Optimal Planning of Distribution Generation for Distribution Network Regarding to Losses Energy and Harmonic Reduction

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Abstract—**Simultaneous use of nonlinear loads and renewable distributed generation resources with improper allocation in the distribution network creates harmonic distortions and the electrical energy losses. In order to control harmonic distortions and reduce energy losses can be optimized planning with various combinations of renewable sources prepared. To prove the effectiveness of the proposed method, a 31-buses distributions network including renewable and non-renewable distributed generation resources, non-linear loads and Shunt capacitors can be employed using genetic algorithm. In addition to harmonic load flow based on forward/backward sweep via MATLAB software is analyzed.**

> *Keywords—Genetic Algorithm, Non-Linear Loads, Distribution Generation and Harmonic Distortions*

1. Introduction

Due to the increasing demand for high quality electric energy consumption and limitations on fossil fuels, the use of renewable energy resources in distribution systems has increased. Distributed generation resources in distribution networks are used to reduce the power losses in the power plants and distribution and transmission networks and to improve power quality and network reliability. Improper placement of distributed generation units will not only increase the losses but also causes system performance problems [1].

In addition, due to increasing non-linear loads in distribution networks, the optimal allocation of distributed generation resources in the presence of capacitors and non-linear loads is so crucial. Non-linear loads and renewable energy resources cause harmonic distortions because of using converters.

Thus optimal planning for the proposed system must be noticed [2,3].

Artificial algorithms can be used for optimal planning of the distribution system components, including capacitors and distributed generation resources. For example, the artificial algorithm bee colony is used to determine the optimal sizing of distributed generation in order to optimize the active power [4,5]. In order to have losses reduction and voltage profile improvement considering stability and capacity of distribution lines in a 33-buses and 69-buses network, genetic algorithms have been used for optimal capacitor placement and distributed generation resources [6]. [7,8] the optimal capacitor placement in radial distribution system is done to reduce losses and to improve voltage profile considering economic dispatch using fuzzy systems.

In this paper, in order to achieve the optimal allocation of distributed generation resources with several scenarios in the presence of non-linear loads and shunt capacitors for the network including harmonic distortions, the harmonic load flow method using forward/backward sweep is used and genetic algorithms have also been used for the optimal placement of distributed generation resources for reducing energy losses. The objective function includes the annual energy losses and voltage restrictions on different buses, total harmonic distortions and penetration limits and candidate buses for the installation of distributed generation resources. The proposed method is applied on a 31-buses system and the simulation results in MATLAB software show the ability of the proposed method to improve the energy losses and total harmonic distortions [9,10,2].

2. Background

The main objective of this paper is to use the distributed generation resources with the proper placement in order to reduce annual energy losses and the harmonic distortion. First, distributed

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generation and the power quality are studied and then a definition for the harmonic load flow and genetic algorithm for optimal planning is presented [2].

2-1 Distributed Generation

The comprehensive and unrestricted definition of distributed generation resources is as follows : The electrical energy source which is directly connected to the distribution network or consumer and supplies a part of the network power consumption [11,12,13]. In this paper wind turbines and solar cells as well as a non-renewable source are used.

2-2 Power Quality

The power quality includes the specifications of the power network which provide the ability to function adequately for the equipment. Regarding the power quality, the consumers' opinions are in priority. Any changes in the quantities of voltage, current, and frequency causing the failure or improper performance of consumers' equipment affect the power quality. Harmonics are one of the important factors reducing the power quality [14,15].

2-3 Load Flow

Designing and exploiting a power system aims to supply the loads required for the network. Load flow computes the electrical quantities of a power system in a steady-state for determined and specific loads [16,17,18]. In this paper, forward/backward sweep is the method of load flow.

2-4 Genetic Algorithms

Genetic algorithm is a statistical method for optimization and search. The basic idea of this approach is driven from the Darwinian evolutionary theory. This algorithm is used for optimal placement of distributed generation in order to reduce annual energy losses [19].

3. Problem and Modeling
3.1 Statement of the problem

A 31-buses distribution network IEEE is investigated. This network consists of seven non-linear loads and 3 types of distributed generation resources and 7 shunt capacitors. Renewable distributed generation resources include wind turbines and solar cells and there also is a non-renewable distributed generation resource with a fixed power. To minimize annual energy losses and harmonic control, genetic algorithm and load flow technique with the use of forward/backward sweep method in the MATLAB software are used [2].
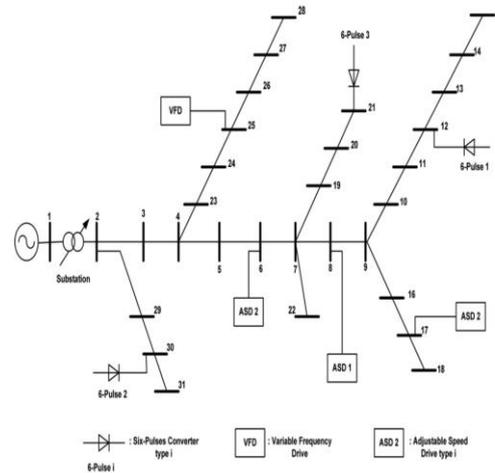

Figure 1. 31-bus network IEEE

3.1.1 Objective Function

Objective function is the optimal allocation of distributed generation resources to reduce annual energy losses:

$$OF = \text{Min}\{P_{loss}^{year}\} \qquad (1)$$

Assumptions considered in this regard include the following items:

A. Only one type of distributed generation resource can be connected to a bus.

B. All units of distributed generation are able to work in unity power factor.

C. A local distribution company should not make any improvement in the system.

Distribution system studied assumed on the maximum limit for investment in capacity on any bus and to determine the optimal mix of distributed energy resourses of 5 scenarios considered

$$P_{Loss} = \sum_{i=1}^{nb} \left| B_{ij}^{(h)} \right|^2 . R_i = [\text{R}]^T \left| A_{ij}^{(h)} \right| . [\text{I}^{(h)}]^2 \qquad (2)$$

Where nb is the number of branches and R is the matrix of line resistance and h is the number of harmonics.

3.1.2 Limitations

Provisions intended for this problem include [2,3]:
- The size and angle of the slack bus voltage:

$$V_1 = 1, \delta_1 = 0.0 \qquad (3)$$

- Voltage limitation in buses:

$$V_{min} \leq V_{BUS} \leq V_{max} \qquad (4)$$

- Line capacity constraints:

$$0 \leq B_{ij} \leq B_{ij}^{max} \qquad (5)$$

- THD constraints:

$$THD_{BUS} \leq THD_{max} \qquad (6)$$

- Limitations on the number of buses:
  n = 6-8-12-13-15-17-18-20-21-25-28-30-31

3-2 Harmonic Load Flow Method

Due to non-linear loads and renewable distributed generation resources, harmonic analysis of the distribution network is of importance. The analysis determines the amount of harmonic distortions in different buses of the distribution network and the way they can be removed. Forward/backward sweep is a powerful technique that is used in the distribution system. However, because of frequencies similar to capacitors' resonance frequency, this method cannot be directly used until the harmonic currents absorbed by the bus capacitors of distributed networks are not determined. After determining the currents absorbed by the capacitors, this method can be used to find out the relationship between bus harmonic currents, line currents, and harmonic rank of bus voltages [20,21,22].

3-2-1 Current Backward Sweep

Current harmonics can be described by the following vector:

$$\left[I^{(h),k} \right] = \begin{bmatrix} Ih^{(h),k} \\ \cdots \\ Is_s^{(h),k} \end{bmatrix} \qquad (7)$$

I_h and I_s are the harmonic flows injected by non-linear loads and linear impedances absorbed by the shunt capacitors in the h harmonic order, respectively. For distribution systems with m harmonic resources and n shunt capacitors, the current vector rank will be (m + n) × 1. Then, a coefficient vector will be defined, which describes the current flow among the branches:

$$\left[A_{ij}^{(h),k} \right] = \begin{bmatrix} Ah_{ij}^{(h),k} \\ \cdots \\ As_{ij}^{(h),k} \end{bmatrix} \qquad (8)$$

$$B_{ij}^{(h),k} = \left[A_{ij}^{(h),k} \right]^T \left[I^{(h),k} \right] \qquad (9)$$

Here, the coefficient vector of harmonic currents between i and j buses is in the h-order harmonic and they are vectors of harmonic current coefficients injected by non-linear loads and linear impedance and harmonic currents absorbed by the shunt capacitors between i and j buses in the h-order harmonic.

Line voltage drop caused by the system harmonic vector will be as follows:

$$\Delta V_{ij}^{(h),k} = Z_{ij}^{(h)} \left[A_{ij}^{(h),k} \right]^T \left[I^{(h),k} \right] \qquad (10)$$

[HA$^{(h)}$] is the connecting matrix between the bus voltage vector and the system harmonic vector and [Has$^{(h)}$] is composed of row vectors in accordance with the buses of the shunt capacitors. This relationship can be written as follows:

$$\left[V^{(h),k} \right] = \left[HA_{ij}^{(h),k} \right] \left[I^{(h),k} \right] \qquad (11)$$

$$\left[Vs^{(h),k} \right] = \left[HAs^{(h),k} \right] \left[I^{(h),k} \right] \qquad (12)$$

$$Vs_i^{(h),k} = -Is_i^{(h),k} \times Zs_i^{(h)} \qquad (13)$$

So

$$\left[HLF^{(h),k} \right] \left[Is^{(h),k} \right] = -\left[HA_{sh}^{(h),k} \right] \left[Ih^{(h),k} \right] \qquad (14)$$

3-2-2 Current Forward Sweep

Now, one can easily calculate line current, voltage drop and the voltage of buses caused by harmonic currents:

$$\left[V^{(h),k+1} \right] = \left[V^{(h),0} \right] + \left[V^{(h),k} \right] \qquad (15)$$

Now, this repetition for h-order harmonic continues until the following criterion is reached:

$$\left| V_i^{(h),k+1} - V_i^{(h),k} \right| \leq \varepsilon \quad \text{for } i = 1 \cdots N \qquad (16)$$

3.3 Modeling Components
3-3-1 Load Model

Load model is generated by using the IEEE-RTS system in which the data on the intensity of solar radiation and wind speed are modeled hourly by beta and weibull Pdf$_s$. Each year is divided into four seasons and one day is considered to represent that season. Therefore, there will be 96 different time sections

Figure 2 and Table 1 show the load model and the specifications of non-linear loads in the considered system.
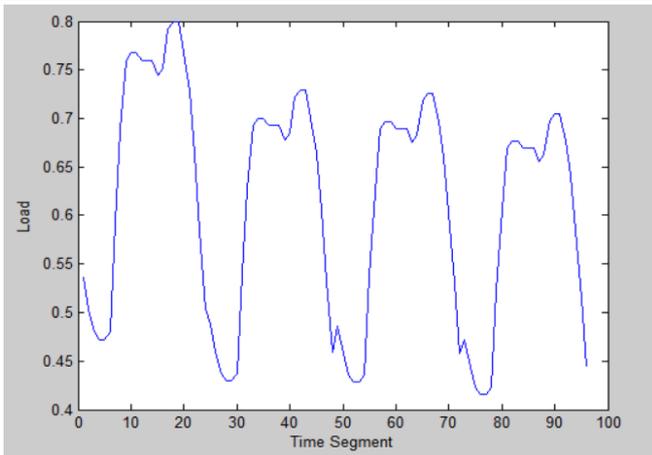
Figure 2. Load Model

Table 1. Specifications of non-linear loads

Bus number	non-linear load Type	kW	kVAR
6	bandwidth module	575	626
8	PWM ASD first speed drive	1447	758
12	The first six-pulse	1147	576
17	PWM ASD second speed	500	700
21756	The third six-	1315	756
25	six-pulse VFD	457	229
30	The second six-pulse	527	442

3-3-2 Wind Speed Model

A common expression for the wind speed is a function of rail probability density [12]:

$$f(v) = \left(\frac{2v}{c^2}\right)\exp(-(v/c)^2) \tag{17}$$

$$v_m = \int_0^\infty vf(v)dv = \int_0^\infty \left(\frac{2v^2}{c^2}\right)\exp(-(v/c)^2)dv = \sqrt{\pi}/2 \tag{18}$$

$$c = 1.128V_m$$

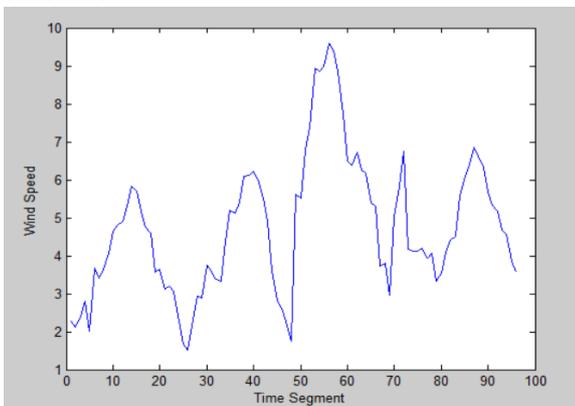Where v is the wind speed and c is the scale parameter.

Figure 3. Annual curve of the wind speed in the studied problem

3-3-3 Intensity of the Solar Radiation Model

Beta probability density function is used for the intensity of solar radiation.

$$f_b(s) = \begin{cases} \dfrac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} s^{(\alpha-1)}(1-s)^{(\beta-1)} & ,0 \le s \le 1 \\ 0, ow \end{cases} \tag{19}$$

Where s is the intensity of solar radiation in kW/m^2, f probability density function. S, α and β are parameters of unction Γ. Figure 3 and 4 show the annual curve of wind speed and the annual curve of the solar radiation in the studied system, respectively.
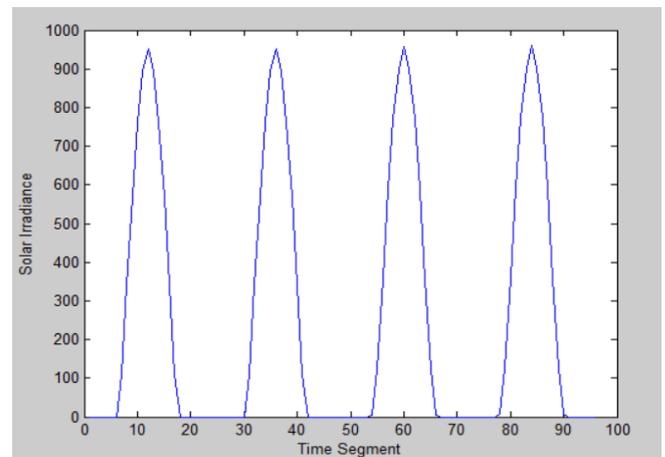

Figure 4. Annual solar radiation intensity curve

3-4 Calculating Output Power
3.4.1 Wind Turbine

Based on the available information on the wind turbine, the output power is calculated based on the following equation:

$$P(v) = \begin{cases} 0, & 0 \le v_i \le v_{ci} \\ P_{rated} * \dfrac{(v_i - v_{ci})}{(v_r - v_{ci})}, & v_{ci} \le v_i \le v_r \\ P_{rated} * h_{vi}, & v_r \le v_i \le v_{co} \\ 0, & v_i \le v_{co} \end{cases} \tag{20}$$

The output power of a wind turbine depends on the wind speed.

3-4-2 Solar Cell

The output power of the solar cell depends on the intensity of solar radiation and the region temperature. First, the beta probability density function for each time zone is generated and its output power is calculated based on different obtained states by this Pdf.

3-5 Scenario Plans

Scenario 1: In this scenario, none of the distributed generation resources is not connected to the system.
Scenario 2: In this case, only non-renewable distributed generation resource with fixed power is connected to the distribution network.
Scenario 3: In this scenario, a single wind turbine and the non-renewable distributed generation resource are added to the system.
Scenario 4: There are a solar unit and a non-renewable distributed generation resource in the system.
Scenario 5: In this scenario, two wind turbines and a solar unit are added to the system.

4-Simulation and Comparison of the Selected Scenarios

4.1 Scenario 1

In this scenario in which none of the distributed generation resources is not connected to the system, the annual energy loss is equal to[1]:

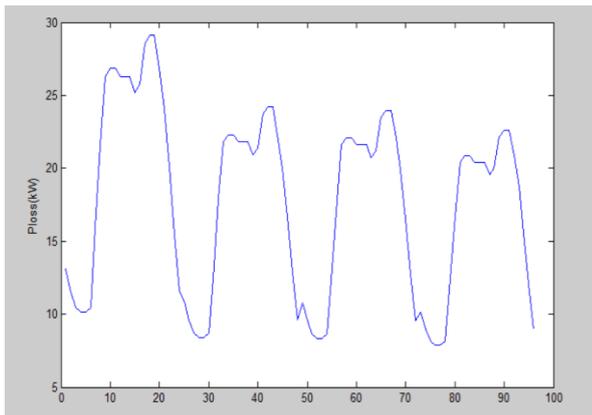$$\mathbf{P_{loss}} = 1.4964 \times 10^7 \, kWh$$

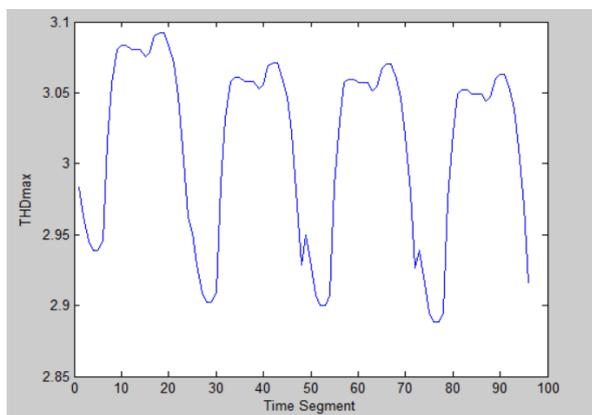Figure 5. The curve of annual losses in watts for the scenario 1

Figure 6. The maximum THD on an annual basis for the scenario 1

4.2 Scenario 2:

In this case, a single non-renewable distributed generation unit as much as 6.5 MW at bus No. 6 is the optimal result of this scenario and the losses in this case are equal to:
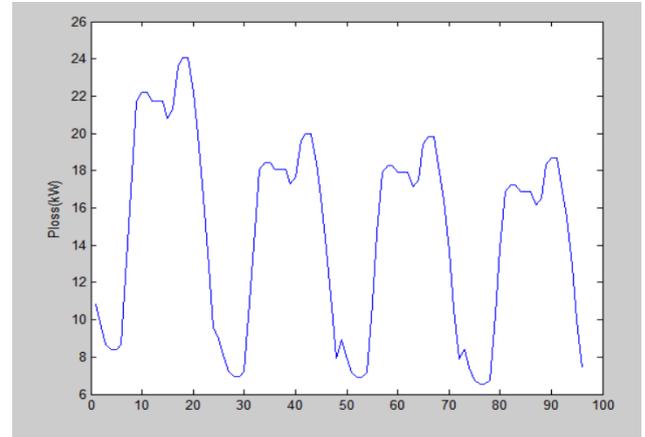
$$P_{loss} = 1.2346 \times 10^7 \, kWh$$

Figure 7. Annual losses curve resulting from Scenario 2

Figure 8. The maximum THD on an annual basis for the scenario 2

Figure 9. The objective function curve obtained from the genetic algorithm for scenario 2

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[1] In order to optimize, GA tool of the MATLAB software is used.

4.3 Scenario 3:

The non-renewable unit with 15% of contribution and the wind unit with 85% of contribution are connected to the bus No. 30 and the bus No. 17, respectively. In this case, the annual losses will be equal to $1.1757 \times 10^7 kWh$.

Figure 10. The annual losses curve resulting from Scenario 3
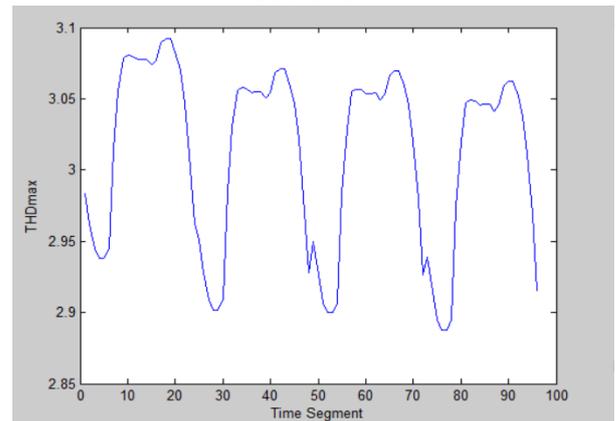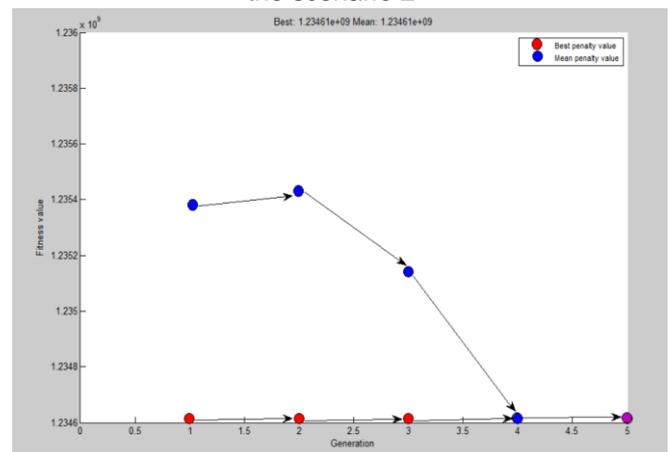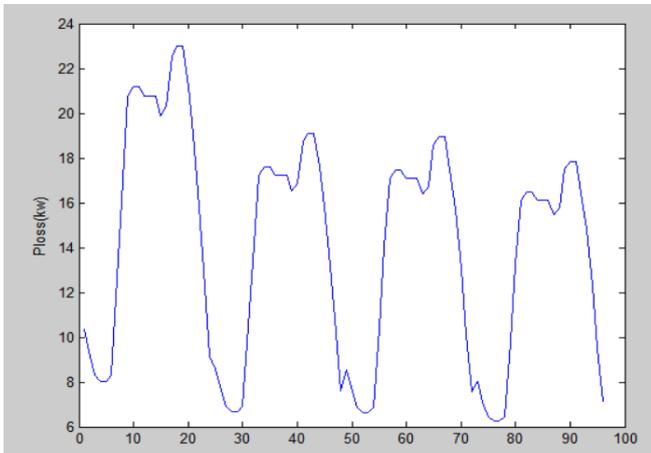

Figure 11. The maximum THD on an annual basis for the scenario 3

Figure 12. The objective function curve obtained from the genetic algorithm for scenario 3

4.4 Scenario 4:

In this scenario, the non-renewable unit with 10% of contribution and the solar unit with 90% of contribution are connected to the bus No. 18 and the bus No. 28, respectively. In this case, the annual losses will be equal to P_{loss}= $1.1757 \times 10^7 kWh$.

Figure 13. The annual losses curve resulting from Scenario 4
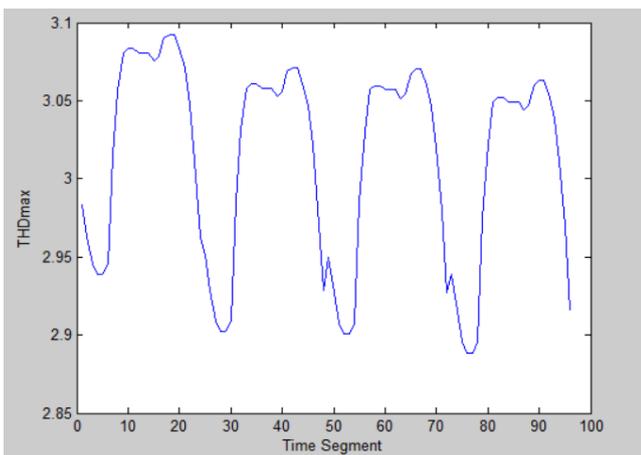

Figure 14. The maximum THD on an annual basis for the scenario 4

Figure 15. The objective function curve obtained from the genetic algorithm for scenario 4

4.5 Scenario 5:

In this case, a wind unit with 15% of contribution and a wind unit with 90% of contribution are connected to the bus No. 6 and the bus No. 25, respectively. Moreover, a solar unit with 52% of contribution is connected to the bus No.17. In this case, the annual losses will be equal to:

Ploss= $1.1763 \times 10^7 \, kWh$

Figure 16. The annual losses curve resulting from Scenario 5

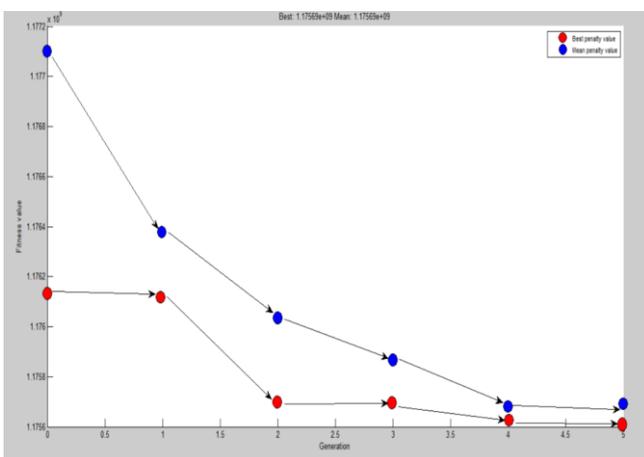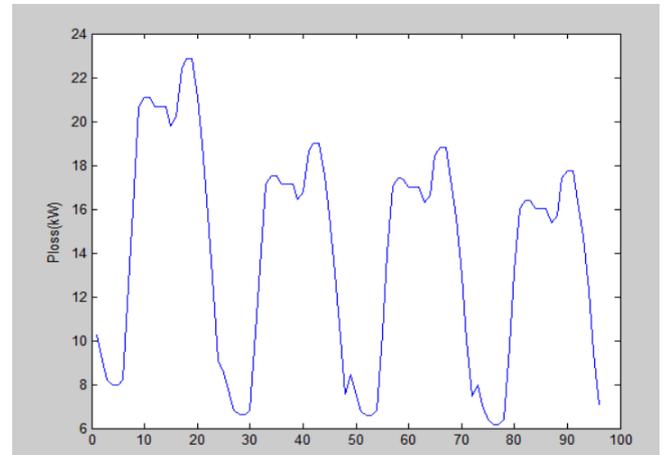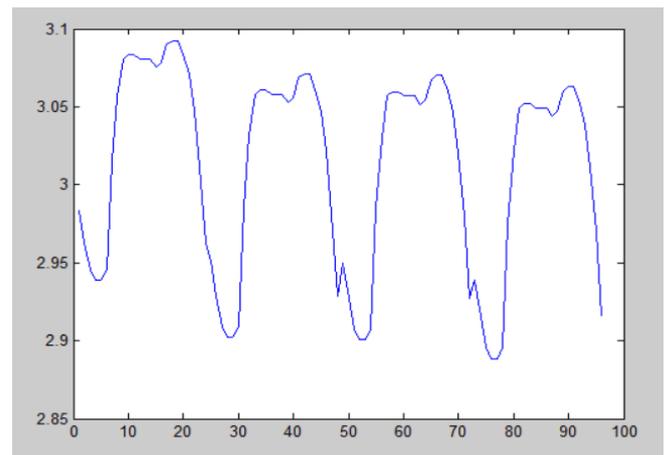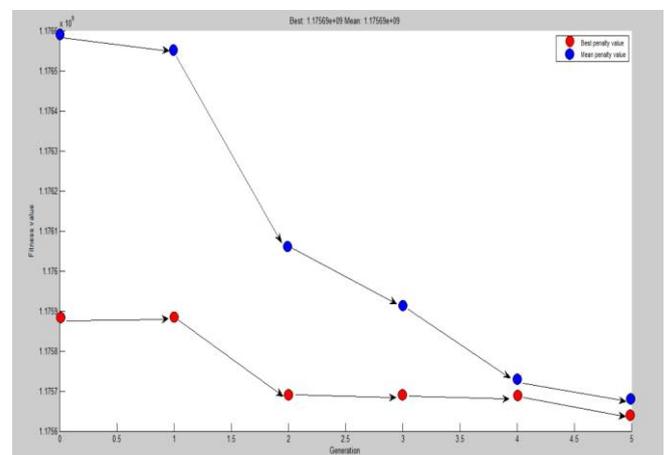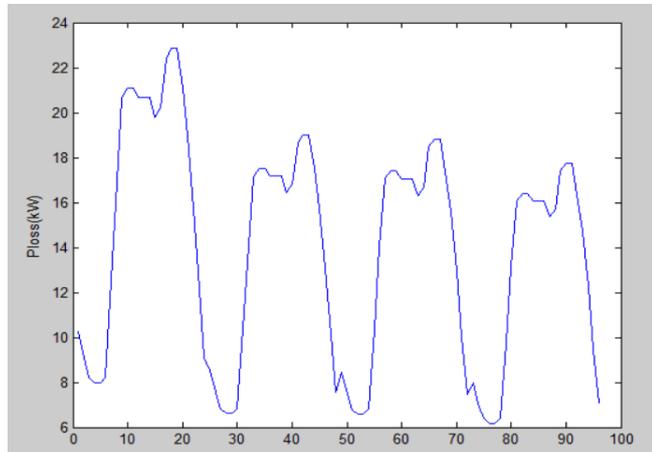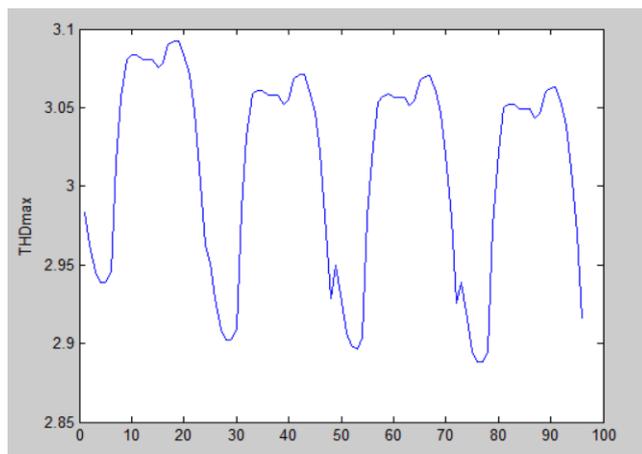Figure 17. The maximum THD on an annual basis for the scenario 5
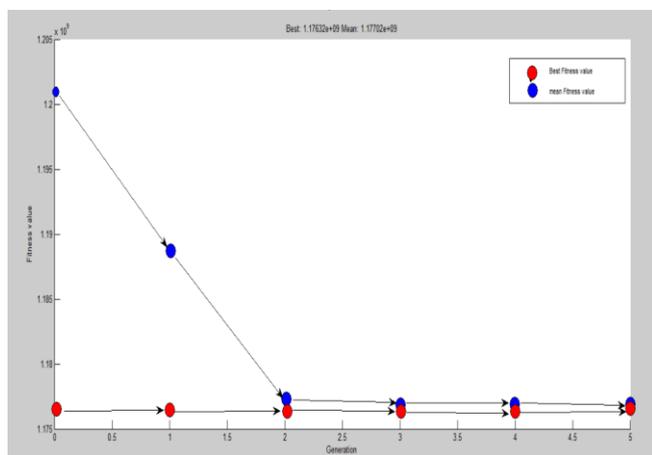
Figure 18. The objective function curve obtained from the genetic algorithm for scenario 5

4-6 Results of Solar and Wind Resources Placement Based on Genetic Algorithm Analysis

To address the issue, a genetic algorithm which produces 10 chromosomes per iteration is used. Each chromosome shows the position of distributed generation resources and their genes represent the position of each resource. The first and second genes show the position of the first and second wind turbines, respectively. The third gene shows the position of solar power plant in the micro-grid. This table shows the investigation results of a generation:

Table 2. Optimization results

Chromosome			Fitness value*
#	**Gene 1**	**Gene 2**	**Gene 3**	
1	**18**	**31**	**13**	**1.1760**
2	**21**	8	**6**	**1.1775**
3	**28**	8	**12**	**1.1773**
4	**6**	18	8	**1.1776**
5	**15**	18	18	**1.2346**
6	**8**	**12**	**17**	**1.1776**
7	**17**	**30**	**21**	**1.1761**
8	**20**	**12**	**15**	**1.1778**
9	**21**	**13**	**21**	**1.2363**
10	**17**	**12**	**15**	**1.1776**

* This column is multiplied by 10^7.

4.7 Analysis Based on Losses in Scenarios 1 and 5 in Summer:

This table shows that energy losses in Scenario 5 to Scenario 1 have fallen about 13% at all hours of the summer. In scenario 1, losses in some hours of the summer exceeded 25 kW while the amount of losses never exceeded 22 kW in scenario 5 because of positioning distributed generation resources.

Table 3. Comparison of Scenarios 1 and 5 regarding the losses

Hour	Scenario 1	Scenario 5	Percentage of drop
1	11.8825	10.2650	13.6162
2	10.5061	9.0759	13.6162
3	9.5293	8.2321	13.6162
4	9.2143	7.9600	13.6162
5	9.2143	7.9600	13.6162
6	9.5293	8.2321	13.6153
7	14.4957	12.5224	13.6107
8	19.5794	16.9141	13.6012
9	23.8931	20.6406	13.5917
10	24.4001	21.0785	13.5781
11	24.4009	21.0792	13.5703
12	23.8957	20.6428	13.5654
13	23.8954	20.6426	13.5572
14	23.8949	20.6421	13.5408
15	22.8982	19.7811	13.5530
16	23.3916	20.2073	13.5822
17	25.9444	22.4126	13.6019
18	26.4704	22.8670	13.6084
19	26.4703	22.8669	13.6159
20	24.3951	21.0742	13.6157
21	21.9201	18.9361	13.6162
22	18.2354	15.7530	13.6162
23	14.1060	12.1858	13.6162
24	10.5061	9.0759	13.6162

Figure 19. Comparison of scenarios 1 and 5 based on losses (lower: Scenario 5 and upper: Scenario 1)

4-8 Analysis Based on Maximum Harmonic Distortion

Reviewing the maximum THE in the scenarios 1 and 2 in the summer in Table 4 shows that using a non-renewable distributed generation resource reduces THD.

Table 4. The results of maximum THD in the scenarios 1 and 2

Hour	Scenario 1	Scenario 2	Percentage of drop
1	2.9834	2.9834	0
2	2.9623	2.9623	0
3	2.9447	2.9447	0
4	2.9384	2.9384	0
5	2.9384	2.9384	0
6	2.9447	2.9447	0
7	3.0147	3.0142	0.0004
8	3.0564	3.0551	0.0012
9	3.0806	3.0787	0.0019
10	3.0830	3.0805	0.0025
11	3.0829	3.0800	0.0029
12	3.0805	3.0774	0.0031
13	3.0805	3.0776	0.0029
14	3.0806	3.0781	0.0025
15	3.0756	3.0737	0.0019
16	3.0782	3.0771	0.0011
17	3.0901	3.0897	0.0003
18	3.0923	3.0923	0
19	3.0923	3.0923	0
20	3.0832	3.0832	0
21	3.0706	3.0706	0
22	3.0472	3.0472	0
23	3.0106	3.0106	0
24	2.9623	2.9623	0

However, because of lack of added productive capacity, the difference is not significant. To prove to this issue, a new scenario instead of the scenario 2 is considered. A non-renewable unit as much as 1 MW is added to the bus 6. The result of comparing two scenarios 1 and 2b in summer are as follows:

Table5- THD maximum between the two scenarios 1 and 2b

Hour	Scenario 1	Scenario 2b	Percentage of drop
1	2.9834	2.7033	9.3885
2	2.9623	2.6721	9.7957
3	2.9447	2.6466	10.1220
4	2.9384	2.6377	10.2349
5	2.9384	2.6377	10.2349
6	2.9447	2.6466	10.1220
7	3.0147	2.7507	8.7552
8	3.0564	2.8166	7.8431
9	3.0806	2.8564	7.2765
10	3.0830	2.8600	7.2320
11	3.0829	2.8597	7.2426
12	3.0805	2.8554	7.3076
13	3.0805	2.8556	7.3028
14	3.0806	2.8559	7.2919
15	3.0756	2.8480	7.3993
16	3.0782	2.8529	7.3185
17	3.0901	2.8736	7.0052
18	3.0923	2.8777	6.9404
19	3.0923	2.8777	6.9405
20	3.0832	2.8621	7.1702
21	3.0706	2.8409	7.4788
22	3.0472	2.8025	8.0285
23	3.0106	2.7447	8.8319
24	2.9623	2.6721	9.7957

Light diagram is related to the new scenario and shows lower THD compared to the dark diagram.
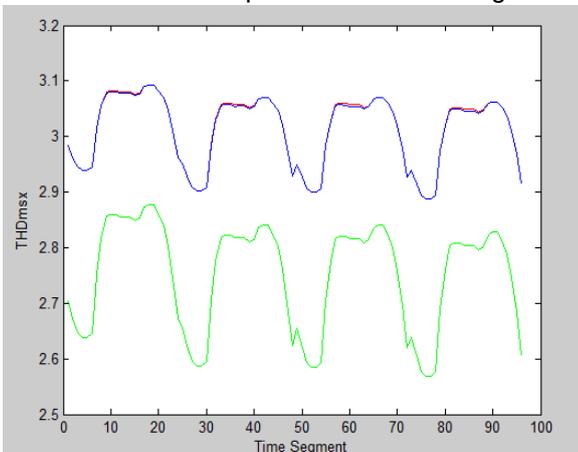

Figure 20. Comparative diagrams of the annual maximum THD figures for scenarios 1, 2 and 2 B (respectively upper, top of the upper and lower)

4-9 Analysis Based on Maximum Harmonic Distortion Generation in The Scenarios 1 and 4

In scenario 1, only non-linear loads act as a resource of harmonic generation and in scenario 4, a solar source as a new harmonic source is added to this resources.

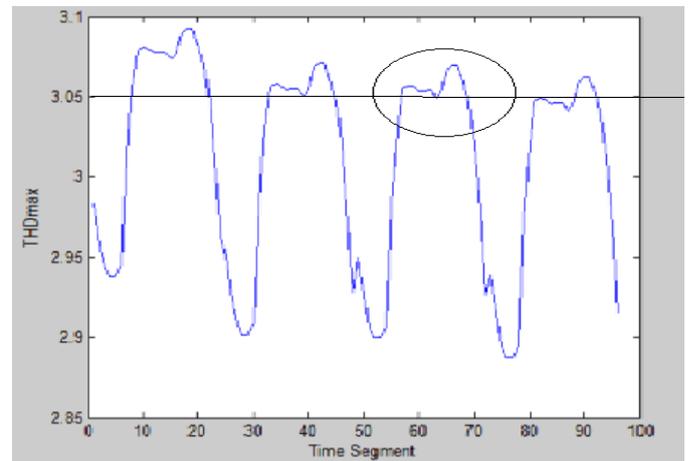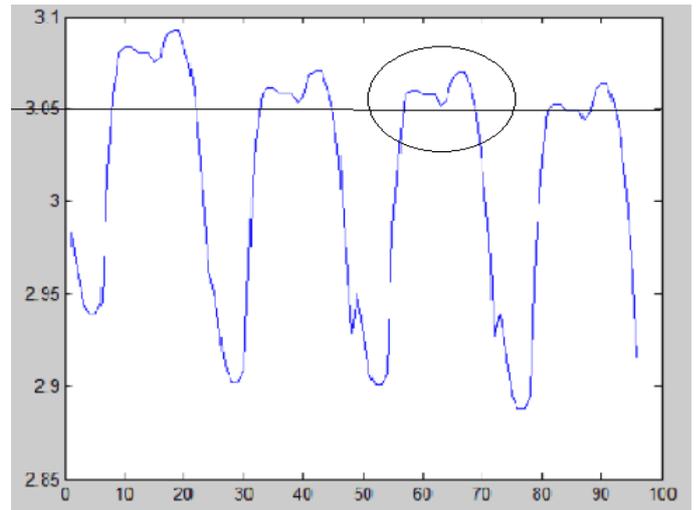Figure 27 and Table 6 compares scenarios 1 and 4 of THDmax to show that.

Figure 21. Comparison of Scenarios 1 and 4 regarding THD_{max} (lower: Scenario 4 and upper: Scenario 1)

Table 6. THD increase for scenario 4 compared to Scenario 1

Hour	scenario1	scenario 4	Percentage of drop
1	2.9834	2.9837	0.0111
2	2.9623	2.9627	0.0117
3	2.9447	2.9451	0.0122
4	2.9384	2.9388	0.0123
5	2.9384	2.9388	0.0123
6	2.9447	2.9451	0.0122
7	3.0147	3.0150	0.0102
8	3.0564	3.0566	0.0089
9	3.0806	3.0809	0.0082
10	3.0830	3.0832	0.0081
11	3.0829	3.0832	0.0081
12	3.0805	3.0808	0.0082
13	3.0805	3.0808	0.0082
14	3.0806	3.0808	0.0082
15	3.0756	3.0759	0.0084
16	3.0782	3.0785	0.0083
17	3.0901	3.0903	0.0079
18	3.0923	3.0926	0.0078
19	3.0923	3.0926	0.0078
20	3.0832	3.0834	0.0081
21	3.0706	3.0708	0.0085
22	3.0472	3.0474	0.0092
23	3.0106	3.0109	0.0103
24	2.9623	2.9627	0.0117

According to the table, by adding a solar source as a new harmonic source to the THD system, the maximum for buses had a natural increase. However, due to low capacity injection into the manufacturers in this issue, this difference does not seem to be significant.

Figure 27 and Table 6 show the comparisons of Scenarios 1 and 4 in terms of THD_{max}.

Figure 21. Comparison of Scenarios 1 and 4 in terms of THD_{max}

Table 6. THD increase for Scenario 4 with respect to Scenario 1

5. Conclusion

In this paper, distributed generations were used to reduce losses in the harmonic polluted distribution system. This approach faces some critical challenges, one of which is the load flow in the distribution system despite the presence of harmonic loads. The forward/backward sweep method was used to solve the problem. Another challenge is the issue of uncertainties in wind speed and solar radiation for the renewable distributed generations. For the purpose of resolving this issue, the railway and beta probability density functions are used. The use of renewable resources that are properly located significantly reduces the loss rate while they could have a negligible impact on THD which does not make it over the limit.

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