Distributed Generation Effects on Unbalanced Distribution Network Losses Considering Cost and Security Indices

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Abstract — Due to the increasing interest on renewable sources in recent years, the studies on integration of distributed generation to the power grid have rapidly increased. In order to minimize line losses of power systems, it is crucially important to define the size and location of local generation to be placed. Minimizing the losses in the system would bring two types of saving, in real life, one is capacity saving and the other one is energy saving. In this paper, our aim would be optimal distributed generation allocation for voltage profile improvement and loss reduction in distribution network. Harmony Search algorithm (HSA) was used as the solving tool; the problem is defined and objective function is introduced according to losses, security and cost indices. The applied load flow method is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which were developed based on the topological structure of the distribution systems.

This method is executed on 13 bus unbalanced distribution system and show robustness of this method in optimal and fast placement of DG, efficiency for improvement of voltage profile, reduction of power losses and cost.

Index Terms - Unbalanced radial distribution network, Distribution load flow, power losses, Harmony Search algorithm (HSA), Optimal placement.

I. Introduction

DISTRIBUTION generation generally refers to small scale (typically 1Kw-10Mw) electric generation that supply electricity to consumers that are close to its interconnection point or that are interconnected to the electric distributed system. There are many reasons a customer may choose to install a distributed generator. DG can be used to supply the customer s entire electricity supply for peak shaving (generating a portion of a customer's electricity onsite to reduce the amount of electricity purchased during peak price period). It can also be used to increase system reliability by performing intentional islanding in some remote places; it is economical to interconnect a DG to supply the customers instead of constructing new distribution lines.

DGs include technical, economical, regulatory, and possibly environmental challenges. As in the majority of planning process, a cost function is normally constructed to represent the overall operating and investment costs of a distribution planning area. Engineering parameters such as capacity, reliability, power losses, voltage regulation, power quality, load demand, are associated with the operation and investment. There can be several cost functions based on various planning scenarios. Objective functions and their constraints are solved using various optimization methods.

Expansion of DG requires an appropriate modeling and analysis of the networks in which they are embedded. A general procedure for determining the optimal DG location therefore becomes necessary so as to ensure that their effects on distribution systems are positive, that they minimize electrical grid losses and they maintain an acceptable voltage profile [1]. Several papers have been published in which one of the criteria to find the optimal DG location is minimization of power losses [2, 3].

Wang and Nehrir in [4] present analytical approaches for determining optimal location of DG units with unity power factor in power system to minimize the power losses. In [5], Harrison and Wallace employ an optimal power flow technique to maximize DG capacity with respect to voltage and thermal constraints.

Several optimization techniques have been applied to DG placement, such as genetic algorithm [6], tabu search [7], heuristic algorithms [8, 9] and analytical based methods [10].

In all of optimization techniques it must be considered that distribution networks are radial and its R:X ratio is very high. And also due to unbalance, distribution network matrices are ill conditioned and conventional load flow methods based on Gauss–Siedel and Newton–Raphson techniques are inefficient in solving such networks. Because of this drawback, Teng [11] presents a three-phase backward/forward procedure.

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In recent years several efforts have been done to optimize and replace the tradition power systems with new power systems by renewing their structure. The studies conducted by EPRI show that the distribution generation will reach to %25 by year 2010. The most advantage of DG is proximity to consumer which results decreasing costs of transfer and distribution. Employing the optimal allocation of DG in electricity network brings many advantages. But the improper allocation causes many problems in the network, such as: increasing losses, damaging voltage state, voltage flicker, protection, harmonic, stability [12, 13].

In this paper Harmony Search Algorithm (HSA) is presented as the optimization technique for the allocation of generators in distribution networks, in order to loss reduction in distribution network. In section II it is presented a brief discussion about distributed generation effects issues. Section III describes power flow in distribution network. The problem formulation is presented in section IV and Harmony Search Algorithm (HSA) method is discussed in section V. Section VI portrays the 13 bus unbalanced distribution systems used in the paper. .Finally, the major contributions and conclusions of the papers are summarized.

II. Distributed Generation Effects

The need for more flexible electric systems, changing regulatory and economic scenarios, energy savings, environmental impact and the need to protect sensitive loads against network disturbances are providing the impulsion to the development of dispersed generation and storage systems based on a variety of technologies.

When an optimal DG site is selected there is a significant beneficial impact on power losses and on improvement of the voltage levels [14].

The main reasons for the increasingly widespread use of dispersed generation are: Improvement of power quality indices, growing requirements for high reliability, DG units are closer to customers (Transmission and Distribution (T&D) costs are reduced), available plants ranging in capacity from 10 KW to 15MW and appropriate for both domestic and industrial use, easier to find sites for small generators, DG plants require shorter installation times and the investment risk is not so high. [15-17]

The planning of the electric system with the presence of DG requires the definition of several factors, such as: the best technology to be used, the number and capacity of the units, the best location, the network connection way, etc. the impact of DG in system operating characteristics, such as electric losses, voltage profile, reliability, THD, stability and security, needs to be appropriately evaluated. The selection of the best places for installation and the size of the DG units in large distribution system is complex combinatorial optimization problem.

III. Power Flow in Distribution Network

A. Review

Load flow is a very important and fundamental tool for the analysis of any power system and is used in the operational as well as planning stages. Certain applications, particularly in distribution automation and optimization of a power system, require repeated load flow solution. For those applications, it is important to solve the load flow problem as efficient as possible.

Even though the Fast decoupled Newton method [18] works well for transmission system, its convergence performance is poor for most radial distribution systems due to their high R/X ratios which deteriorate the diagonal dominance of the jacobian matrix. For these reasons, several non-Newton types of methods [19]-[22], that consist of forward/backward sweeps on a ladder system have been proposed.

A new algorithm used in this section for calculations of load flow. The only input data of this algorithm is the conventional bus-branch oriented data used by most utilities. This algorithm can be solved the distribution load flow directly. It means that the time-consuming LU decomposition and forward/backward substitution of the Jacobian matrix or the admittance matrix, required in the traditional Newton Raphson and Gauss implicit matrix algorithms, are not necessary in the new development.

B. Proposed Method

The presented method is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices which were developed based on the topological structure of the distribution systems and is widely implemented for the load flow analysis of the distribution systems. The details of both matrices can be found in [23].

The method proposed here requires only one base case load flow to determine the optimum size and location of DG. The equivalent-current-injection based model is more practical. For bus Si, the complex load is expressed by:

$$Si = (Pi + jQi) \qquad i = 1, \ldots, N. \tag{1}$$

At each bus i, the corresponding equivalent current injection is specified by:

$$I_i = \left(\frac{P_i + jQ_i}{V_i}\right)^* \qquad i = 1, 2, 3, ..n \tag{2}$$

Where V_i is the node voltage, Pi + jQi is the complex power at each bus i, n is the total number of buses, '*' symbolizes the complex conjugate of operator.

The equivalent current injection of bus i can be separated into real and imaginary parts by (2):

$$re(I_i) = \frac{P_i \cos(q_i) + Q_i \sin(q_i)}{|V_i|} \tag{3}$$

$$\mathrm{im}(I_i) = \frac{P_i \sin(\theta_i) + Q_i \sin(\theta_i)}{|V_i|} \tag{4}$$

Where θ_i is the angle of i^{th} node voltage.

The branch current B is calculated with the help of BIBC matrix. The BIBC matrix is the result of the relationship between the bus current injections and branch currents. The elements of BIBC matrix consist of ‘0’s or ‘1’s:

$$[B]_{nb\times 1} = [BIBC]_{nb\times(n-1)}.[I]_{(n-1)\times 1} \tag{5}$$

Where nb is the number of the branch, [I] is the vector of the equivalent current injection for each bus except the reference bus.

it can be seen that the bus voltage can be expressed as a function of branch currents, line parameters, and the substation voltage. Similar procedures can be performed on other buses; therefore, the relationship between branch currents and bus voltages can be expressed as:

$$\Delta V = [Z]_{nb\times(n-1)}.[B]_{(n-1)\times 1} \tag{6}$$

The voltage drop from each bus to the reference bus is obtained with BCBV and BIBC matrices as:

$$[\Delta V]_{(n-1)\times 1} = [BCBV][BIBC].[I] \tag{7}$$

Where BCBV matrix is responsible for the relations between branch currents and bus voltages. The elements of BCBV matrix consist of the branch impedances. A building algorithm for BIBC and BCBV matrix can be found in [23]. The solution for distribution load flow can be obtained by solving (12) iteratively:

$$I_i^k = I_i^r(V_i^k) + jI_i^i(V_i^k) = \left(\frac{Pi + jQi}{V_i^k}\right)^* \tag{8}$$

$$[\Delta V^{k+1}] = [DLF][I^k] \tag{9}$$

$$[\Delta V^{k+1}] = [V^0] + [\Delta V^{k+1}] \tag{10}$$

With the help of this approach, the total power losses can be expressed as a function of the bus current injection:

$$Ploss = \sum_{i=1}^{nb} |B_i|^2 .R_i = [R]^T \left|[BIBC].[I]\right|^2 \tag{11}$$

IV. Problem Formulations

A. Security Index

The security index for contingency analysis of a power system is expressed as follows [24, 25]:

$$J_V = \sum_i w_i \left|V_i - V_{ref,i}\right|^2 \tag{12}$$

$$J_P = \sum_j w_j \left(\frac{S_j}{S_{j,amx}}\right)^2 \tag{13}$$

Where:

V_i, w_i : Voltage amplitude and associated weighting factor for i_{th} bus respectively.

S_j, w_j : Apparent power and associated weighting factor for j_{th} line respectively.

$V_{ref,i}$: Nominal voltage magnitude which is assumed to be $1pu$ for all load buses (i.e. PQ buses) and to be equal to specified value for generation buses (i.e. PV buses).

$S_{j,max}$: Apparent power nominal rate of j_{th} line or transformer.

B. Power Losses

With the help of this approach, the total power losses can be expressed as a function of the bus current injection:

$$P_{Loss} = \sum_{i=1}^{nb} \left|B_{ij}^{(h),k}\right|^2 .R_i = [R]^T \left|[A_{ij}^{(h),k}]^T.[I^{(h),k}]\right|^2 \tag{14}$$

And the losses indices defined as:

$$J_{Losses} = \sum_{j=1}^{nb} \alpha_j .Max(0,(P_j^{DG} - P_j^{Base})) \tag{15}$$

P_j^{DG} : Losses in j^{th} branch after installation DG

P_j^{Base} : Losses in in j^{th} branch in base case (before installation DG)

n_b : Number of Branch

C. Total Investment Cost Function

Investment cost in optimal DG allocation is an important criterion. In this paper, purchasing and installment cost ($C_{P\&I}$) and active and reactive power generation cost for ith DG (C_{PQ}) are considered.

$$J_{Cost} = \sum_{i=1}^{DG} ((\beta_1.(C_{PQ}) - \beta_2(C_{P\&I}))) \tag{16}$$

β_1, β_2 : weighting factors

D. Objective Function

For placement of DG units, it is necessary to define objective function to solving this problem. According to structure of placement algorithm, the objective function should be selected for reducing of power losses, cost and increasing of voltage profile and system security. So, for this purpose, the precise active power losses reduction as an objective function has selected. Fitness function is expressed as below:

$$F = a_1.J_P + a_2.J_V + a_3.J_{Cost} + a_4.J_{Losses} \tag{17}$$

The coefficient α_4 to α_4 are optimized by trial and error to 0.3017,0.6105, 0.2190 and 0.04 respectively.

V. Harmony Search Algorithm

Over the last decades, a large number of algorithms have been developed to solve various optimization problems. The computational drawbacks of existing numerical methods have obligated researchers to trust in heuristic and meta-heuristic algorithms based upon simulations to solve optimization problems. The major common factor in heuristic algorithms is to merge rules and arbitrariness to emulate natural phenomena. In this paper, a solution procedure names HS is exploited to gain the optimal solution.

Harmony search (HS) is a new meta-heuristic optimization technique emulating the music improvisation process where musicians improvise their instrument's pitches seeking for a perfect state of harmony [26].

Whereas musical instruments are played with certain discrete musical notes according to musician's experiences or arbitrariness in an improvisation process, design variables can be assigned with certain discrete values according to computational intelligence or arbitrariness in the optimization process. While musicians improve their experiences based on an artistic standard, design variables in computer memory can be enhanced based upon objective function.

Musical performances seek to find pleasing harmony as determined by an artistic standard, while the optimization process seeks to find a global solution as determined by an objective function [26].

In music improvisation, each player sounds any pitch within the possible range, together making one harmony vector. If all the pitches make a good harmony, that experience is stored in each player's memory, and the possibility to make a good harmony is increased next time. Likewise, in the engineering optimization, each decision variable initially chooses any value within the possible range, together making one solution vector. If all the values of decision variables make a good solution, that experience is stored in each variable's memory, and the possibility to make a good solution is also increased next time [27]-[29]. The methodology of HS can be demonstrated as follows:

First, consider an n-dimensional search space, and a specific number which determines the size of decision variables. The i^{th} design variable is an n-dimensional vector which can be limited between appropriate predefined boundaries as follows:

$$X_i = (x_{i1}, x_{i2}, x_{i3}, \ldots, x_{in})^T \quad LX_i \le X_i \le UX_i \,. \tag{18}$$

Also, the HS algorithm parameters can be defined by the following terms:

HMS	Harmony memory size or the number of solution vectors in the harmony memory
HMCR	Harmony memory considering rate
PAR	Pitch adjusting rate
NI	Number of improvisations
N	Number of decision variables

Second, initialize the harmony memory. The HM is a memory location where all the solution vectors (sets of decision variables) are stored. The HM matrix is filled with as many randomly generated solution vectors as the HMS.

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}. \tag{19}$$

Third, improvise a new harmony. A new harmony vector is generated based on three rules: memory consideration, pitch adjustment and random selection. Generating a new harmony is called improvisation. The value of the first decision variable (x_1') for the new vector can be taken from any value in the specified HM range. Values of the other design variables are chosen in the same manner.

The HMCR, which differs from 0 to 1, is the rate of choosing one value from the historical values stored in the HM, while 1-HMCR is the rate of randomly selecting one value from the possible range of values.

$$\left.\begin{array}{ll} x_i' \in \{x_i^1, x_i^2, \ldots, x_i^{HMS}\} & \text{with probability HMCR} \\ x_i' \in X_i & \text{with probability (1-HMCR)} \end{array}\right\} \to x_i'. \tag{20}$$

Each component of the new harmony vector is checked to reveal whether it should be pitch-adjusted. This operation exploits the PAR parameter. The rate of pitch adjustment can be expressed as follows:

$$\left.\begin{array}{ll} \text{with probability PAR} & \text{Yes} \\ \text{with probability (1-PAR)} & \text{No} \end{array}\right\} \to x_i'. \tag{21}$$

This is informative that the value of 1-PAR states the rate of doing nothing. If the pitch adjustment decision for x_i' is yes, x_i' can be replaced by the following expression:

$$x_i' + bw \times U(-1,1) \to x_i'. \tag{22}$$

Where, bw is an arbitrary distance bandwidth for the continuous design variable, and U(–1,1) is a uniform distribution from –1 to 1. Therefore, HM consideration, pitch adjustment or random selection can be applied to each variable of the new harmony vector in sequence.

Forth, update harmony memory. If the new harmony vector is better than the worst harmony in the HM, from objective function perspective, the new harmony is included in the HM and the existing worst harmony is excluded from the HM. Finally, if the stopping criterion (maximum number of improvisations) is fulfilled, computation is terminated. Otherwise, the manipulation process of the harmonic vector and the HM are repeated.

In this paper, the number of decision variables is taken to be 10 times of problem variables number (i.e. HMS = 70). Also, the HMCR, the PAR, and the maximum number of searches are considered to be 0.85, 0.35, and 150, respectively.

VI. Simulation Results

An unbalanced distribution network with 13-bus, as shown in Fig 1, is used as a test network to analyze the effects of optimum size and location of DG in unbalance distribution system [30]. The characteristics of this are:

- Short and relatively highly loaded for a 4.16 kV feeder;
- One substation voltage regulator consisting of three single-phase units connected in wye;
- Overhead and underground lines with variety of phasing;
- Shunt capacitor banks;
- In-line transformer;
- Unbalanced spot loads table I.

For a small feeder this will provide a good test for the most common features of distribution analysis software.

Initially, a load flow was performed for the case study without installation of DG. The results are summarized in Table II.

When the DG is not present in the system, voltage profile at peak loading condition is shown in Fig.2.

As we can see from Fig.2, in some buses, the voltage is below the lower limit and in some others the voltage is higher the upper limit. The impact of installing two DGs in the case study network with optimal sitting and sizing is presented in table III. Comparing the results in this table with table II, we can conclude that with installing two DGs, the voltage magnitude is improved (Fig 3). Fig 4 shows comparison of voltage profile of the case study network in three phases without and with two optimal DGs.

In table IV, active and reactive power losses with and without installation of DGs are presented, respectively.

It is obvious that installing DG causes the reduction of total active and reactive power losses. The candidates buses were obtained from the objective function described in section IV. As described in table IV the optimum location for two DGs are 9 and 12 buses. Thereby, the optimum sizes are as below:

$$P_{DG1} = 1140kW, Q_{DG1} = 235kVAr$$

$$P_{DG1} = 1300kW, Q_{DG1} = 370kVAr$$

TABLE I.

LOAD DATA FOR 13 BUS UNBALANCED DISTRIBUTION TEST SYSTEM

Phase	Ph-1	Ph-1	Ph-2	Ph-2	Ph-3	Ph-3	Load
Node	kW	kVAr	kW	kVAr	kW	kVAr	Model
3	0	0	190	175	0	0	Y-PQ
4	0	0	230	132	0	0	D-Z
6	180	110	160	125	120	90	Y-PQ
7	385	220	385	220	385	220	D-PQ
8	0	0	0	0	170	151	D-I
9	485	190	68	60	290	212	Y-PQ
12	0	0	0	0	170	80	Y-I
13	138	96	0	0	0	0	Y-Z
TOTAL	1158	606	973	627	1135	753	

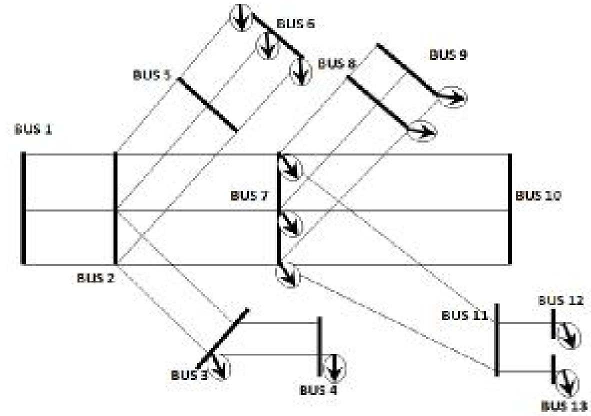

Fig.1 IEEE 13 bus unbalanced distribution system[30]

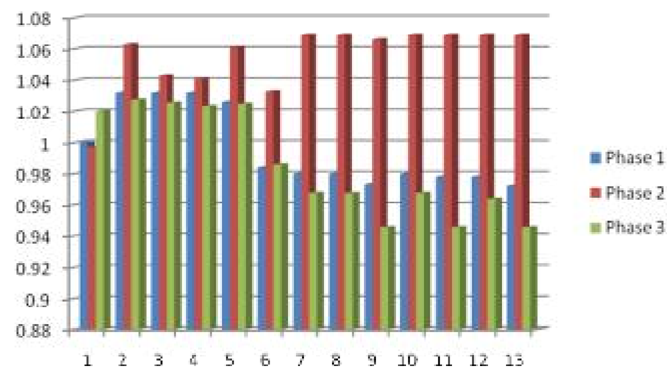

Fig.2. 13 bus voltage profile without installation of DG

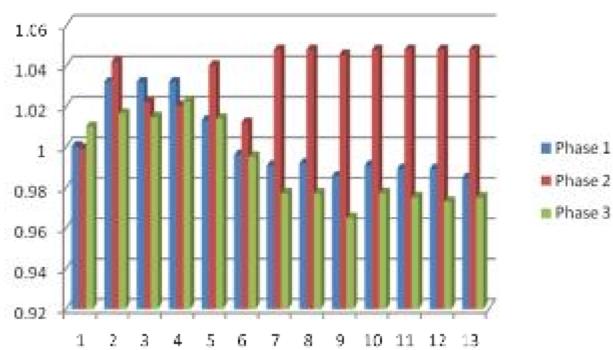

Fig 3. 13 bus voltage profile with installation of 2 DGs in optimum locations

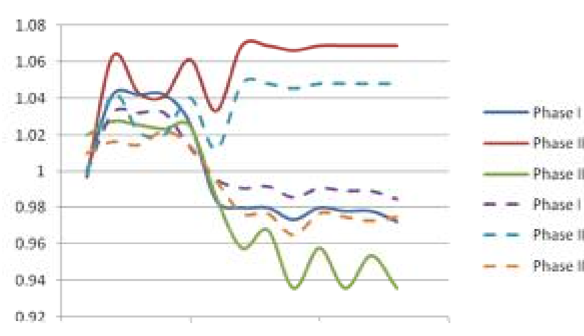

Fig. 4 Comparison between voltage profile before and after installation of DGs (dotted lines are voltages after DGs installation)

TABLE II
RESULTS of POWER FLOW WITHOUT INSTALATION of DG

	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13
V(Phase I)	1	1.042	1.042	1.042	1.026	0.984	0.98	0.98	0.9735	0.98	0.9781	0.9781	0.9725
V(Phase II)	0.997	1.063	1.0429	1.0411	1.0611	1.0328	1.0689	1.0689	1.0663	1.0689	1.0689	1.0689	1.0689
V(Phase III)	1.02	1.0274	1.0255	1.0234	1.0248	0.986	0.9578	0.9677	0.9358	0.9578	0.9358	0.9538	0.9358
V(angle I)	0	-2.51	-2.51	-2.51	-2.61	-3.33	-5.41	-5.42	-5.63	-5.41	-5.45	-5.45	-5.37
V(angle II)	-120.00	-122.83	-122.96	-121.97	-122.88	-123.33	-123.45	-123.45	-123.63	-123.45	-5.41	-5.41	-5.41
V(angle III)	+120.00	118.83	118.86	118.90	118.82	118.34	117.02	115.02	115.03	117.02	116.92	116.78	116.92

TABLE III
RESULTS of POWER FLOW AFTER INSTALATION of TWO DGs

	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5	Bus 6	Bus 7	Bus 8	Bus 9	Bus 10	Bus 11	Bus 12	Bus 13
V(Phase I)	1	1.032	1.032	1.032	1.013	0.996	0.9907	0.9917	0.9855	0.9907	0.9891	0.9891	0.9845
V(Phase II)	0.999	1.0421	1.0219	1.0202	1.0402	1.0119	1.0479	1.0479	1.0454	1.0479	1.0479	1.0479	1.0479
V(Phase III)	1.01	1.0165	1.0146	1.0225	1.0139	0.9951	0.9769	0.9768	0.9649	0.9769	0.9749	0.9729	0.9749
V(angle I)	0	-2.41	-2.41	-2.41	-2.52	-3.18	-5.27	-5.34	-5.52	-5.27	-5.21	-5.21	-5.25
V(angle II)	-120.00	-121.83	121.96	-120.97	-121.88	-122.33	-122.45	-122.45	-122.63	-122.45	-122.45	-122.45	-122.45
V(angle III)	+120.00	116.93	116.96	116.99	116.92	116.44	115.12	113.12	113.13	115.12	114.99	114.88	114.88

TABLE IV.
RELATED DATA WITH AND WITHOUT INSTALATION DGS

Case Study / Data	Without DG	After Installations of 2 DGs
Total Losses Phase I kW /kVAr	43.21+ 155.31i	26.51+ 121.41i
Total Losses Phase II kW /kVAr	6.92+ 40.12i	3.75+ 35.12i
Total Losses Phase III kW /kVAr	81.13+ 129.850i	56.94+ 108.71i
Total Losses (kW)	131.26 kW	87.20 kW
Optimum Locations (Bus No.)	-	9, 12
Size (kW)	-	1140, 1300
Size (kVAr)	-	235, 370

VII. CONCLUSION

This study presents and evaluates an analytical method which is used to determine the optimal placement and sizing of DG in a unbalanced distribution system, so as to minimize total power loss for the uniformly, cost and increase system security. As a result distributed system profile will increase. The optimal size and location of the DG, is determined by the harmony search algorithm (HSA) considering problem formulation described in section IV. The loads in unbalanced distribution network are considered as constant power, current and impedance load. It must mention that optimum size of the DG is heavily under influence of the load models, the optimum location does not change with the chosen model.

The results of execution on 13 bus unbalanced distribution system were clarified robustness of this method in optimal and fast placement of DG. The results showed efficiency of this method for improvement of voltage profile, reduction of power losses, cost and also an increase in power transfer capacity, maximum loading and voltage stability margin. The determination of the optimal size and placement DGs, in case that distribution network has harmonic load will be undertaken by considering the other constraints (such as Total Harmonic Distortion (THD) as a future work.

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