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Effects of Distributed Generation penetration on system power losses and voltage profiles

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Abstract- In present times, the use of DG systems in large amounts in different power distribution systems has become very popular and is growing on with fast speed. Although it is considered that DG reduces losses and improves system voltage profile, this paper shows that this is not always true. The paper presents a GA-IPSO based approach which utilizes combined sensitivity factor analogy to optimally locate and size a multi-type DG in IEEE 57-bus test system with the aim of reducing power losses and improving the voltage profile. The multi-type DG can operate as; type 1 DG (DG generating real power only), type 2 DG (DG generating both real and active power) and type 3 DG (DG generating real power and absorbing reactive power). It further shows that though the system losses are reduced and the voltage profile improved with the location of the first DG, as the number of DGs increases this is not the case. It reaches a point where any further increase in number of DGs in the network results to an increase in power losses and a distortion in voltage profile.

Index Terms- Distributed Generation (DG), Particle Swarm Optimization (PSO), Genetic Algorithm (GA), system loss reduction, voltage profile improvement

I. Introduction

Distributed generation (DG) is small-scale power generation that is usually connected to distribution system. The Electric Power Research Institute (EPRI) defines DG as generation from a few kilowatts up to 50MW [1]. CIGRE define DG as the generation, which has the characteristics (CIGRE, 1999): it is not centrally planned; it is not centrally dispatched at present; it is usually connected to the distribution networks; it is smaller than 50-100MW. Ackermann *et al.* have given the most recent definition of DG as: "DG is an electric power generation source connected directly to the distribution network or on the customer side of the meter." [2].
In most power systems, a large portion of electricity demand is supplied by large-scale generators. This is because of economic advantages of these units over small ones. However, in the last decade, technological innovations and a changing economic and regulatory environment have resulted in a renewed interest for DG units. A study by the Electric Power Research Institute (EPRI) indicated that by 2010, 25% of the new generation was to be distributed. Natural Gas foundation concluded that this figure could be as high as 30% [3]. Different technologies are used for DG sources such as photo voltaic cells, wind generation, combustion engines, fuel cells and other types of generation from the resources that are available in the geographical area [4].

Systems Power Loss Minimization and Voltage Profile Improvement

Normally, the real power loss reduction draws more attention for the utilities, as it reduces the efficiency of transmitting energy to customers. Nevertheless, reactive power loss is obviously not less important. This is due to the fact that reactive power flow in the system needs to be maintained at a certain amount for sufficient voltage level. Consequently, reactive power makes it possible to transfer real power through transmission and distribution lines to customers. System loss reduction by strategically placed DG along the network feeder can be very useful if the decision maker is committed to reduce losses and to improve network performance (e.g. on the level of losses and/or reliability) maintaining investments to a reasonable low level [5]. This feature may be very useful in case of revenue recovered by distribution company (DISCO) which is not only based on the asset value but also on network performance. Studies indicate that poor selection of location and size of a DG in a distribution system would lead to higher losses than the losses without DG [6a, 6b]. In a power system, the system operator is obligated to maintain voltage level of each customer bus within the required limit. To ensure voltage profiles are satisfactory in distribution systems, different standards have been established to provide stipulations or recommendations. For example, the American National Standards Institute (ANSI) standard C84.1 has stipulated that voltage variations in a distribution system should be controlled within the range of -13% to 7% [7]. Actually in practice, many electricity companies try to control voltage variations within the range of ±6%. One of the upcoming widely adopted methods for improving voltage profiles of distribution systems is introducing distributed generation (DG) in distribution systems. The DG units improve voltage profiles by changing power flow patterns. The locations and size of DGs would have a significant impact on the effect of voltage profile enhancement.

Distributed Generation penetration, placement and sizing

Usually, DGs are integrated with the existing distribution system and lots of studies are done to find out the best location and size of DGs to produce utmost benefits. The main characteristics that are considered for the identification of an optimal DG location and size are the minimization of transmission loss, maximization of supply reliability and maximization of profit of the distribution companies (DISCOs). Due to extensive costs, the DGs should be allocated properly with optimal size to enhance the system performance in order to minimize the system loss as well as to get some improvements in the voltage profile while maintaining the stability of the system. The effect of placing a DG on network indices usually differs on the basis of its type, location and load at the connection point [8]. Thus interconnection planning of DG to electrical network must consider a number of factors. The factors include DG technology; capacity of DG unit; location of DG connected and network connection type [9, 10].

II. FORMULATIONS

Power flow sensitivity factors

The real and reactive power flow in a line *l* connecting two buses, bus *i* and bus *j* can be expressed as:

$$P_{ij}=V_iV_jY_{ij}\cos(\theta_{ij}+\delta_{ij})-V_i^2Y_{ij}\cos\theta_{ij}$$

$$Q_{ij}=-V_iV_jY_{ij}\sin(\theta_{ij}+\delta_{ij})+V_i^2Y_{ij}\sin\theta_{ij}-\frac{V_i^2Y_{sh}}{2}$$

From these equations the power flow sensitivity factors can be evaluated using;

$$\begin{bmatrix}\frac{\partial P_{ij}}{\partial P_n}\\ \frac{\partial P_{ij}}{\partial Q_n}\end{bmatrix}=\begin{bmatrix}F_{P-P}\\ F_{P-Q}\end{bmatrix}=\left[J^T\right]^{-1}\begin{bmatrix}\frac{\partial P_{ij}}{\partial\delta}\\ \frac{\partial P_{ij}}{\partial V}\end{bmatrix}\qquad\begin{bmatrix}\frac{\partial Q_{ij}}{\partial P_n}\\ \frac{\partial Q_{ij}}{\partial Q_n}\end{bmatrix}=\begin{bmatrix}F_{Q-P}\\ F_{Q-Q}\end{bmatrix}=\left[J^T\right]^{-1}\begin{bmatrix}\frac{\partial Q_{ij}}{\partial\delta}\\ \frac{\partial Q_{ij}}{\partial V}\end{bmatrix}$$

Power loss sensitivity factors

The real and reactive power losses in a line *k* connecting two buses, bus *i* and bus *j* can be expressed as;

$$P_{L(ij)}=g_{ij}(V_i^2+V_j^2-2V_iV_j\cos\delta_{ij})$$

$$Q_{L(ij)}=-b_{ij}^{sh}(V_i^2+V_j^2)-b_{ij}(V_i^2+V_j^2-2V_iV_j\cos\delta_{ij})$$

From these equations the power flow sensitivity factors can be evaluated using;

$$\begin{bmatrix}\frac{\partial P_{L(ij)}}{\partial P_n}\\ \frac{\partial P_{L(ij)}}{\partial Q_n}\end{bmatrix}=\begin{bmatrix}S_{P-P}\\ S_{P-Q}\end{bmatrix}=\left[J^T\right]^{-1}\begin{bmatrix}\frac{\partial P_{L(ij)}}{\partial\theta}\\ \frac{\partial P_{L(ij)}}{\partial V}\end{bmatrix}\qquad\begin{bmatrix}\frac{\partial Q_{L(ij)}}{\partial P_n}\\ \frac{\partial Q_{L(ij)}}{\partial Q_n}\end{bmatrix}=\begin{bmatrix}S_{Q-P}\\ S_{Q-Q}\end{bmatrix}=\left[J^T\right]^{-1}\begin{bmatrix}\frac{\partial Q_{L(ij)}}{\partial\theta}\\ \frac{\partial Q_{L(ij)}}{\partial V}\end{bmatrix}$$

The combined sensitivity factor of each bus is obtained as follows;

$$CSF_i=(F_{P-Pi}\times F_{Q-Pi})+(F_{P-Qi}\times F_{Q-Qi})+(S_{P-Pi}\times S_{Q-Pi})+(S_{P-Qi}\times S_{Q-Qi})$$

Multi-objective function

The multi-objective index for the performance calculation of distribution systems for DG size and location planning considers the below mentioned indices by giving a weight to each index.

Real power loss reduction index

Real Power Loss Reduction Index (PLRI) is expressed as:

$$PLRI=\frac{P_{L(base)}-P_{L(DGi)}}{P_{L(base)}}$$

Reactive power loss reduction index

Reactive Power Loss Reduction Index (QLRI) is expressed as;

$$QLRI=\frac{Q_{L(base)}-Q_{L(DGi)}}{Q_{L(base)}}$$

Voltage profile improvement index

The Voltage Profile Improvement Index (VPII) is defined as;

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$$VPII = \frac{1}{\lambda + \max_{1}^{n}(|1 - V(n)|)}$$

Multi-objective based problem formulation

In order to achieve the performance calculation of distributed systems for DG size and location the Multi-Objective Function (MOF) is given by;

$$MOF = w_1 PLRI + w_2 QLRI + w_3 VPII$$

Where;

w_1 , w_2 and w_3 are the respective weights assigned to each factor.

The sum of the absolute values of the weights assigned to all the impacts should add up to one.

That is;

$$|w_1| + |w_2| + |w_3| = 1$$

These weights are indicated to give the corresponding importance to each impact indices and depend on the required analysis. The weights vary according to engineer's concerns.

Operational constraints formulation

The above formulated multi-objective function is minimized subject to various operational constraints so as satisfy the electrical requirements for the distribution network.

Load balance constraint

For each bus, the following load regulations should be satisfied;

$$P_{gni} - P_{dni} - V_{ni} \sum_{j=1}^{N} V_{nj} Y_{nj} \cos(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0$$

$$Q_{gni} - Q_{dni} - V_{ni} \sum_{j=1}^{N} V_{nj} Y_{nj} \sin(\delta_{ni} - \delta_{nj} - \theta_{nj}) = 0$$

Real and reactive power generation limit

This refers to the upper and lower real and reactive power generation limit of generators at bus-i.

$$P_{gi}^{\min} \le P_{gi} \le P_{gi}^{\max}, i = 1,2,\dots N_g$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max}, i = 1,2,\dots N_q$$

Voltage limit

The voltage must be kept within standard limits at each bus.

$$V_i^{\min} \le V_i \le V_i^{\max}, i = 1,2,\dots. N_b$$

DG real and reactive power generation limit

This includes the upper and lower real and reactive power generation limit of distributed generators connected at bus-i.

$$P_{DGi}^{\min} \le P_{DGi} \le P_{DGi}^{\max}, i = 1,2,\dots N_{DG}$$

$$Q_{DGi}^{\min} \le Q_{DGi} \le Q_{DGi}^{\max}, i = 1,2,\dots N_{DG}$$

III. PROPOSED METHODOLOGY

The flow chart shown gives the implementation steps of the proposed GA-IPSO based approach for optimal allocation of DG units. System power flow and power loss sensitivity factors have being used in order to come up with the candidate buses for DG location. The results of these sensitivity factors are then passed to GA which gives possible DG sizes for each location. This is done by randomly initializing the DG sizes for each location and then optimizing these values using a predefined multi-objective function.

The output of the GA algorithm is handed over to the IPSO for further optimization. The GA output which is handed to IPSO comprise of some sets of solutions each having a DG location and the associated DG size. IPSO then uses these GA optimized results as its set of initial particles. This assists to achieve faster convergence.

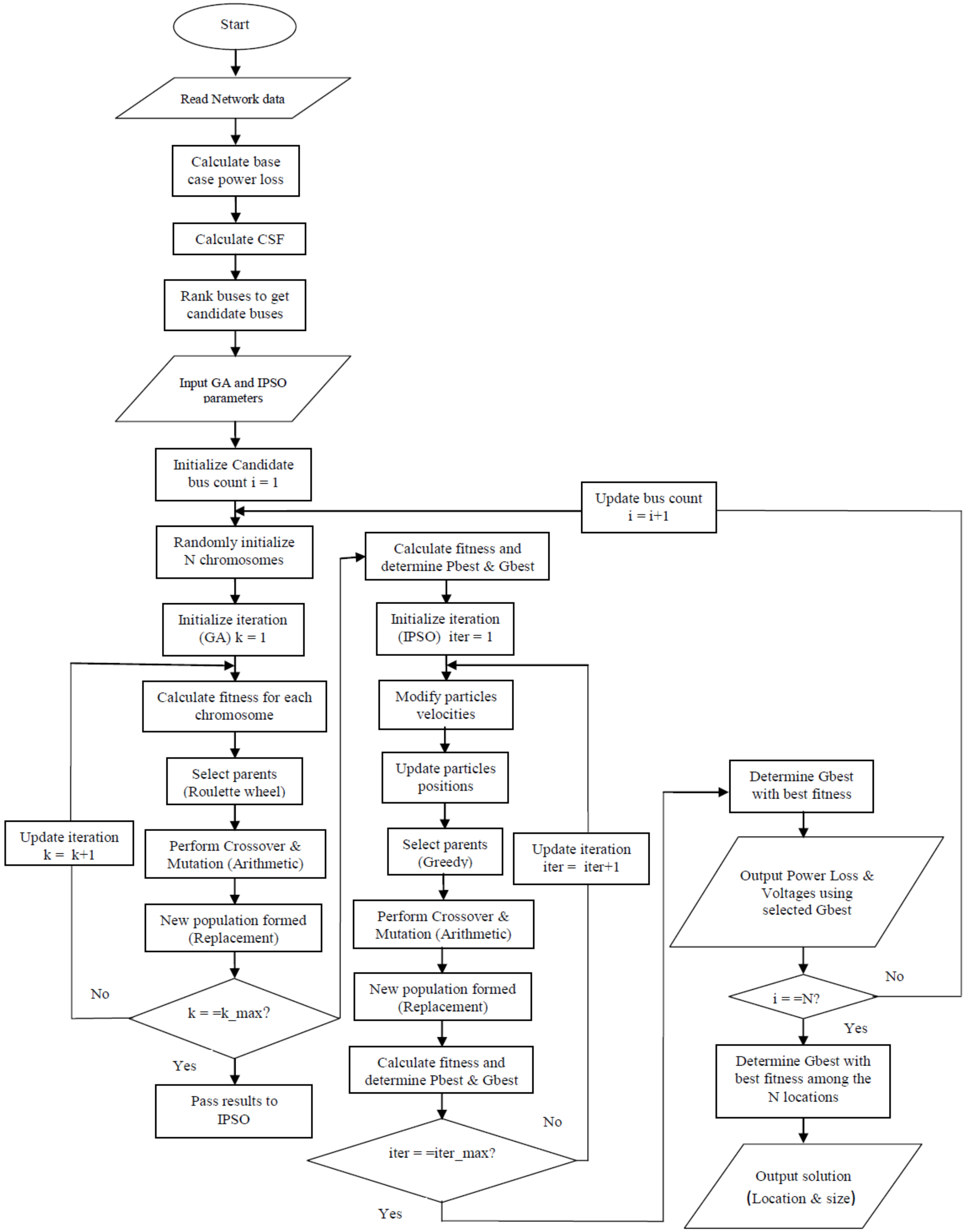

Figure 1: A flowchart for the proposed methodology

IV. RESULTS AND DISCUSSIONS

The number of DGs to be included in a power network can be limited by several factors. The two main factors are the undesirable effects on power system parameters and the economical factors. This research was mainly concerned with the system power losses and the voltage profile of the network and thus the effects of DG penetration on these system parameters have been investigated. Having considered both an interconnected and radial distribution networks and verified the robust of the method [11], the researchers chose an IEEE 57-bus test system for this study. The DG limits were taken to be as follows; 0MW - 48MW for real power limit (Type 1, 2 and 3 DGs), 0Mvar – 12Mvar for reactive power limit (Type 2 DG) and -12Mvar – 0Mvar for reactive power limit (Type 3 DG).

Table 1: Results for CSF, Fitness and optimal DG sizes for Multi-type DGs located on chosen candidate buses

Candidate Bus	Combined Sensitivity Factor (CSF)	Type 1 DG		Type 2 DG		Type 3 DG	
		Best Fitness	Optimal DG Size (MW)	Best Fitness	Optimal DG Size (MW+jMVar)	Best Fitness	Optimal DG Size (MW-jMVar)
20	2.1061	0.9353	33.2021	0.926	37.6749+j11.9859	0.9353	32.7253-j0.001
21	2.8008	0.9004	46.5596	0.8836	48.0000+j10.4589	0.9013	48.0000-j1.5419
22	2.8791	0.8746	46.8139	0.8611	47.9106+j6.3397	0.8777	48.0000-j6.1658
23	2.9762	0.8766	47.3897	0.866	45.8303+j4.6948	0.8831	46.0081-j7.5359
24	3.2714	0.8922	47.4899	0.8909	45.2434+j9.8077	0.897	47.9426-j6.2209
25	5.4205	0.9045	42.6524	0.894	39.1268+j11.7171	0.9057	35.988-j0.0013
26	3.1434	0.8924	47.0261	0.8878	47.9842+j11.4922	0.8924	47.9842-j0.5083
30	6.3047	0.9117	34.919	0.8988	41.4083+j11.9527	0.9127	30.4329-j0.001
31	7.8862	0.9158	28.9128	0.911	28.6948+j3.3142	0.9251	21.8681-j3.1198
32	8.4795	0.9101	33.9803	0.892	40.9075+j10.5395	0.9109	32.1819-j0.2996
33	8.608	0.9164	30.8295	0.8982	35.4590+j12.0000	0.9164	31.3338-j0.001
34	5.4583	0.8809	42.2194	0.8659	48.0000+j10.2438	0.8809	47.3603-j0.8602
35	5.0239	**0.87**	47.9067	0.8666	48.0000+j3.5331	0.8864	47.9929-j8.4063
36	4.5135	**0.8647**	47.2636	**0.8518**	47.6629+j11.9389	**0.8647**	47.6629-j0.0618
37	4.0675	**0.8703**	43.7156	0.8665	43.7301+j6.0236	0.8806	43.7301-j5.9769
38	2.533	0.8725	46.9809	**0.8596**	48.0000+j5.4762	**0.8755**	48.0000-j6.8463
39	4.1402	**0.8713**	47.1203	**0.8605**	47.9977+j7.6497	0.8837	48.0000-j7.2272
40	4.4436	0.8729	47.9143	**0.8589**	47.9997+j11.7857	**0.8729**	47.6203-j1.1514
42	2.2378	0.9017	43.569	0.898	38.8838+j12.0000	0.9037	38.8838-j0.001
48	2.0026	0.881	47.1642	0.8678	48.0000+j11.2684	0.881	48.0000-j0.7325
56	2.8485	0.8758	47.7474	0.8714	46.7052+j11.9966	**0.8758**	46.7052-j0.0044
57	3.3324	0.9003	43.0099	0.8879	46.8758+j11.8312	0.9003	42.9512-j1.3107

After calculating the combined sensitivity factors, the buses were arranged in order of sensitivity and those with a factor of more than 2.0 were selected as the candidate buses. Table 1 shows the results of the optimal DG sizes for each respective candidate location and the associated best fitness achieved for all the three types of DGs. Both real and reactive power losses are considered in while investigating the effect of DG penetration on system power losses. The number of DGs was assumed to increase from one, two, three and then four. This was done sequentially ensuring that the candidate bus with the most optimal size was chosen first followed with the others in the same order. Thus the most optimal DG location and size was included in the four cases.

Effects of DG penetration on power system losses

Table 2: Effects of type 1 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW	MW	Mvar	MW	Mvar	%MW	%Mvar
One	36	47.2636	22.583	131.751	5.46	21.98	19.47	14.3
Two	36	47.2636	22.178	120.69	5.865	33.041	20.91	21.49
	35	47.9067						
Three	36	47.2636	23.818	116.903	4.225	36.828	15.07	23.96
	35	47.9067						
	37	43.7156						
Four	36	47.2636	28.846	120.153	-0.803	33.578	-2.86	21.84
	35	47.9067						
	37	43.7156						
	39	47.1203						

Table 3: Effects of type 2 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW+jMVar	MW	Mvar	MW	Mvar	%MW	%Mvar
One	36	47.6629+j11.9389	21.764	131.309	6.279	22.422	22.39	14.59
Two	36	47.6629+j11.9389	21.216	122.358	6.827	31.373	24.34	20.41
	40	47.9997+j11.7857						
Three	36	47.6629+j11.9389	19.137	112.787	8.906	40.944	31.76	26.63
	40	47.9997+j11.7857						
	38	48+j5.4762						
Four	36	47.6629+j11.9389	22.023	113.789	6.02	39.942	21.47	25.98
	40	47.9997+j11.7857						
	38	48+j5.4762						
	39	47.9977+j7.6497						

Table 4: Effects of type 3 DG penetration on system power losses

Number of DGs	Bus No.	DG Size	Power Losses		Power Loss Reduction		% Power Loss Reduction	
		MW-jMVar	MW	Mvar	MW	Mvar	%MW	%Mvar
One	36	47.6629-j0.0618	22.566	131.621	5.477	22.11	19.53	14.38
Two	36	47.6629-j0.0618	22.345	121.093	5.698	32.638	20.32	21.23
	40	47.6203-j1.1514						
Three	36	47.6629-j0.0618	20.104	111.248	7.939	42.483	28.31	27.63
	40	47.6203-j1.1514						
	38	48-j6.8463						
Four	36	47.6629-j0.0618	22.656	107.823	5.387	45.908	19.21	29.86
	40	47.6203-j1.1514						
	38	48-j6.8463						
	56	46.7052-j0.0044						

As it can be seen from table 2 the introduction of only one type 1 DG on bus 36 reduced the real power losses from the base case scenario of 28.043MW to 22.583MW and the reactive losses from 153.731Mvar to 131.751Mvar. The inclusion of the second DG in

the system further reduced both real and reactive power losses to 22.178MW and 120.69Mvar. The introduction of the third DG reduces only the reactive power losses to 116.903Mvar while on the other hand results to an increase in the real power losses to 23.818MW though this value is still less than the base case real power loss value. It is also of interest to note that the inclusion of the fourth DG in the system results to increase in both real and reactive power losses. As a matter of fact the real power losses are increased to a value greater than the case without DG in the network. Thus when considering this type of DG the optimal number of DGs to be placed in this case is two when considering real power losses reduction and three when considering reactive power losses only. This is because the introduction of an additional DG results to an increase in the power losses from the previous case.
From the results in table 3, the introduction of the first optimally placed and sized type 2 DG in the network reduced the real power losses from the base case value of 28.043MW to 21.764MW and the reactive power losses from 153.731Mvar to 131.309Mvar. The inclusion of the second and third DG in the network further reduces the real power losses to 21.216MW and 19.137MW and the reactive power losses to 122.358Mvar and 112.787Mvar respectively. It is evident that the introduction of the fourth DG in the network increases both real and reactive power losses in the system from the previous case. Thus the optimal number of DGs for real reactive power loss reduction when considering this type of DG was determined to be three.
The optimal placement and sizing of the first type 3 DG in the network results to a decrease in real power losses of the system from a base case loss of 28.043MW to 22.566MW and reactive power losses from 153.731Mvar to 131.621Mvar as shown in table 4. The introduction of the second and third DGs in the network further reduces the real power losses to 22.345MW and 20.104MW and reactive power losses to 121.093Mvar and 111.248Mvar respectively. It is important to note that though the inclusion of the fourth DG in the network results to a further reduction in reactive power losses to 107.823Mvar, it results to an increase of real power losses from the previous 20.104MW to 22.656MW though this value is still less than the base case real power loss value. Thus the optimal number of DGs in the system is three when considering real power losses but all the four DGs can be included in the network if the objective is to reduce reactive power losses.

Effect of DG penetration on Bus Voltage Profile

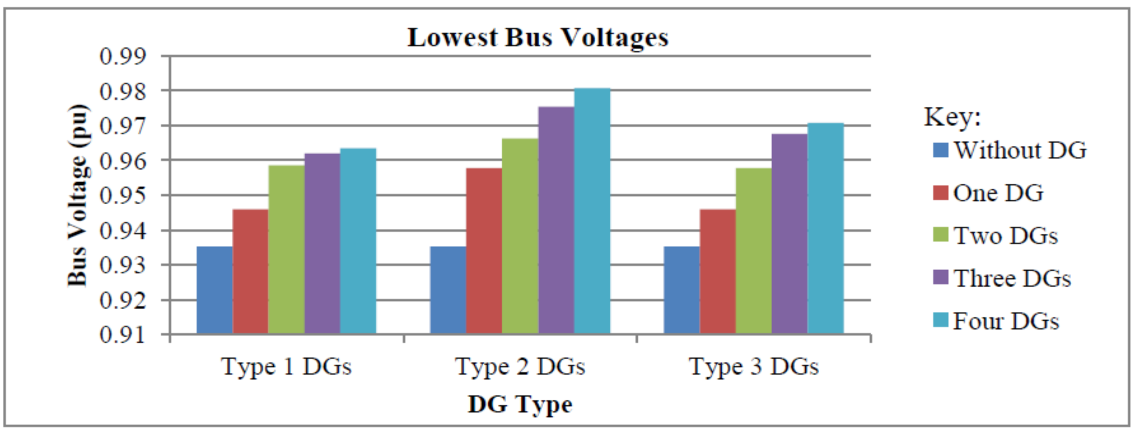

Figure 2: A graph of the lowest bus voltages for different DG types and DG numbers

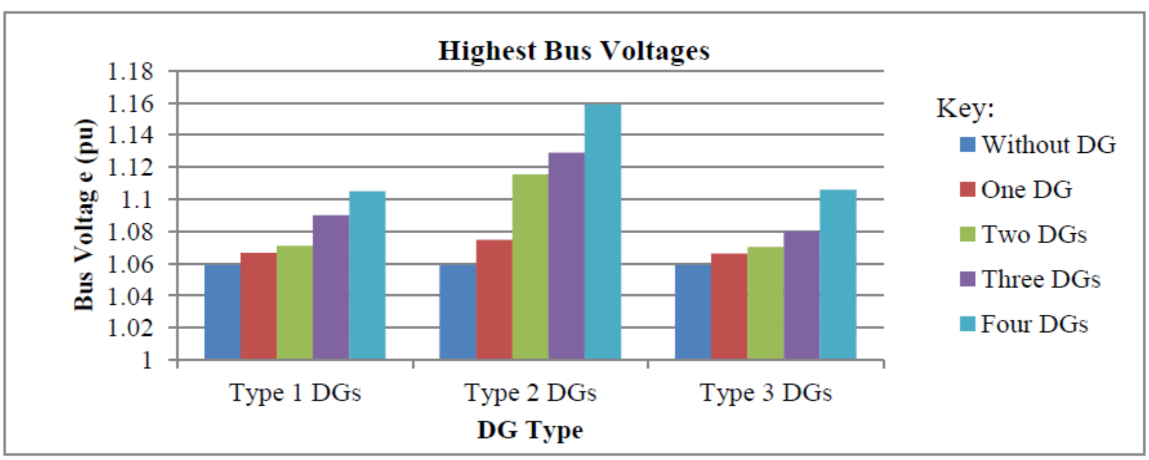

Figure 3: A graph of the highest bus voltages for different DG types and DG numbers

From figure 2 above it can be seen that all the three cases resulted to an increase in the lowest bus voltage level. It also important to note that there was an increase for each additional DG added in the network up to the fourth DG. Since the most ideal case was to have this voltage as close to 1pu as possible it can be concluded that type 2 DG performed better in this case compared to the other two types. This is because its lowest bus voltage level with four DGs in the system was 0.9807pu, though this might compromise the highest bus voltage value as evident in figure 3.
With the effects of the different DG types and numbers on lowest bus voltage in mind it can be seen that the same effects are shown for the highest bus voltages. That is all the three types of DGs results to an increase in the highest bus voltage level with an increase in number of DGs in the network. This increase might limit the number of DGs to be included in a system depending on the voltage limit specifications given by the particular country's regulation authorities.

V. CONCLUSION

After using the GA-IPSO method to study the effects of DG penetration on power losses and voltage profile. It was clearly shown that the system power losses reduced with the introduction on DGs in to the network up to an optimal number where any further DG inclusion resulted to an increase in system power losses. The voltage profile also behaved in a similar manner where further DG introduction from the optimal number resulted to deviation of bus voltages outside the acceptable limits. Thus the objectives of the research work were achieved successfully.

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