Power Distribution Network Voltage Profile Enhancement with the Presence of Renewable DG

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***Abstract*—This paper presents power distribution network voltage profile enhancement with the presence of renewable DG. The study involves the utilization of sensitivity analysis (SA) as an analysis tools of determination of renewable DG installation location in the distribution system. However, only two types of renewable DG are presented in this paper which are solar DG and wind DG. Then, an optimization technique so called as Evolutionary Programming (EP) is used to determine the optimal size of the renewable DG based on minimum voltage enhancement. The simulation will be carried on the IEEE 15 Bus Radial Distribution System. Response for voltage profiles enhancement were observed during with or without renewable DG. Results obtained from the proposed techniques revealed that the voltage of power distribution network can be enhanced with the presence of renewable DG.**

Index Terms*—*Voltage Improvement, Reactive Loading, Evolutionary Programming, Sensitivity Analysis.

I. Introduction

Global economic growth forced utility companies to expand electrical grid in order to meet the increasing demand of electricity. However, this could not be achieved in short time due to several limitation. Therefore power system problems such as voltage outages, breakdowns, lightning and switching surges which in turn leads to system collapse may occur. Besides, researches have been conducted prove that the rate of emissions due to conventional method of using fossil fuel as energy sources have been increasing throughout the years; hence causes global warming [1]. Therefore, renewable energy offers promising alternative to improve power distribution network system in term of stability, voltage enhancement, loss reduction and provide solution to the problem of high greenhouse gas emissions [2].

Renewable Distributed generation (DG) is normally defined as small generation units which generation capacity of less than 10MW that uses renewable resources such as fuel cells, wind farm and photovoltaic installed in the distribution system that is not a part of central power system and is located close to the load [3]. The integration of DG in the distribution system can significantly impacts the power flow and voltage profile of the system. However the integration of DG into the distribution system is not an easy task. The placement and sizing of DG at non-optimal places can result in increase in system loses, voltage fluctuations, system collapse and implying in an increase in generation costs and therefore having the negative impact to the power system [4]. Therefore, an optimal size DG should be allocated in a way such that it enhances system performance and reduces system loss [2].

Voltage Profile Enhancement is a process of increasing the voltage in a power system network. The voltage is increased to its possible maximum acceptable voltage profile to prevent voltage instability in power system network which can cause voltage collapse in the system hence increase the cost for power system planning. Voltage profile enhancement can be achieved through power compensation schemes such as Distributed Generation (DG), Active Power Scheduling (APS), Transformer Tap Changer Setting (TTCS), Reactive Power Dispatch (RPD), and Static VAR compensation[5].

It is essential to determine the size and location of renewable DG to improve distribution network voltage. In practice, voltage sensitivity factor calculates which bus candidate that donates the highest voltage sensitivity to the injected active and reactive power. The highest the voltage stability indicates the best bus candidate for DG placement [4]. In [6], bus which sensitive to the active power loss due to the injected power is as the sensitive bus of the system. This analysis is called as loss sensitivity analysis. While in [7] sensitivity analysis based on voltage sag is proposed for DG placement the bus that suffer the highest number of voltage sag due to the randomly faults generated is considered as the best bus for DG placement.

While for DG sizing, in [4, 6] the authors proposed evolutionary programming (EP) to determine the optimal size of DG such that it reduces power loss and increase the system stability. While in [7], particle swarm optimization technique is used to calculate the optimal sizing of DG considering that the amount of DG will be able to minimize economic loss in the system. In [4] the authors proposed fuzzy logic EP is used to determine the size of DG.

In previous researches, various techniques were used to evaluate system performance. In [2] the authors proposed reactive loadablity as a tool to evaluate system stability as higher amount of maximum reactive load the system can indicate the system is stability. While in [8-11] authors discussed the use of voltage stability index (VSI) in evaluating system stability whereas the system is able to maintain voltage above allowable voltage, the system is categorized as stable. Besides, in [9, 12, 13] loss indices measure the amount the loss in the power system which in turns indicates the system stability. The lower the loss indices determine the system is more stable. While in [12] the authors proposed overall voltage profile improvement in evaluating voltage improvement in the system. This paper only focuses on the enhancement of the system voltage profile. Whereby the improvement could be achieve by installing DG to the system. Hence the sensitivity analysis based on voltage changes due to injected reactive load for renewable DG placement and Evolutionary Programming (EP) based minimum voltage enhancement for DG sizing and selection are the most suitable method to be used. Methods such as sensitivity analysis based on loss indices and voltage sag only applicable on DG placement based on system loss and voltage sag. While, loadability and VSI methods applicable in determine the DG sizing using system loadability and stability which it is not suitable to determine voltage enhancement.

However this research has limitation where voltage profile enhancement technique does not determine the system stability. Hence this this technique could not be used to conclude that with the correct DG placement using the proposed sensitivity analysis and EP the test system stability can be improved.

II. System Modeling

A. Test system

In this paper, IEEE 15 radial distribution system bus is considered as shown in Figure 1. Here bus 1 is connected to the main grid. The base power is 100kVA and the base voltage is 11kV, total load in the system is 1.2264 MW, 1.2476 MVAr [14]. The distribution lines are modeled as R+jX. The test system data with distribution of system loads in different nodes are given in appendix.

B. Renewable DG modelling

In this paper as for problem solving of sizing and placement of DG distribution system, there are four types of DG can be used[15].

1. Type I

Type I DG is a DG which supplies only real power to the distribution network. Photovoltaic system is an example of Type I DG.

2. Type II

Type II DG is a DG which supplies only reactive power to the distribution network. Synchronous generator is an example of Type II DG.

3. Type III

Type III DG is a DG which consumes reactive power to produce real power to the distribution network. Wind turbine uses induction generator to generate electricity but they consume reactive power to produce real power. Wind turbine is an example of Type III DG.

4. Type IV

Type IV DG is a DG which regulates the bus voltage in distribution network. Type IV DG unit produce real power injection by the DG will require reactive power to regulate the bus voltage.

In this research only two types of DG will be used which are Type I (photovoltaic system) and Type III (wind farm).

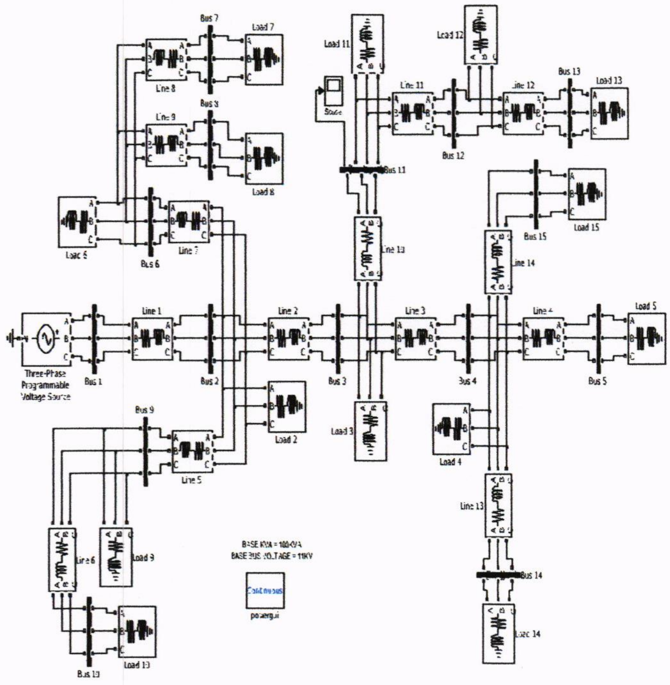

Figure 1 IEEE 15 radial distribution system bus

III. Methodology

This research proposed the implementation of renewable DG integration into power distribution system using sensitivity analysis and evolutionary programming to determine the suitable renewable DG placement and optimal renewable DG sizing. Hence, the following presents the methodologies of conducting this research.

A. Sensitivity Analysis for renewable DG placement

In this paper the sensitivity analysis starts with calculations of sensitivity of the change in bus voltage profile with respect to the changes of reactive power demand in the distribution system. Sensitivity value can be formulated as shown in Equation 1.

$$\frac{\partial\alpha}{\partial\beta} = \frac{\partial\alpha_1 - \partial\alpha_2}{\partial\beta_1 - \partial\beta_2}\, x\, 100\% \qquad (1)$$

The highest sensitivity value indicates the bus is the bus is the most sensitive to the change of reactive power while the sensitivity value indicates the bus is the least sensitive to the change of reactive power. Figure 2 flowchart proposed for DG placement using sensitivity analysis.

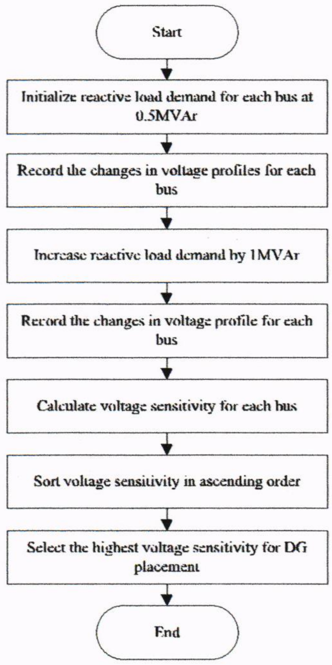

Figure 2 DG placememt flowchart

B. Evolutionary Programming for renewable DG sizing

The one of the objectives of this paper is to determine the suitable DG the optimal size of renewable DG so that minimum voltage of the system could be enhanced[16]. Thus, EP based minimum voltage profile enhancement with the incremental of reactive load is used to calculate the optimal size of renewable DG. Hence, for each incremental of reactive load, new optimal DG size will be calculated that enhance the minimum voltage profile. As a result, a set of renewable DG size is produced for each incremental of reactive load. Thus, only particular DG size that is repetitively produced will be selected as the suitable DG size to be installed.

1) Minimum allowance voltage profile

Load flow program based on the maximum loading condition for selected bus is initially run in order to determine and set the voltage constrain or minimum allowance of voltage profile of the system.

2) Initialization

Initially, a series of random number are generated to represent the new renewable DG size to be installed at bus x which functioned as the control parameters. The selected bus x with the population size is 20, therefore 20 random number for variables namely x_{solar} were generated ranging from$\left[P_{Gxsolar}^{min}, P_{Gxsolar}^{max}\right]$ for solar type DG, x_{wind} $\left[P_{GxwindP}^{min}, P_{GxwindP}^{max}\right]$ and $\left[Q_{GxwindQ}^{min}, Q_{GxwindQ}^{max}\right]$ for wind type DG. These variables are assigned to represent the renewable DG size to be installed at bus x. These parameters are initial populations or parents. The fitness constraint is set so that the 20 random numbers for each variable are generated by program is satisfying the predetermined fitness.

3) Fitness 1 Computation

Fitness is the equation to be optimized. For this study, the minimum voltage profile is the fitness equation. The minimum voltage profiles and transmission losses for all 20 accepted populations in the pool are calculated in the m. file name 'Fitness_01'.

4) Mutation

Mutation is performed on the random number, x_i to produce offsprings. It is implemented using Gaussian Mutation Technique based on the Equation 2:

$$x_{i+m,j} = x_{i,j} + N\left(0, \beta\left(x_{jmax} - x_{jmin}\right)\left(\frac{f_i}{f_{max}}\right)\right) \tag{2}$$

Where:

$x_{i+m,j}$ = Offspring
$x_{i,j}$ = parents
N = Gaussian random variable with Mean μ and variance γ^2
B = mutation scale, $0 < B < 1$
x_{jmax} = Maximum random number for every variable
x_{jmin} = Minimum random number for every variable
f_i = Fitness for the i random number
f_{max} = Maximum fitness

5) Fitness 2 Computation

In this process, new voltage profile are calculated using the offsprings generated in mutation process. These data are arranged in array out3 which have the same matrix size as array out2.

6) Combination and Selection

The offspring produced from the mutation process are combined with the parents to undergo a selection in order to identify the candidates that have chance to be transcribed into the next generation. By combining the parents and offsprings in series, the number of rows will be doubled. The purpose of selection process is to select the survival of the fittest. Since the objective of this study is to maximize the minimum voltage profile as the fitness, therefore the population will be ranked in descending order based on the minimum voltage profile value. The first half (20) population will be taken as the new generation.

7) Stopping Criterion

Convergence Test is specified by the difference in maximum fitness and minimum fitness must be less than or equal to 0.0001 as in Equation 3. If it is not reached, the process will repeat.

$$fitness_{max} - fitness_{min} \leq 0.0001 \tag{3}$$

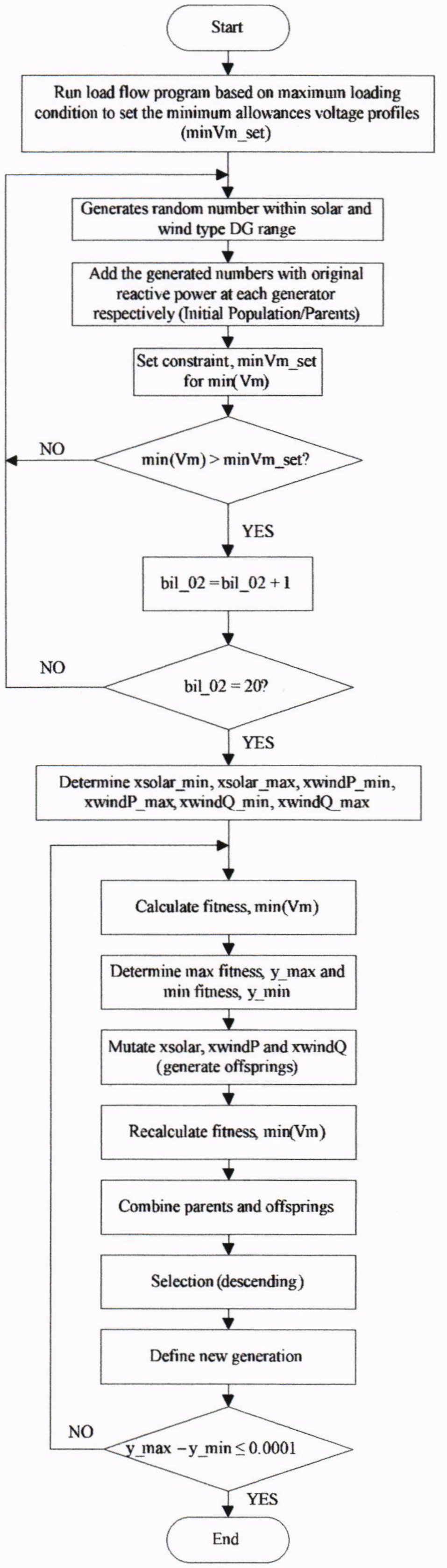

Figure 3 Flowchart of DG sizing using EP

C. DG Size selection

The selection of DG sizing is conducted by observing which DG size enhance voltage profiles the most. EP process produces forty sets of optimal DG sizes for both DG types. However the produced DG sized are already optimized such that each DG size improves the minimum voltage of the system. Hence no additional process required to be conducted in order to select the DG size. As a result, the selection will be conducted by selecting the first rank of the DG size produced by EP.

IV. RESULT AND DISCUSSION

A. Base case

Base case is where the load flow program is run using the default value of line and bus data of the test system to obtain the results as reference to this research. Henceforth, voltage profiles obtained towards the completion of this research will be compared to the reference in order to determine the any improvement from the proposed methodology.

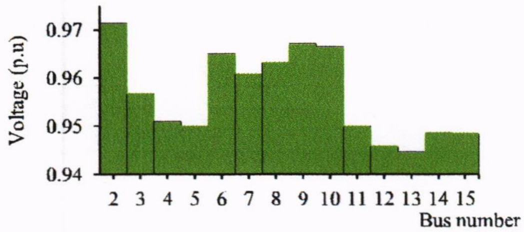

Figure 4 Voltage profile for base case

Figure 4 shows the voltage profile of base case study. Bus 2, 9 and 10 has the highest voltage level at 0.9864, 0.9847, and 0.9843 respectively. As for bus 12, 13, and 15, this bus has the lowest voltage level at 0.9460, 0.9447, and 0.9486 respectively. It can be seen that as the bus 12, 13, 14, and 15 getting further from the generator bus, the voltage drop is becoming significant. While bus 2, 9 and 10 that operated near to the generator bus has higher voltage level.

B. Sensitivity Analysis

Sensitivity analysis as explained in section III (A) was evaluated at each bus. Firstly the voltage changes for each bus is determined and the results were depicted in Table 1(a) and ranked in Table 1(b).

TABLE 1 VOLTAGE PROFILE CHANGES RESULTS

Bus	$V_{changes}$, V
2	0.00614
3	0.01184
4	0.01458
5	0.02150
6	0.00635
7	0.00744
8	0.00665
9	0.00653
10	0.00673
11	0.01808
12	0.02768
13	0.03640
14	0.02415
15	0.02014

(a)

Rank	Bus
1	13
2	12
3	14
4	5
5	15
6	11
7	4
8	3
9	7
10	10
11	8
12	9
13	6
14	2

(b)

Table 1shows that bus 13 with highest voltage changes to the change of reactive load is chosen to be the suitable placement for DG. Next, the test system is further tested with SA technique. Each bus's results are depicted in Table 2(a) and sorted in descending orders as tabulated in Table 2(b). The bus with highest SA value is selected as the optimal place for the DG. Hence, the best renewable DG placement is at bus 13.

TABLE 2 SENSITIVITY ANALYSIS RESULTS

Bus	Sensitivity Analysis (%)
2	1.2282
3	2.3675
4	2.9153
5	4.3009
6	1.2702
7	1.4880
8	1.3295
9	1.3066
10	1.3453
11	3.6155
12	5.5366
13	7.2791
14	4.8300
15	4.0271

(a)

Rank	Bus
1	13
2	12
3	14
4	5
5	15
6	11
7	4
8	3
9	7
10	10
11	8
12	9
13	6
14	2

(b)

The above results show that bus 13 with the highest SA index value is chosen as the optimal placement for the DG. In order to analyze the effectiveness of the result, a 50 kW sized DG is installed to bus 13. As a result the test system improves the minimum voltage at bus 13 from 0.9447 to 0.9486. As comparison similar DG sized is installed at different bus; bus 2 and 7. As a result the test system improves the minimum voltage at bus 13 to 0.9453.

TABLE 3 IMPACT ON VOLTAGE PROFILE TO PROPER DG PLACEMENT

Bus no.	Voltage, (V)	Improved voltage, (V)	Improved voltage, (%)
13	0.9483	0.004	0.4235
2	0.9453	0.001	0.1058
7	0.9453	0.001	0.1058

C. Maximum Loading Condition

To determine voltage constraint for DG sizing, first maximum loading condition of selected bus; bus 13 is obtained. Figure 5 shows the maximum loading condition of all buses in the system. The test system shows that bus 13 can only sustain as much as 2 MVAr of reactive load demand before the system collapses. Hence, the maximum loading condition required for voltage constraint is 2MVAr.

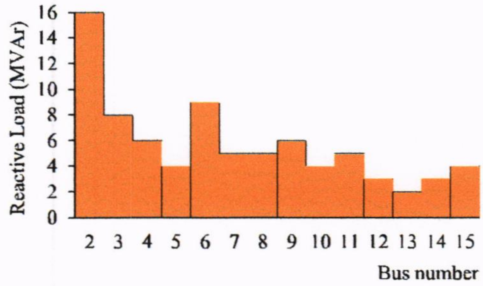

Figure 5 Maximum loading condition for voltage profile constraint

D. DG sizing

As for the selection of the optimal solar DG size, only the first rank of solar DG size produced by EP at each load condition which is 0.0467346 MW is considered as the most optimal DG size to be installed at bus 13. In order to investigate the effectiveness of the results, further study comparing the selected minimum voltage profile of DG size with five randomly chosen DG size with their minimum voltage profile before and after the solar DG installation is conducted.

TABLE tabulate the data of minimum voltage before and after solar DG installed to the test system.

TABLE 4 VOLTAGE PROFILE COMPARISON BETWEEN BEFORE AND AFTER INSTALLATION OF SOLAR DG

Reactive Load (MVAr)	0	1	2
Base case			
DG size	Voltage, V		
-	0.9473192	0.8791186	0.7835306
Base case with wind type DG			
DG size	Voltage, V		
0.0467346	0.9506585	0.8831217	0.7884277
0.0467223	0.9506582	0.8831207	0.7884264
0.0467099	0.9506579	0.8831196	0.7884251
0.0467037	0.9506578	0.8831191	0.7884245
0.0465156	0.9506536	0.8831036	0.7884056
0.0465095	0.9506533	0.8831026	0.7884043

As a result Table 4 shows solar DG with the size of 0.0467346 MW improved the minimum voltage the most for reactive load at 0, 1, and 2 MVAr. Other solar DG sizes are not able to improve the system voltage as much as 0.0467346 MW. Therefore, it can be concluded that the optimal size of solar DG that EP can produced that improved minimum voltage is 0.0467346 MW.

As for wind DG sizing, only the first rank of wind DG size produced by EP which is 0.0465218 MW, 0.0423083 MVAr is considered as the most optimal DG size to be installed at bus 13. In order to investigate the effectiveness of the results, further study comparing the selected minimum voltage profile of DG size with three randomly chosen DG size with their minimum voltage profile before and after the wind DG installation is conducted. Table 5 tabulates the data of minimum voltage before and after wind DG installed to the test system.

TABLE 5 VOLTAGE PROFILE COMPARISON BETWEEN BEFORE AND AFTER INSTALLATION OF WIND DG

Reactive Load (MVAr)		0	1	2
Base case				
DG size		Voltage, V		
-	-	0.9473192	0.8791186	0.7835306
Base case with wind type DG				
DG size		Voltage, V		
0.0465218	0.0423083	0.9516088	0.8863774	0.7933512
0.0465153	0.0423021	0.9516082	0.8863753	0.7933484
0.0465023	0.0422896	0.9516080	0.8863743	0.7933470

As a result Table 5 shows wind DG with the size of 0.0465218 MW, 0.0423083 MVAr improved the minimum voltage the most for reactive load at 0, 1, and 2 MVAr. Other wind DG sizes are not able to improve the system voltage as much as 0.0465218 MW, 0.0423083 MVAr. Therefore, it can be concluded that the optimal size of wind DG that EP can produced that improved minimum voltage is 0.0465218 MW, 0.0423083 MVAr.

E. Comparison base case, base case with and without Renewable DG

With the selected optimal solar and wind type DG sizes obtained, the selected DG sizes was tested on the test system to observe the system's voltage profile. The results obtained are plotted with the base case to observe any voltage profile enhancement after both renewable DG installed. The simulations are conducted separately.

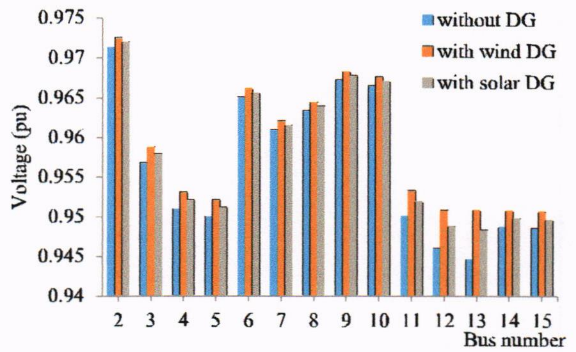

FIGURE 6 COMPARISON OF VOLTAGE PROFILE ENHANCEMENT FOR WITHOUT AND WITH RENEWABLE DG

Figure 7 above shows that there are similarities in all case studies. Firstly, bus2, 9 and 10 remain the highest voltage level of the system. While bus12, 13, and 15 remain lowest voltage level voltage profile of the system. However with renewable DG installed at bus 13, the voltage profile at bus 13 and adjacent buses have significantly improved. For wind type DG the voltage at bus 13 improved as much as 0.9508 compared to 0.9483 for solar type DG. While all the adjacent bus within the DG installation location which is bus 12, 14 and 15 their voltage profiles due to injected active and reactive power to the system. Apparently, all the remaining bus; bus 3, 4, 5, 6, 7, 8, 9, 10 and 11 also experienced small voltage improvement due to the renewable DGs. Clearly, the graph above shows that the wind DG provides the best voltage improvement compared to solar DG.

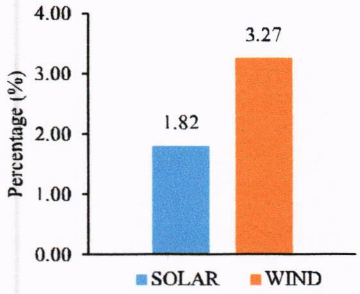

Figure 7 Percentage of voltage improvement for both renewable energy DGs

Figure 8 shows the percentage of overall voltage improvement for both renewable DGs. Solar DG improved overall voltage profile as much as 1.82% while wind DG improved as much as 3.27% which is much higher than solar DG. Henceforth, it can be concluded that voltage profile of power distribution network can be improved as much as 1.82 to 3.27% with the presence of renewable energy DG.

V. CONCLUSION

This research presents power distribution network voltage profile enhancement with the presence of renewable DG. Techniques as so called as sensitivity analysis and evolutionary programming have been used for solving the placement and optimal sizing of renewable DG namely solar DG and wind DG respectively. These techniques was tested on IEEE 15 Bus Radial Distribution System. Sensitivity analysis based on bus voltage changes with respect to the change of reactive load is used to determine the best renewable DG placement. While evolutionary programming with the objective function of maximizing the bus voltage is used to determine the optimal size for both solar and wind DG. As a result, the best renewable DG placement is at bus 13. While the optimal solar type DG and wind type DG size is 0.0465218 MVAr, 0.0465218 MW, 0.0423083 MVAr, 0.0465218 MVAr respectively. Optimal size of solar and wind DG improved the overall bus voltage up to 1.82% and 3.27% respectively.

In conclusion, voltage profile of the power distribution network system can be improved with the presence of renewable DG with the proposed methods. As future recommendation, multiple DG installation approach can be used to in order to provide better voltage profile improvement compare to single DG installation. However this could only be achieved by proper DG placement and sizing. Hence, other optimization technique such Multi-Agent Evolutionary

Programming could be used since the technique provide better optimization process and faster than conventional EP.

VI. APPENDIX

TABLE 4 LINE DATA FOR IEEE 15 BUS RADIAL DISTRIBUTION SYSTEM

Bus	Sending End Bus	Receiving End Bus	Line Data			
			R	X	R_{pu}	X_{pu}
1	1	2	1.3531	1.3235	0.001118	0.001094
2	2	3	1.1702	1.1446	0.000967	0.000946
3	3	4	0.8411	0.8227	0.000695	0.000680
4	4	5	1.5235	1.0276	0.001251	0.000849
5	2	9	2.5573	1.7249	0.002114	0.001423
6	9	10	1.0882	0.7340	0.000899	0.000607
7	2	6	1.2514	0.8441	0.001034	0.000698
8	6	7	2.0132	1.3579	0.001664	0.001122
9	6	8	1.6867	1.1377	0.001394	0.000940
10	3	11	1.7955	1.2110	0.001484	0.001000
11	11	12	2.4484	1.6515	0.002023	0.001365
12	12	13	2.0132	1.3579	0.001664	0.001122
13	4	14	2.3208	1.5047	0.001844	0.001244
14	4	15	1.1970	0.8074	0.000989	0.000667

TABLE 5 BUS DATA FOR IEEE 15 BUS RADIAL DISTRIBUTION SYSTEM

No	P_{load} (MW)	Q_{load}(MVAr)
1	0.000000	0.000000
2	0.044100	0.044100
3	0.070000	0.071414
4	0.140000	0.142830
5	0.044100	0.044100
6	0.140000	0.142830
7	0.140000	0.142830
8	0.070000	0.071414
9	0.070000	0.071414
10	0.044100	0.044100
11	0.140000	0.142830
12	0.070000	0.071414
13	0.044100	0.044100
14	0.070000	0.071414
15	0.14000	0.142830

VII. ACKNOWLEDGMENT

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