, a general three-phase unbalanced bus i is supposed to consist of linear load and shunt capacitor for reactive power compensation. Total non-sinusoidal current phasor at bus i in the presence of harmonics can be mathematically expressed as

$$\left[\bar{I}_{Total(i)}\right]_{abc} = \left[\sum_{h=1}^{H} \bar{I}_{Load(i)}{}^{(h)}\right]_{abc} + \left[\sum_{h=1}^{H} \bar{I}_{C(i)}{}^{(h)}\right]_{abc} \tag{1}$$

In above Equation, h=1 indicates fundamental frequency current phasors, while higher values (h > 1) represent distortion currents of various harmonic orders of concern. In the proposed work, only odd harmonics are considered in non-linear DG and the maximum harmonic order H is taken to be 15. Also, for the sake of clarity, the term indicating harmonic order is shown in the superscript in the presented mathematical analysis.

Harmonic Current through Linear Load due to Bus Voltage Distortion

The first term on the right-hand side of Eq. (1) represents distortion current flow through the linear load is computed as per frequency-dependent load model proposed by International Council on Large Electric Systems (CIGRE). This term, which indicates harmonic current through the linear load due to bus voltage distortion, is mostly neglected in the harmonic analysis. However, it becomes significant during large voltage distortion, and is therefore included in the proposed work by following mathematical expressions:

$$\left[\bar{I}_{Load(i)}{}^{(h)}\right]_{abc} = \left[\bar{V}_{(i)}{}^{(h)}\right]_{abc} / \left[\bar{Z}_{Load(i)}{}^{(h)}\right]_{abc} \tag{2}$$

Resistance and reactance of above frequency-dependent load impedance are expressed below as proposed by CIGRE [21]:

$$\left[R_{Load(i)}{}^{(h)}\right]_{abc} = \left[\bar{V}_{(i)}{}^{(1)}\right]_{abc}^{2} / \left[P_{(i)}{}^{(1)}\right]_{abc}$$

$$\left[X_{Load(i)}{}^{(h)}\right]_{abc} = h \cdot \left[\bar{V}_{(i)}{}^{(1)}\right]_{abc}^{2} / \left[Q_{(i)}{}^{(1)}\right]_{abc}$$

Harmonic Currents Absorbed by Shunt Capacitors

Presence of voltage harmonics in non-linear DG would lead to large harmonic currents in the shunt capacitor installed for the purpose of power factor improvement. At fundamental frequency, shunt capacitors installed in the distribution network provide reactive power compensation and improve power factor, while at harmonic frequencies, these act as sink for the distortion currents [22-23]. Consequently, there is a possibility of harmonic amplification in the network due to harmonic currents absorbed by shunt capacitors in the interconnected distribution system. In this article, harmonic currents of various orders absorbed by shunt capacitors due to voltage distortion in non-linear DG are assessed by basic circuit equations. A simplified analysis is presented for the following 6-bus RDS interconnected with non-linear DG and two shunt capacitors as shown in Figure 1.

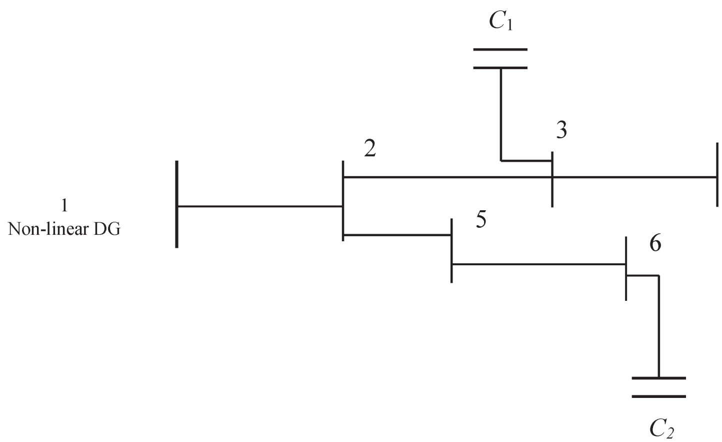

Figure 1. A 6-bus Interconnected RDS having Non-linear DG

Applying loop law from non-linear DG located at bus *1* to two shunt capacitors C_1 and C_2 at buses *3* and *6* respectively in above RDS, two vector equations for an unbalanced three-phase system can be obtained as below:

$$\left[\overline{V}_{NLDG}^{(h)}\right]_{abc} - \left[\overline{Z}_{12}^{(h)} + \overline{Z}_{23}^{(h)} + \overline{Z}_{C_1}^{(h)}\right]_{abc} \left[\overline{I}_{C_1}^{(h)}\right]_{abc} - \left[\overline{Z}_{12}^{(h)}\right]_{abc} \left[\overline{I}_{C_2}^{(h)}\right]_{abc} = 0 \tag{3}$$

$$\left[\overline{V}_{NLDG}^{(h)}\right]_{abc} - \left[\overline{Z}_{12}^{(h)}\right]_{abc} \left[\overline{I}_{C_1}^{(h)}\right]_{abc} - \left[\overline{Z}_{12}^{(h)} + \overline{Z}_{25}^{(h)} + \overline{Z}_{56}^{(h)} + \overline{Z}_{C_2}^{(h)}\right]_{abc} \left[\overline{I}_{C_2}^{(h)}\right]_{abc} = 0 \tag{4}$$

Rearranging above two multi-dimensional equations, harmonic currents absorbed by shunt capacitors C_1 and C_2 due to non-linear DG at bus *1* for the three-phase system can be computed as:

$$\begin{bmatrix} \overline{I}_{C_1}^{(h)} \\ \overline{I}_{C_2}^{(h)} \end{bmatrix}_{abc} = \begin{bmatrix} \overline{Z}_{12}^{(h)} + \overline{Z}_{23}^{(h)} + \overline{Z}_{C_1}^{(h)} & \overline{Z}_{12}^{(h)} \\ \overline{Z}_{12}^{(h)} & \overline{Z}_{12}^{(h)} + \overline{Z}_{25}^{(h)} + \overline{Z}_{56}^{(h)} + \overline{Z}_{C_2}^{(h)} \end{bmatrix}_{abc}^{-1} \begin{bmatrix} \overline{V}_{NLDG}^{(h)} \\ \overline{V}_{NLDG}^{(h)} \end{bmatrix}_{abc} \tag{5}$$

From Eq. (5), three-phase capacitor current phasors in the unbalanced RDS can be computed by substituting values of all other known parameters.

HARMONIC DISTORTION AND LOSSES IN THE PRESENCE OF NON-LINEAR DG

In the proposed work, power flow results are obtained by formulating appropriate data structures for unbalanced three-phase distribution network and by considering complete harmonic phasors. The algorithm is executed in MATLAB environment to obtain required results. Since convergence loop in the program incorporates values of both harmonic magnitude and phase angles, the results offer an accurate assessment of harmonic propagation in the network.

Bus Voltage and Current THDs

Values of THD_V and THD_I are the most widely used indices for distortion analysis. The following mathematical equations express the two indices for bus *i* in three-phase RDS [24]:

$$\left[THD_{V(i)}\right]_{abc} \; in\,\% = \left[\sqrt{\sum_{h=2}^{H} \left|V_{(i)}^{(h)}\right|^2} \,/\, \left|V_{(i)}^{(1)}\right| \right]_{abc} \times 100 \tag{6}$$

$$\left[THD_{I(i)}\right]_{abc} \; in\,\% = \left[\sqrt{\sum_{h=2}^{H} \left|I_{(i)}^{(h)}\right|^2} \,/\, \left|I_{(i)}^{(1)}\right| \right]_{abc} \times 100 \tag{7}$$

Harmonic Power and Energy Losses due to Non-Linear DG and Their Economic Impact

Evaluation of power losses in the integrated distribution systems is another significant aspect in determining the operational effectiveness of DGs, and has been discussed in some research papers for sinusoidal operating conditions. In this article, real and reactive harmonic power losses in various lines of the distribution network due to non-linear DG are computed from harmonic line currents and impedances as per following mathematical expressions:

$$\left[P_{Loss(l)}{}^{(h)}\right]_{abc}=\left[\left|\bar{I}_{Line(l)}{}^{(h)}\right|^{2}.R_{Line(l)}{}^{(h)}\right]_{abc} \quad (8)$$

$$\left[Q_{Loss(l)}{}^{(h)}\right]_{abc}=\left[\left|\bar{I}_{Line(l)}{}^{(h)}\right|^{2}.\mathrm{X}_{Line(l)}{}^{(h)}\right]_{abc} \quad (9)$$

In the above equations, $\left[R_{Line(l)}{}^{(h)}\right]_{abc}$ and $\left[X_{Line(l)}{}^{(h)}\right]_{abc}$ and are line resistance and reactance values of line l computed at harmonic frequencies of concern. Total line losses in the entire distribution network for various harmonic orders are subsequently calculated and energy loss profile is obtained by taking values from [11] as below:

$$Annual\,energy\,loss=\left[P_{Loss(Total)}\right]_{abc}*8760 \quad kWh$$

$$Annual\,energy\,loss\,\mathrm{exp}\,enditure=Annual\,energy\,loss*0.06 \quad \$$$

NUMERICAL RESULTS AND DISCUSSION

The proposed algorithm has been tested on two RDS: IEEE-13 bus unbalanced and IEEE-18 bus, both interconnected with non-liner DG having distorted voltage. The limits of individual voltage harmonics in the non-linear DG under investigation are taken as 4% of the fundamental, as specified in IEEE-1547-2003 Standard. Further, for the fundamental-frequency power flow analysis, widely used PQ model of DG has been considered.

IEEE-13 Bus Interconnected RDS

IEEE-13 bus unbalanced RDS is investigated by taking line and load data from [25]. A non-linear DG (Delta connected in PQ mode) is interconnected at node 671abc, supplying fundamental real power of 300 kW and reactive power of 197 Kvar in each phase. Load flow results have been obtained for THDV and THDI at all buses of three phases, along with harmonic power and energy loss profile for various harmonic orders. As THDV and THDI values depict considerably similar variation in all the three phases, therefore only middle phase b results have been shown in Tables 1 and 2.

Graphical variation of THD values of phase b for various odd harmonics (up to order 15) is illustrated in Figure 2 and 3.

Table 3 depicts harmonic power losses (real and reactive), and annual energy loss expenditure due to non-linear DG in 13-bus RDS.

Figure 4 presents variation of real and reactive power losses, while Figure 5 shows the variation of annual energy expenditure with harmonic order *h* in 13-bus interconnected RDS under study.

Impact of Non-Linear DG on Distribution Network Voltages and Currents

THD values of voltage and current indicate the extent of power quality disturbance occurring at various buses. Load flow results of the 13-bus interconnected RDS reveal a wide variation of these values for different orders of voltage harmonics in non-linear DG. It is observed that both THD_V and THD_I at most buses are considerably higher for 5th order voltage harmonic, even for its permissible limit of 4% (of the fundamental) as per IEEE-1547-2003 standard. For instance, THD_V and THD_I values of 12.3% and 12% respectively are found at bus *675b* for the 5th order, indicating harmonic amplification corresponding to this order in the presence of shunt capacitors.

Energy Loss due to Non-Linear DG and its Economic Assessment

Large values of THD_V and THD_I further lead to increase in total *rms* current and voltage for the particular harmonic order. Consequently, as observed in Table 3 and Figure 4, 5th order voltage harmonic in 13-bus RDS has resulted in the significantly large values of real and reactive power losses (223.2 *kW* and 535.1 *Kvar* respectively) in the interconnected distribution system, leading to 85.7% additional energy loss expenditure annually. From Figure 4, it is also observed that harmonic reactive power loss for various harmonic orders is considerably higher than the corresponding harmonic real power loss, due to proportionately large values of harmonic line reactance as compared to resistance.

Table 1. THDV values of phase b in IEEE-13 bus three-phase unbalanced RDS having non-linear DG

Bus no.	THD_V (%) for voltage harmonic of order h in non-linear DG							
	1	3	5	7	9	11	13	15
650b	0	0	0	0	0	0	0	0
632b	0	1.9	6.7	3.4	2.2	1.8	1.3	1.0
645b	0	1.7	6.8	3.3	1.9	1.6	1.5	0.9
646b	0	1.8	6.8	3.4	2.1	1.6	1.0	0.9
633b	0	1.5	6.7	3.4	2.1	1.5	1.1	1.0
634b	0	1.8	6.7	3.3	2.6	1.1	1.0	1.0
671b	0	1.6	11.4	3.4	1.8	1.0	0.9	0.9
680b	0	1.8	11.4	3.5	2.1	1.4	1.1	0.9
692b	0	1.7	11.4	3.4	2.2	1.3	1.0	1.0
675b	0	1.8	12.3	3.5	2.1	1.1	0.9	0.9

Table 2. THDV values of phase b in IEEE-13 bus three-phase unbalanced RDS having non-linear DG

Bus no.	THD_I (%) for voltage harmonic of order h in non-linear DG							
	1	3	5	7	9	11	13	15
650b	0	0	0	0	0	0	0	0
632b	0	0	0	0	0	0	0	0
645b	0	1.2	12.1	2.4	2.7	2.3	2.2	2.1
646b	0	1.3	12.4	2.5	2.5	2.2	2.3	1.7
633b	0	0	0	0	0	0	0	0
634b	0	1.3	5.4	1.9	1.7	1.8	1.7	1.6
671b	0	1.0	10.7	1.4	1.2	1.1	1.2	1.1
680b	0	0	0	0	0	0	0	0
692b	0	0	0	0	0	0	0	0
675b	0	1.2	12.0	1.4	1.3	1.3	1.2	1.2

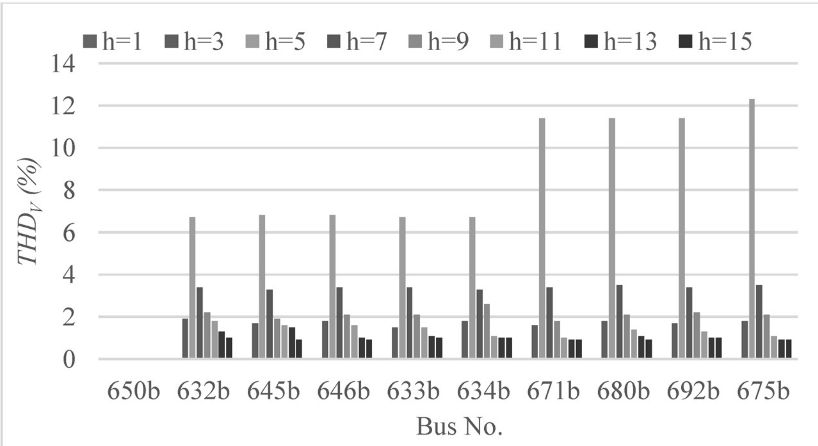

Figure 2. Bus THDV values of phase b in IEEE-13 bus RDS

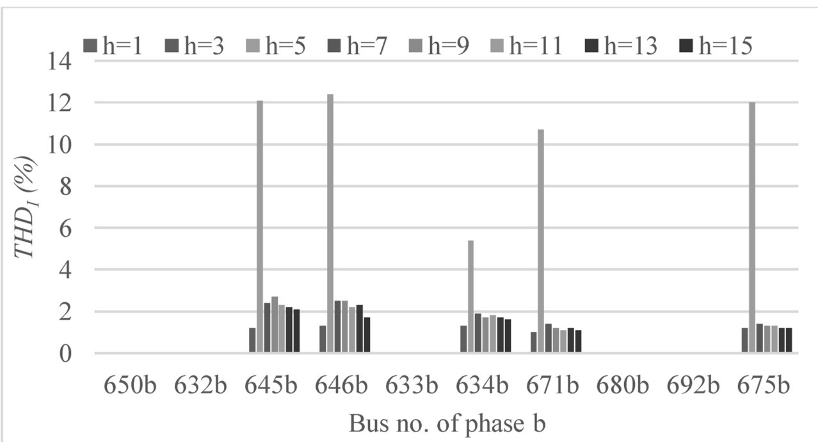

Figure 3. Bus THDI values of phase b in IEEE-13 bus RDS

Table 3. Harmonic power losses and loss expenditure in IEEE-13 bus RDS due to non-linear DG

Parameter	Value for voltage harmonic of order *h* in non-linear DG							
	1	3	5	7	9	11	13	15
$\left[P_{Loss}^{(h)}\right]_{abc}$ *(kW)*	120.2	121.4	223.2	129.9	127.5	126.4	124.7	121.6
$\left[Q_{Loss}^{(h)}\right]_{abc}$ *(kvar)*	335.3	336.9	535.1	356.8	351.3	339.4	338.3	336.9
Annual energy loss *(kWh)*	1053162	1063647	1955275	1137924	1117011	1106826	1092662	1064803
Annual energy loss expenditure *($)*	63189.7	63818.8	117316.5	68275.4	67020.7	66409.6	65559.7	63888.2
Increase in loss expenditure *(%)**	0	1.0	85.7	8.0	6.1	5.1	3.8	1.1

*with respect to fundamental

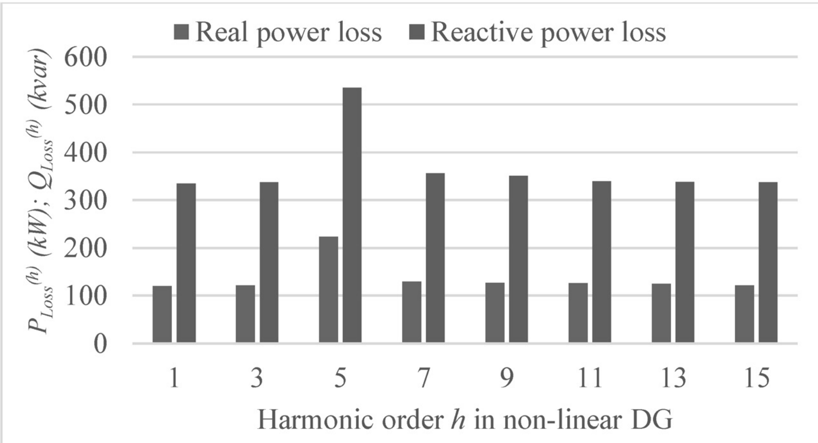

Figure 4. Variation of real and reactive power loss with h in 13-bus RDS

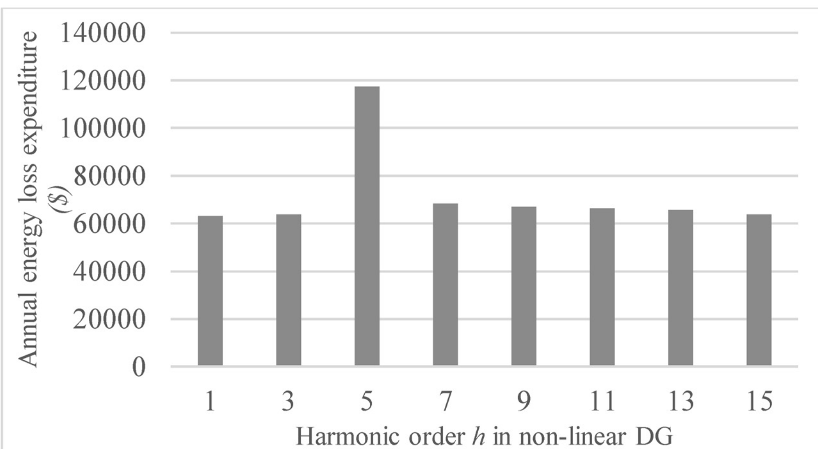

Figure 5. Variation of annual energy loss expenditure with h in 13-bus RDS

IEEE-18 Bus Interconnected RDS

IEEE-18 bus RDS has been investigated by taking its line and load data from [26]. A DG of 1000 *kW* and 500 *Kvar* is connected at bus *1*, along with ten shunt capacitors at various locations in this RDS. Results for THD_V and THD_I are shown in Tables 4 and 5, and their graphical variation with *h* is illustrated in Figure 6 and 7.

Harmonic power loss and energy loss expenditure are presented in Table 6, while their graphical variation is shown in Figure 8 and 9.

Table 4. THD_V values in IEEE-18 bus RDS having non-linear DG

Bus No.	THD_V (%) for voltage harmonic of order *h* in non-linear DG							
	1	3	5	7	9	11	13	15
51	0	0	0	0	0	0	0	0
50	0	1.6	0.5	0.4	0.4	0.4	0.4	0.4
1	0	5.9	2.6	1.9	1.8	1.5	1.3	1.1
2	0	6.1	2.6	1.8	1.6	1.4	1.3	1.2
9	0	6.1	2.7	1.7	1.5	1.4	1.1	1.0
3	0	7.6	3.2	2.8	2.5	1.2	1.1	1.0
4	0	8.4	3.2	2.7	2.5	1.9	1.4	1.2
5	0	10.5	3.5	2.8	2.4	1.8	1.5	1.3
6	0	10.6	3.6	2.8	2.4	1.6	1.5	1.3
7	0	10.8	3.8	2.9	2.6	1.5	1.2	1.1
8	0	11.1	3.9	2.8	2.4	1.3	1.1	0.9
20	0	11.4	2.9	2.3	2.2	1.7	1.5	1.2
21	0	11.2	3.7	2.7	2.4	1.9	1.7	1.3
22	0	10.2	3.8	2.6	2.2	1.8	1.6	1.2
23	0	10.8	3.8	2.8	2.2	1.8	1.6	1.2
24	0	10.2	3.9	2.9	2.6	1.7	1.4	1.3
25	0	10.7	3.7	2.7	2.6	1.8	1.5	1.2
26	0	10.8	3.8	2.8	2.6	1.7	1.5	1.2

Table 5. THD_I values in IEEE-18 bus RDS having non-linear DG

Bus No.	THD_I (%) for voltage harmonic of order *h* in non-linear DG							
	1	3	5	7	9	11	13	15
51	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0
1	0	6.1	2.2	2.0	1.7	1.6	1.3	0.9
2	0	3.6	1.8	1.7	1.5	1.3	1.2	1.1
9	0	5.9	2.4	1.3	1.8	1.3	1.2	1.7
3	0	6.2	1.9	1.6	1.4	1.3	1.1	1.0
4	0	9.3	3.5	2.4	1.7	1.5	1.4	1.2
5	0	10.5	3.1	2.3	2.2	1.9	1.6	1.4
6	0	9.1	3.7	2.2	1.7	1.5	1.2	1.0
7	0	9.1	3.9	2.7	2.4	2.3	1.9	1.5
8	0	10.7	3.4	2.7	2.1	1.6	1.4	1.5
20	0	13.7	3.1	2.5	2.2	1.7	1.4	1.1
21	0	12.9	3.5	2.6	2.4	1.6	1.5	1.3
22	0	12.2	3.2	3.0	2.5	1.7	1.6	1.2
23	0	12.1	3.1	2.8	2.3	1.6	1.4	1.2
24	0	11.8	3.2	2.6	1.9	1.6	1.4	1.3
25	0	11.2	3.7	3.2	2.5	2.1	1.8	1.4
26	0	10.6	3.6	3.3	2.5	2.3	1.7	1.6

Table 6. Harmonic power losses and loss expenditure in IEEE-18 bus RDS due to non-linear DG

Parameter	Value for voltage harmonic of order *h* in non-linear DG							
	1	3	5	7	9	11	13	15
$\left[P_{Loss}^{(h)}\right]_{abc}$ *(kW)*	296.8	452.9	310.5	307.3	304.6	302.0	299.7	298.8
$\left[Q_{Loss}^{(h)}\right]_{abc}$ *(kvar)*	1473.2	1879.7	1503.1	1483.6	1482.0	1481.0	1478.3	1477.9
Annual energy loss *(kWh)*	2599878	3967103	2719857	2692152	2668689	2645330	2625618	2617689
Annual energy loss expenditure *($)*	155993	238026	163191	161529	160121	158720	157537	157061
Increase in loss expenditure *(%)**	0	52.6	4.6	3.5	2.6	1.7	1.0	0.7

*with respect to fundamental

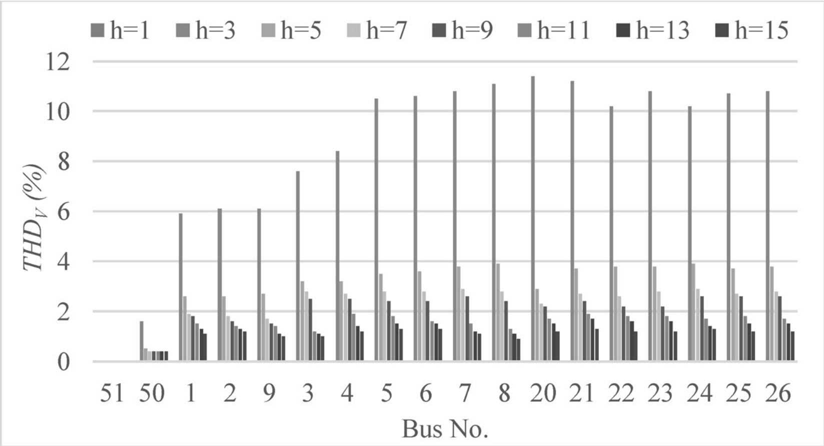

Figure 6. Bus THDV values in IEEE-18 bus RDS

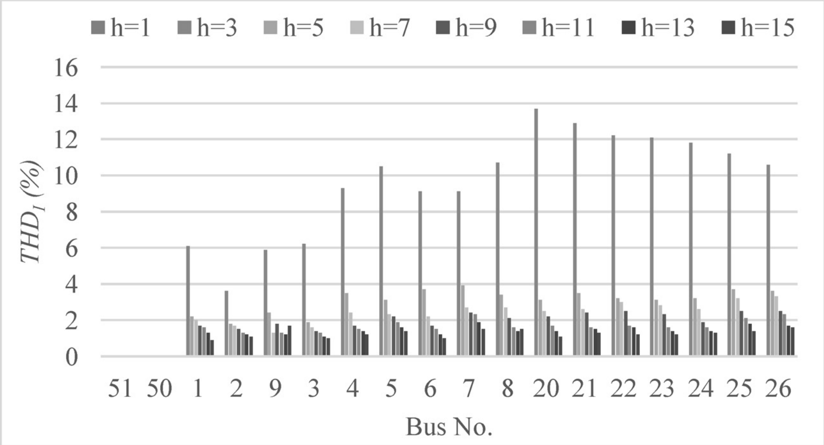

Figure 7. Bus THDI values in IEEE-18 bus RDS

Variation of THD_V and THD_I with h in 18-bus Interconnected RDS

Results indicate that 18-bus interconnected RDS is susceptible to harmonic amplification for 3rd order voltage harmonic in DG, as large voltage and current distortions are observed at most buses for this order. It can therefore be concluded that some specific order of harmonic voltage—even within permissible limits—can give rise to severe voltage and current distortions in the interconnected distribution system

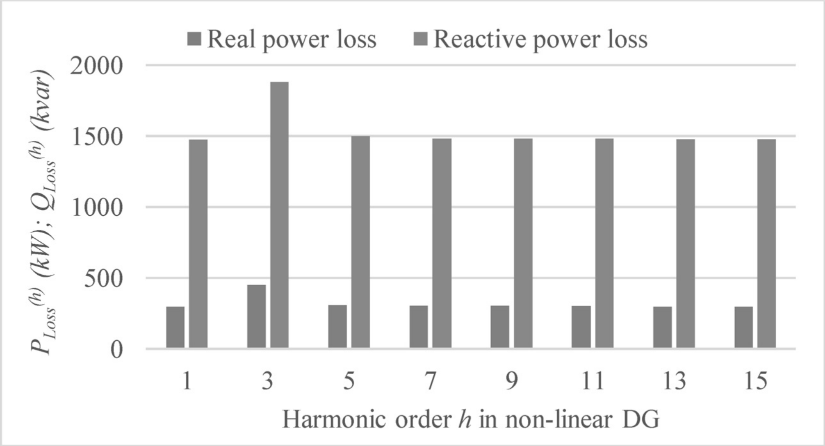

Figure 8. Variation of real and reactive power loss with h in 13-bus RDS

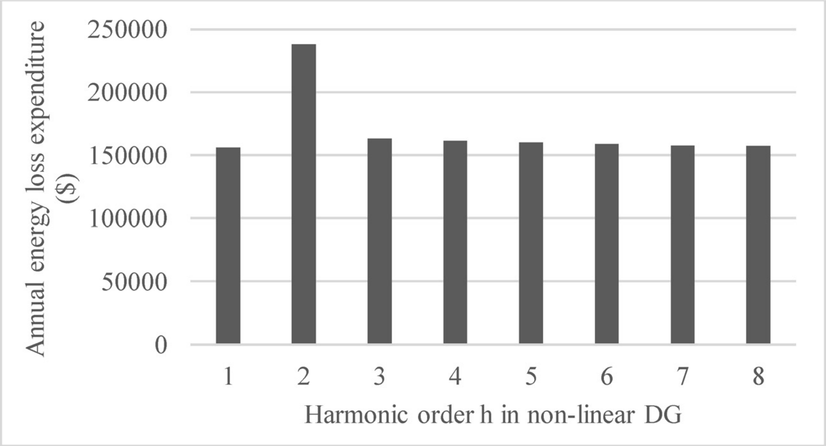

Figure 9. Variation of annual energy loss expenditure with h in 18-bus RDS

Annual Energy Expenditure due to Non-Linear DG in 18-Bus RDS
Annual energy loss expenditure is seen to increase by 52.6% in the presence 3rd order voltage harmonic in non-linear DG as compared to fundamental frequency loss expenditure. Therefore, even permissible level of certain harmonic order in non-linear DG can have significant impact on annual energy loss and on the economic efficiency in interconnected distribution network.

CONCLUSION

An analytical assessment of harmonic distortions caused by non-linear DG and its economic consequences in the interconnected distribution network has been presented. The methodology involves multi-frequency analysis of integrated RDS by considering harmonic current phasors absorbed by capacitors due to voltage distortion in the DG. The algorithm also incorporates frequency-dependent load model for computing distortion current through the linear load. Results of THD_V, THD_I, annual energy loss and loss expenditure have been obtained for two test systems. Numerical results reveal that interconnection of non-linear DG having distorted voltage, even within permissible limits of IEEE-1547-2003 standard, can lead to large distortion in the entire network for a particular harmonic order. For such harmonic order, considerably large values of annual energy loss and loss expenditure have been observed for the integrated distribution system. The results therefore demonstrate that harmonic interaction studies of non-linear DGs are crucial for the realistic assessment of power quality and economic efficiency in the integrated distribution systems.

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