

## Harmonic Analysis Considering DG Allocation and Load Growth in the Radial Distribution System

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**Abstract:** In the radial distribution system (RDS), the existence of nonlinear loads causes the generation of harmonic currents, which lead to a lot of problems in the system and equipment, such as electronic equipment is used to control the system due to its effectiveness and accuracy. But these are led to an increase in power losses, equipment will be damaged because of overloads, distortion in voltage and current waveforms. So, the importance of harmonic analysis is increased in the last researches and application for designing and determining its effect in the distribution system. Its benefit appears in finding how much the waveforms for voltage and current are distorted in all the buses in RDS. In this study, we will use the direct approach method to calculate harmonic load flow (HLF) analysis depending on two matrices BIBC and BCBV to determine the relationship between first branch current and bus injection, second branch current with bus voltage. This method is robust and more efficient in solving HLF. It will be applied on IEEE 34 bus system by using a hybrid optimization technique HPOGWO to determine the size for the distributed generated DG. Single, double, and triple units will inject to enhancement voltage profile considering load growth with harmonic sources (HRS) and comparing with the network without HRS.

**Keywords:** radial distribution system; harmonic; distributed generation; optimization; load growth.

### Introduction:

Our needs for Electrical Energy increase rapidly every day, its different application in work, industry, traveling, medical, residence and, so on, increase the electrical energy demand. This rapid increase forced the researchers to develop novel techniques to generate, transmit additional power and control the system by concentrating on the power system performance and make it smarter hour by hour [1].

Because of this, the injection of power electronic and switching devices and nonlinear loads in RDS increases very fast due to their accuracy, fast time response, high efficiency in controlling system. But the harmonic current induced in the system causes a lot of problems, which appear in the high losses, equipment damage interference in the communication system. The voltage and current waveforms are distorted as a result of harmonics. So, the importance of HLF

solutions is increased in designing and analyzing the RDS to quantify and determine the distortion in waveforms for current and voltage at different busses in the system and find the existence of a resonant problem with its dangerous effect in the system [2].

A lot of methods try to solve HLF, in [3] depend on frequency response and presents a frequency domain. In [4] presents the time domain but one of the disadvantages of this method is the absence of constraints for load flow. In [5] depending on Newton-Raphson for HLF with a repetitive solution.

The Direct Approach is used to solve the HLF solution in RDS, it approves it robust, efficient in large systems [6],[7]. analysis depending on two matrices BIBC and BCBV to determine the relationship between first branch current and bus injection, second branch current with bus voltage. The HRS are inserted in bus 15, 25, 33 for 34\_bus system contains 5 order of harmonic 5th, 7th, 11th, 13th, 17th [8].

Load growth is another large problem is faced by the RDS it defined as the normal increase in load per year, it can be solved by expanding the RDS with DG units in the best site and size [9],[10].

In this paper, four cases are discussed in the 34\_bus system, direct approach will use to solve HLF and HPOGWO to find the best size of DGs unit inserting in the system, then comparing the results with HRS and without HRS considering single double and triple DG units.

## Mathematical Model

### Load flow analysis for RDS

To discuss and solve the RDS presented in the fundamental load flow [6]

- (1) At the kth iteration of load flow the current injection  $I_i^k$  of bus i can be calculated as follow:

$$I_i^k = \left( \frac{P_i + jQ_i}{V_i^k} \right)^* \quad (1)$$

At bus i, the active power is  $P_i$  and reactive power is  $Q_i$  the voltage is  $V_i^k$ .

- (2) Applying KCL to find the branch current and bus injection relationship as follow:

$$[B] = [BIBC][I] \quad (2)$$

Where matrix BIBC contains only 0,1 to represent the relationship between branch and injection current.

- (3) The relationship between bus voltage and branch current is found by (3):

$$[\Delta V] = [BCBV][V] \quad (3)$$

Where matrix BCBV is the impedance matrix represent the branch current to bus voltage relationship.

- (4) To find the voltage mismatch by combined (2), (3):

$$[\Delta V] = [BCBV][BIBC][I]=[DLF][I] \tag{4}$$

Where matrix DLF is a combination of [BIBC] and [BCBV]

From equation (1)

$$V^{k+1} = V_1 - [DLF][I^k] \tag{5}$$

At bus i the load impedance  $Z_i$  can be calculated by:

$$Z_i = \frac{V_i}{\left(\frac{P_i + jQ_i}{V_i}\right)^*} \tag{6}$$

**HLF analysis**

Harmonic analysis is performed in this section by discuss the relationship between harmonic currents, branch currents, and voltages of each harmonic order after finding the effect of harmonic current absorbed by shunt capacitors [2]. The nonlinear loads can be considered as HRS [8].

- (1) The vector form in (7) represents the harmonic current by shunt capacitors and nonlinear load:

$$[I^{(h),k}] = \begin{bmatrix} Ih^{(h),k} \\ \dots \dots \\ IS^{(h),k} \end{bmatrix} \tag{7}$$

Where the vector form  $[I^{(h)}]$  is the harmonic current at hth harmonic order. Harmonic currents are developed from both linear and nonlinear load can be presented by  $[Ih^{(h)}]$ .  $[IS^h]$  is the harmonic current that the shunt capacitor absorbed.

- (2) The coefficient vector [A] for branch between two buses i and j of harmonic current:

$$[A_{ij}^{(h)}] = \begin{bmatrix} Ah_{ij}^{(h)} \\ \dots \dots \\ AS_{ij}^{(h)} \end{bmatrix} \tag{8}$$

Where  $[Ah_{ij}^{(h)}]$  and  $[AS_{ij}^{(h)}]$  are harmonic current coefficient vectors developed from both linear and nonlinear load in the system and absorbed capacitors, respectively for any branch.

- (3) [HA] is the matrix show the relationship between the vector of the system harmonic current and the bus voltage. First to calculate it must find voltage drop in branches by (9):

$$\Delta V_{ij}^{(h),k} = Z_{ij}^{(h)} [A_{ij}^{(h),k}]^T [I^{(h),k}] \tag{9}$$

where  $Z_{ij}^{(h)}$  is the branch impedance in hth order of harmonic then [HA] can be calculated by (10):

$$[V^{(h),k}] = [HAS^{(h),k}] [I^{(h),k}] \tag{10}$$

- (4) To determine [HAss] and [HAsH].the bus voltage for capacitors can e found by (11)

$$[VS^{(h),k}] = [HAS^{(h),k}] [I^{(h),k}] \tag{11}$$

Where  $[HAs^{(h),k}]$  is a vector form for the shunt capacitors buses. But equation (11) should be rewritten as follow (12) due to the shunt capacitor i voltage can be calculated by  $V_{Si}^{(h),k} = -I_{Si}^{(h),k} * Z_{Si}^{(h)}$ ,

$$- \begin{bmatrix} Z_{S_1}^{(h)} I_{S_1}^{(h),k} \\ \vdots \\ Z_{S_{n-1}}^{(h)} I_{S_{n-1}}^{(h),k} \\ Z_{S_n}^{(h)} I_{S_n}^{(h),k} \end{bmatrix} = [HAs^{(h),k} \quad : \quad HAss^{(h),k}] \begin{bmatrix} Ih^{(h),k} \\ \dots \\ I_S^{(h),k} \end{bmatrix} \quad (12)$$

(5) For  $Z_s$  harmonic load impedance for capacitors

$$[Z_S^{(h)}] = \begin{bmatrix} Z_{S_1}^{(h)} \\ Z_{S_2}^{(h)} \end{bmatrix} \quad (13)$$

Then  $[HLF]$  can be calculated depending on  $Z_s$

$$[HLF] = [HAss] + [Z_S] \quad (14)$$

(6) To calculate  $[I_S^{(h)}]$  from (12), (14)

$$[HLF^{(h),k}][I_S^{(h)}] = -[HAs^{(h),k}][Ih^{(h),k}] \quad (15)$$

Depending on (15) y using  $[Ih^{(h),k}]$  data to find  $[I_S^{(h)}]$

(7) Due to harmonic effect in the system Obtain branch current  $[B_{ij}^{(h),k}]$  and bus voltage  $[V^{(h),k}]$

### Load growth calculation

The increase in load year by year and to determine the growth in any year can be calculated as following [9]:

$$P_{Li}(y) = P_{Li}(0) \times (1 + g)^y \quad (16)$$

$$Q_{Li}(y) = Q_{Li}(0) \times (1 + g)^y \quad (17)$$

Where  $g = 7.5\%$  from base year [9] is the rate of annual growth,  $y$  is the year number,  $P_L(y)$  and  $Q_L(y)$  are the active and reactive power at any year, respectively.  $P_L(0)$  and  $Q_L(0)$  are the active and reactive load in the base year ( $y=0$ ).

### Hybrid HPSOGWO algorithm

To benefit from the ability of two techniques and increase the quality and stability of the solution, so a hybrid optimization technique is used to find the solution. Here depends on grey wolf optimizer GWO and particle swarm optimization PSO to improve exploration and exploitation ability for both techniques.

The hybridization is made at a low or high level [11]. In HPSOGWO the variant runs in parallel and combines variants of two functions. So, it uses a low level [12].

After the modification for the technique, the position of the three agents are updated in the search space and the modification is written as follow [12]:

$$\vec{D}_\alpha = |\vec{c}_1 \cdot \vec{x}_\alpha - \omega * \vec{x}| \quad (18)$$

$$\vec{D}_\beta = |\vec{c}_2 \cdot \vec{x}_\beta - \omega * \vec{x}| \quad (19)$$

$$\vec{D}_\delta = |\vec{c}_3 \cdot \vec{x}_\delta - \omega * \vec{x}| \quad (20)$$

The velocity is updated as following [12]:

$$v_i^{k+1} = \omega * (v_i^k + c_1 r_1 (x_1 - x_i^k) + c_2 r_2 (x_2 - x_i^k) + c_3 r_3 (x_3 - x_i^k)) \quad (21)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (22)$$

**Constraints**

- Bus voltage constraints

The voltage in the RDS must follow the minimum ( $V_{min}$ ) and maximum ( $V_{max}$ ) limits to keep the system stable.

$$V_{min} \leq V_i \leq V_{max} \quad (23)$$

- DG size limit

$$\sum_{i=1}^{NDG} P_{DG}(i) \leq \left( \sum_{i=1}^k P_L(i) + \sum_{j=1}^{nb} P_{loss}(j) \right) \quad (24)$$

$$\sum_{i=1}^{NDG} Q_{DG}(i) \leq \left( \sum_{i=1}^k Q_L(i) + \sum_{j=1}^{nb} Q_{loss}(j) \right) \quad (25)$$

The DG units' size will be less than the power load in the base year y=0. In this paper, the lower value that can be injected is 10000 W and the upper value is 4600000 w less than the power in the bae year for the test system.

- Objective function

The objective function focuses on the voltage profile enhancement and keeps the limit of voltages within 0.9 p.u up to 1.05 p.u.

**Simulation results**

In this section, four cases are discussed and applied in the 34\_bus system, the direct approach will use to solve HLF and HPOGW0 to find the best size of DGs units inserting in the system, then comparing the results with HRS and without HRS considering single double and triple DG units to verify the ability of the method in solving the test system taking in account the load growth calculations, and the four cases are organized as follow:

- (1) Without DG without HRS
- (2) Without DG with HRS
- (3) With DG without HRS
- (4) With DG with HRS

- **Standard test system**

The study will be performed in 34 \_bus system RDS [13]. Figure 1 presents the single-line diagram for the test system. The total active and reactive load power at base year 4636.5 kW

and 2873.5 kVAR, the  $V_{min}$  is at bus 27 equal 0.9417 p.u. HRS are inserted in bus 15, 25, 33 for 34\_bus system contains 5 orders of harmonic 5th, 7th, 11th,13th,17th [8]and Figure 2 presents the voltage profile at 5 orders of harmonic.

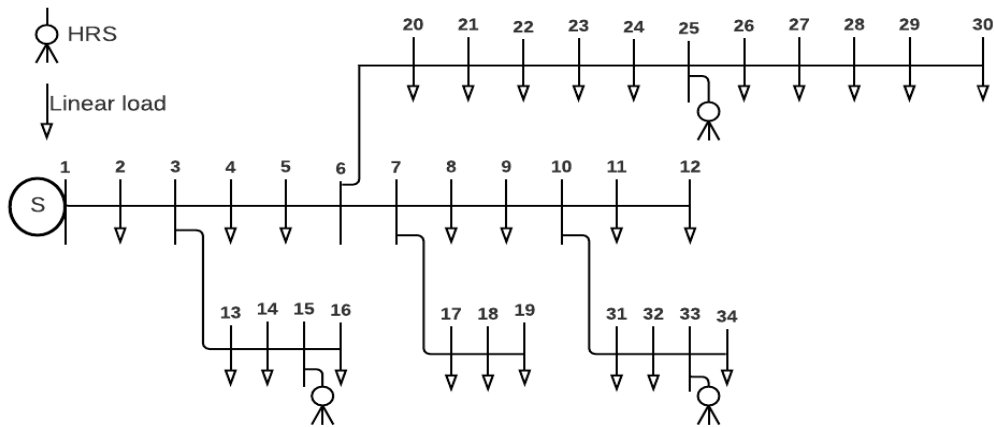


Figure 1. Single line diagram for 34\_ bus RDS

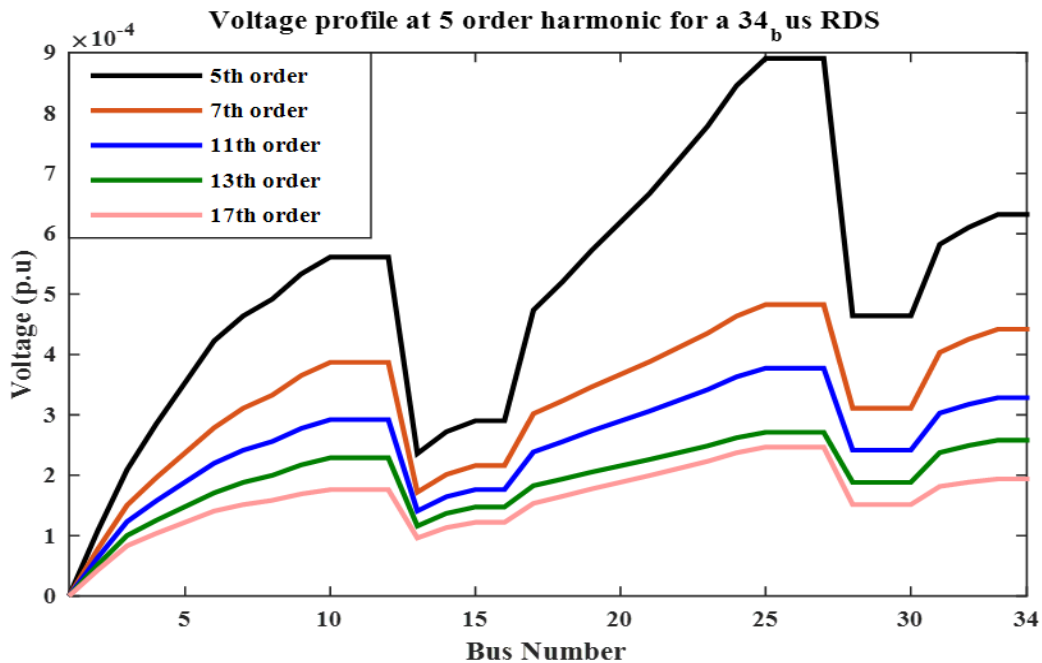


Figure.2. Voltage profile at 5 orders of harmonic

### 1. Without DG Without HRS

In table 1 left side shows the ( $V_{min}$ ) in the system, the violation due to load growth occurs in the 7th year. Figure 3 shows the voltage profile in the system.

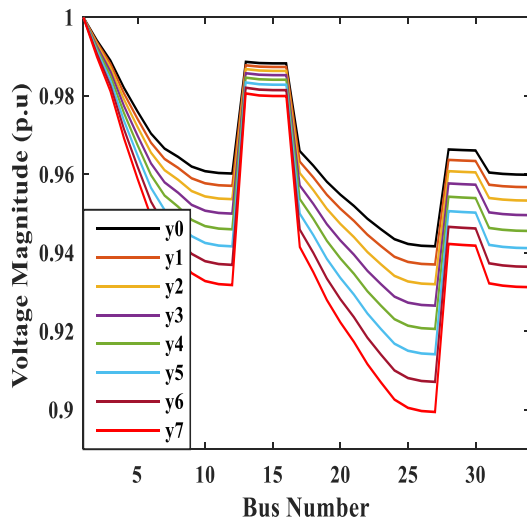
### 2. Without DG With HRS

In table 1 right side shows the ( $V_{min}$ ) in the system the violation due to load growth occurs in the 7th year also the effect of harmonic is appeared here and increases the voltage magnitude

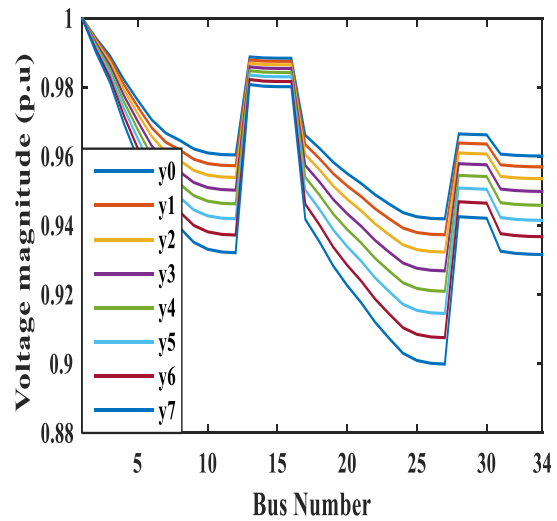
as shown, ( $V_{bus}$ ) is the voltage in the buses before injection the calculations of HLF. Figure 4 shows the voltage profile in the system.

**Table1** Result without DG without HRS and with HRS

Result without DG without HRS		Result without DG with HRS		
Year	V_min	year	V_bus	V_min after HRS
Y0	0.9417	Y0	0.9417	0.9419
Y1	0.9371	Y1	0.9371	0.9373
Y2	0.932	Y2	0.932	0.9323
Y3	0.9266	Y3	0.9266	0.9269
Y4	0.9206	Y4	0.9206	0.9210
Y5	0.9142	Y5	0.9142	0.9146
Y6	0.9072	Y6	0.9072	0.9076
Y7	0.8995	Y7	0.8995	0.8999



**Figure.3.** Voltage profile for 34 bus RDS without DG without HRS



**Figure.4.** Voltage profile for 34 bus RDS without DG with HRS

### 3. With DG Without HRS

#### a) Inserting single DG

In table 2 presents the DG size inserted in the system for each year. the RDS will stand for 15 years and withstands annually increased loads by load growth. Figure 5 presents the voltage profile for this case. Where pgt is the total power injected by the DG unit.

#### b) Inserting double DGs

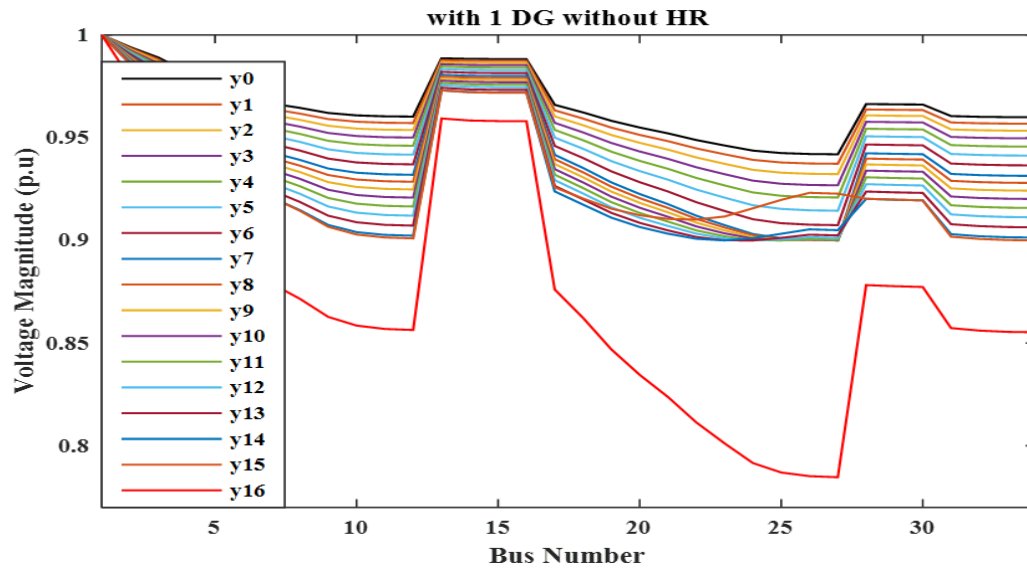
In table 2 two DG units will be inserted in the system, the RDS will withstand for 13 years without violation and the voltage and system limits are within the constraints. Figure 6 presents the voltage profile.

**c) Inserting triple DGs**

In table 2 also three DG units will be inserted in the system the RDS will withstand for 13 years, Figure 7 presents the voltage profile. the total DG size for 3 units in the year 13th equals 4169577 w and that is less than the load power in the base year and be within constraints.

**Table2** Result with DG without HRS:

year	Result with 1 DG without HRS		Result with 2 DG without HRS		Result with 3 DG without HRS		Load growth (w)
	V_min	Pgt (w)	V_min	Pgt (w)	V_min	Pgt (w)	
Y0	0.9419	10000	0.9420	20000	0.9421	30000	4636500
Y1	0.9373	10000	0.9373	20000	0.9375	30000	4.9842*10 <sup>6</sup>
Y2	0.9323	10000	0.9323	20000	0.9325	30000	5.3581*10 <sup>6</sup>
Y3	0.9268	10000	0.9268	20000	0.9270	30000	5.7599*10 <sup>6</sup>
Y4	0.9209	10000	0.9209	20000	0.9211	30000	6.1919*10 <sup>6</sup>
Y5	0.9145	10000	0.9145	20000	0.9146	30000	6.6563*10 <sup>6</sup>
Y6	0.9074	10000	0.9074	20000	0.9076	30000	7.1555*10 <sup>6</sup>
Y7	0.9	18713	0.9	30919	0.9	33536	7.6922*10 <sup>6</sup>
Y8	0.9001	324943	0.9	425646	0.9001	381679	8.2691*10 <sup>6</sup>
Y9	0.9	648415	0.9	850238	0.9002	778363	8.8893*10 <sup>6</sup>
Y10	0.9001	1006175	0.9001	1312879	0.9001	1151306	9.556*10 <sup>6</sup>
Y11	0.9	1394717	0.9	1806337	0.9	1621132	1.02*10 <sup>7</sup>
Y12	0.9	1843984	0.9	2408930	0.9002	2406943	1.104*10 <sup>7</sup>
Y13	0.9	2337691	0.9022	4490697	0.9027	4169577	1.187*10 <sup>7</sup>
Y14	0.9	2921613	0.8204	20000	0.8206	30000	1.276*10 <sup>7</sup>
Y15	0.9	4144471	-	-	-	-	1.372*10 <sup>7</sup>
Y16	0.7847	10000	-	-	-	-	1.475*10 <sup>7</sup>



**Figure.5.** Voltage profile for 34 bus RDS with 1 DG without HRS



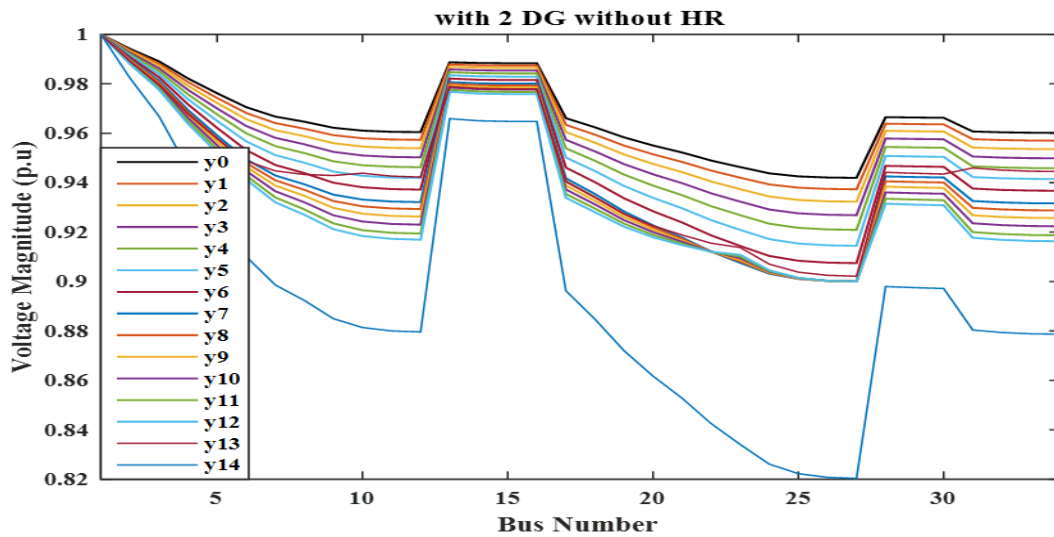


Figure.6. Voltage profile for 34 bus RDS with 2 DG without HRS

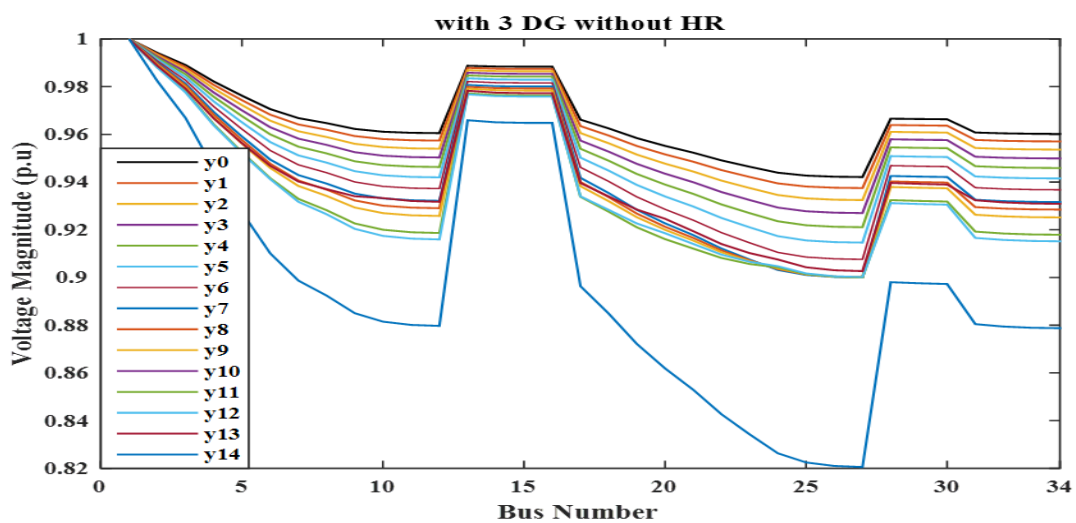


Figure.7. Voltage profile for 34 bus RDS with 3 DG without HRS

#### 4. With DG With HRS

##### a) Inserting single DG

Table 3 will list the result for the system with 1 DG unit, the difference between the voltage magnitude results in case 3 (a) and here in case 4 (a) and the increase in voltages as an effect of HRS existence, this will reflect on the DG's size which decreases here and appear from year 7. Figure 8 shows the voltage profile.

##### b) Inserting double DGs

In table 3 the system will still stable for 13 years the load injected in this year is less than the load in the base year also the summation of Pgt for the system injected for all years with HRS is less than in the same case without HRS. Figure 9 represents the voltage profile.

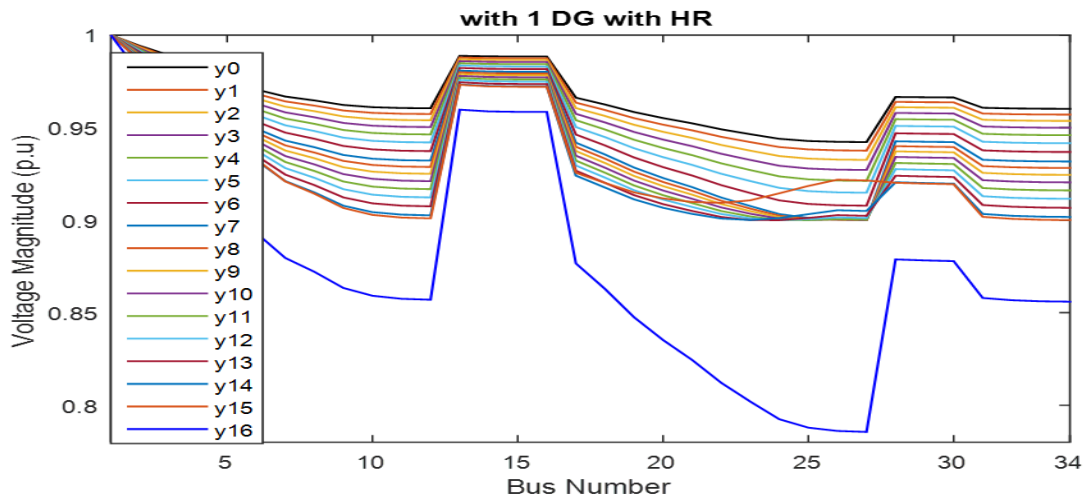
##### c) Inserting triple DGs

Finally, table 3 also presents the result under load growth calculations. The system will still stable for 13 years. Increases the number of DG units in the RDS enhancement the voltage

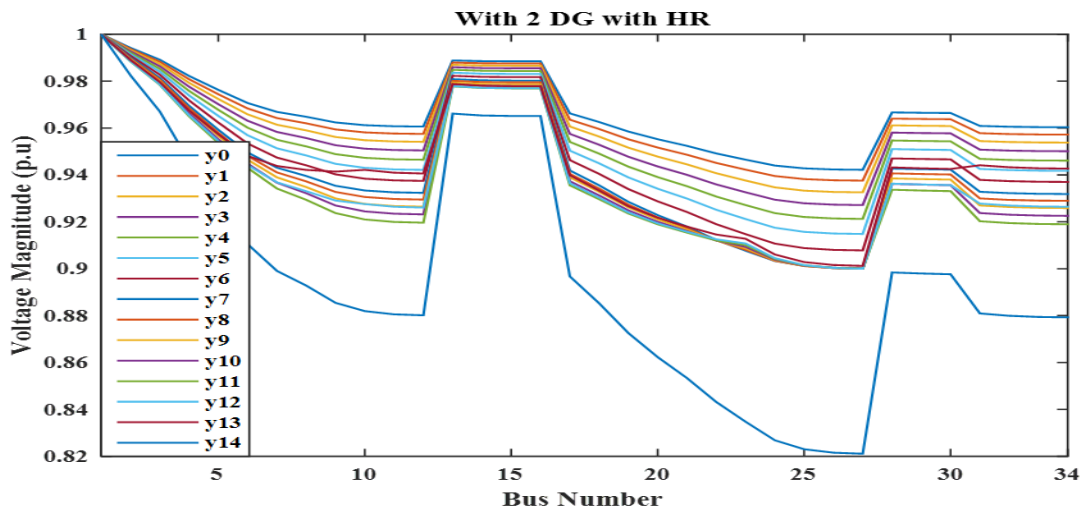
profile and decreases the total size that will be inserted in the system as is shown in the next table. Figure 10 represents the voltage profile.

**Table3** Result with DG with HRS:

	Result with 1 DG with HRS			Result with 2 DG with HRS			Result with 3 DG with HRS			
year	V <sub>bus</sub>	V <sub>min</sub>	Pgt (w)	V <sub>bus</sub>	V <sub>min</sub>	Pgt (w)	V <sub>bus</sub>	V <sub>min</sub>	Pgt (w)	Load growth (w)
Y0	0.9419	0.9422	10000	0.9420	0.9422	20000	0.9421	0.9424	30000	4636500
Y1	0.9373	0.9376	10000	0.9373	0.9376	20000	0.9375	0.9377	30000	4.9842*10 <sup>6</sup>
Y2	0.9323	0.9326	10000	0.9323	0.9326	20000	0.9325	0.9327	30000	5.3581*10 <sup>6</sup>
Y3	0.9268	0.9271	10000	0.9268	0.9272	20000	0.9270	0.9273	30000	5.7599*10 <sup>6</sup>
Y4	0.9209	0.9212	10000	0.9209	0.9212	20000	0.9211	0.9214	30000	6.1919*10 <sup>6</sup>
Y5	0.9145	0.9148	10000	0.9145	0.9148	20000	0.9146	0.915	30000	6.6563*10 <sup>6</sup>
Y6	0.9074	0.9078	10000	0.9074	0.9078	20000	0.9076	0.9080	30000	7.1555*10 <sup>6</sup>
Y7	0.8998	0.9002	10000	0.8998	0.9002	20000	0.8999	0.9004	30000	7.6922*10 <sup>6</sup>
Y8	0.8996	0.9	305162	0.8995	0.9	403245	0.8996	0.9	358247	8.2691*10 <sup>6</sup>
Y9	0.8995	0.9	630718	0.8995	0.9	826982	0.8995	0.9	727471	8.8893*10 <sup>6</sup>
Y10	0.8995	0.9001	984840	0.8995	0.9	1284408	0.9	0.9005	1147820	9.556*10 <sup>6</sup>
Y11	0.8994	0.9	1372644	0.8995	0.9	1781293	0.8995	0.9	1558982	1.02*10 <sup>7</sup>
Y12	0.8994	0.9	1819204	0.8994	0.9	2373657	0.8994	0.9	2351178	1.104*10 <sup>7</sup>
Y13	0.8994	0.9	2310604	0.9006	0.9012	4331486	0.9002	0.9008	3610725	1.187*10 <sup>7</sup>
Y14	0.8994	0.9001	2894052	0.8204	0.8211	20000	0.8206	0.8213	30000	1.276*10 <sup>7</sup>
Y15	0.8994	0.9	4062338	-	-	-	-	-	-	1.372*10 <sup>7</sup>
Y16	0.7847	0.7856	10000	-	-	-	-	-	-	1.475*10 <sup>7</sup>



**Figure.8.** Voltage profile for 34 bus RDS with 1 DG with HRS



**Figure.9.** Voltage profile for 34 bus RDS with 2 DG with HRS

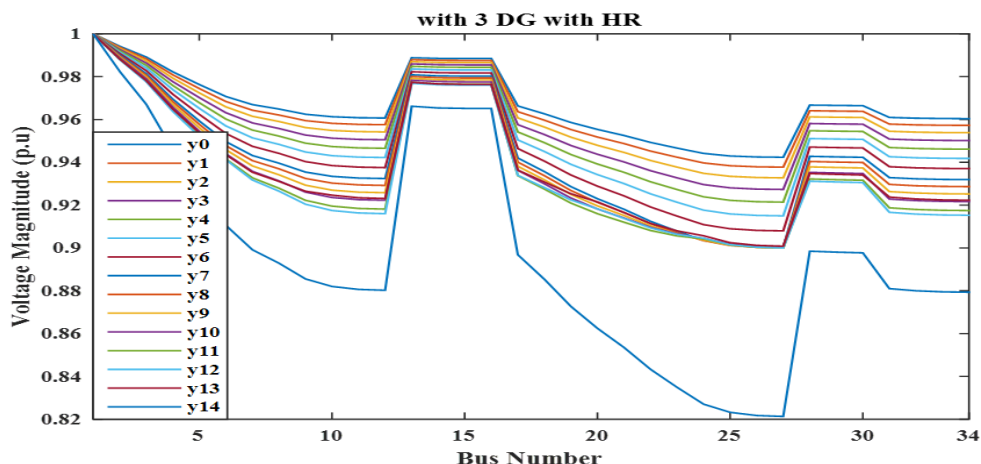


Figure.10. Voltage profile for 34 bus RDS with 3 DG with HRS

### Work comparison

This section will introduce a comparison between results in the case of the existing and absence of HRS. The inserting of nonlinear loads and HRS increase the voltage magnitude of RDS and load flow harmonic distortion and this will affect the DG size that inserted the system and decreases the size of total DG units. Table 4 presents the total power injected into the system  $P_{gt}$  from the previous results. From base year to year 7, the system is stable before inserting any DG or HRS as discussed before in case 1 and case 2 and presented in table 1, so the DG units in these years took the lower value of DG as shown in constraints to enhancement the voltage profile only. From year 7 the DG units inserted are used to make the system stable and keep the voltages within constraints and enhancement the voltage profile to sustain the load growth in the system.

Finally, Comparing the result in table 4 presents the decrease in  $P_{gt}$  in presence of HRS than without HRS for example in year 13 for inserting 3 DG units the load injected equal 4.2 MW in case of the absence of HRS but with HRS in the same year equals 3.6 MW with decreased amount reach to 558 kW.

For single, double, and triple DG units the decrease in power due to the presence of HRS as a summation for 16 years reach 251.16 kW, 304.575 kW, and 758.113 kW respectively. It is clear that in case of increasing the DG units also affects decreasing the size in the presence of HRS.

Table4 Result comparison

year	Inserting 1 DG			Inserting 2 DG			Inserting 3 DG		
	Without HRS	With HRS	The decrease in $P_{gt}$ kW	Without HRS	With HRS	The decrease in $P_{gt}$ kW	Without HRS	With HRS	The decrease in $P_{gt}$ kW
Y0	10000	10000	0	20000	20000	0	30000	30000	0
Y1	10000	10000	0	20000	20000	0	30000	30000	0
Y2	10000	10000	0	20000	20000	0	30000	30000	0
Y3	10000	10000	0	20000	20000	0	30000	30000	0
Y4	10000	10000	0	20000	20000	0	30000	30000	0
Y5	10000	10000	0	20000	20000	0	30000	30000	0
Y6	10000	10000	0	20000	20000	0	30000	30000	0
Y7	18713	10000	8.713	30919	20000	10.919	33536	30000	3.536

Y8	324943	305162	19.781	425646	403245	22.401	381679	358247	23.432
Y9	648415	630718	17.697	850238	826982	23.256	778363	727471	50.892
Y10	1006175	984840	21.335	1312879	1284408	28.471	1151306	1147820	3.486
Y11	1394717	1372644	22.073	1806337	1781293	25.044	1621132	1558982	62.15
Y12	1843984	1819204	24.78	2408930	2373657	35.273	2406943	2351178	55.765
Y13	2337691	2310604	27.087	4490697	4331486	159.211	4169577	3610725	558.852
Y14	2921613	2894052	27.561	20000	20000	0	30000	30000	0
Y15	4144471	4062338	82.133	-	-	-	-	-	-
Y16	10000	10000	0	-	-	-	-	-	-
The total DG size	14720722	14469562	251.16	11485646	11181071	304.575	10782536	10024423	758.113

### Conclusion

The annual load growth and the increase in usage of nonlinear loads in RDS. In this paper, four cases are applied on 34 bus-system to show the effect of HRS and injected DG units in the system. So, it needs to use the direct approach to solve HLF and benefit from the ability of HPSOGWO to find the optimal size of DGs. Single, double, and triple units have been inserted in the RDS. the increase in voltage due to HRS reduced the total DG size that is needed to enhancement the voltage profile and keeps the system stable during the annual increase in load. So, in presence of HRS the DG size decrease and improve the voltage profile.

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