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Load Model Effect Assessment on Optimal Distributed Generation Sizing and Allocation Using Improved Harmony Search Algorithm

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ABSTRACT

The operation of a distribution system in the presence of distributed generation systems has some advantages and challenges. Optimal sizing and siting of DG systems has economic, technical, and environmental benefits in distribution systems. Improper selection of DG systems can reduce these advantages or even result in deterioration in the normal operation of the distribution system. DG allocation and capacity determination is a nonlinear optimization problem. The objective function of this problem is the minimization of the total loss of the distribution system. In this paper, the Improved Harmony Search (IHS) algorithm has been applied to the optimization problem. This algorithm has a suitable performance for this type of optimization problem. Active and reactive power demands of the distribution system loads are dependent on bus voltage. This paper verifies the effect of voltage dependent loads on system power characteristics. The load model has an inevitable impact on DG sizing and placement. The proposed algorithm implemented and tested on 69-bus distribution systems and the impact of voltage dependent load models are demonstrated. The obtained results show that the proposed algorithm has an acceptable performance.

KEYWORDS: Distributed generation, improved harmony search, DG sizing and sitting, load model.

1. INTRODUCTION

DG systems are small power sources that connect to distribution systems. With the increasing demand for electrical power and the technical, economic, and environmental constraints in the construction of new power plants and new transmission lines, DG can efficiently respond to system requirements. DG has predominant specifications. DG's features are listed below:

- DG facilitates the finding of optimal locations for small resources.
- DG has various technologies that help the distribution system planner to select the appropriate technology (such as wind turbine, gas turbine, solar, fuel

cell, and so forth) according to the system's requirement.

- Installing DG systems close to the load causes a reduction in power losses, deferral, or postponement of generation, and transmission or distribution system expansion.
- DG provides the least cost solution to power system problems, such as distribution system over load or voltage problems [1, 2].
- DG provides a reserve service, black start service, and intentional islanding operation for the faultless section under fault conditions and increases system reliability [2].
- During peak load, when electricity prices are at their highest, DG can supply loads and avoids wholesale electricity purchase [3].
- DG improves the voltage profile of the distribution system and enhances power quality.

The DG benefits in distribution systems can be summarized as: economic, technical and environmental advantages. In recent research, different aspects of these benefits have been verified [3–5]. To achieve these benefits, special attention must be given to DG placement and sizing. Improper sizing and siting of DG can cause a rise in voltage in some load buses, power flows from the low voltage into the medium voltage grid because of increased DG units, reduction in the effectiveness of protection equipment, creation of operational difficulties under certain conditions and also causing power quality problems and increasing power loss [6].

Different methods have been proposed for optimal location and sizing of DG systems. The main objective for DG placement is to minimize the losses of power systems. However, other objectives such as voltage profile [2] and reliability [1] improvement, cost minimization [3–5] and maximizing DG capacity and penetration level [7] have been considered in different studies too.

System loss reduction has the most important direct and indirect economic and technical benefits. For this reason, in some countries the regulator sets a loss target and rewards distribution network operators (DNO) if their real losses are lower than the loss target [8]. In references [3–5, 9], the loss reduction effect has been translated into economic terms and the economic effects of the loss reduction in the distribution system have been considered.

In order to attain the aforementioned benefits, the optimal DG size and location should be selected. For this purpose, many interesting algorithms and solutions have been developed. The solution methods vary from one application to another. The algorithms with more objectives and constraints need more data and the implementation of such algorithms is difficult. The differences concern the problems of assumptions, methodology, constraints, and cost functions. The DG planning problem can be a mixed integer nonlinear optimization problem. References [10–14] addressed analytical approaches to DG sizing and placement problems. Wang and Nehrir [10] proposed an analytical method to place the DG in order to minimize the power loss of the system. In this method, the optimal bus is selected based on the admittance matrix and this method only optimizes location and considers the size of the DG as fixed. Acharya et al. [11] used a methodology for single DG placement in order to minimize the total power losses. In this research, an approximate formula for loss calculation and optimal DG capacity at all buses suggested. The best location was obtained from the loss sensitivity factor. Gozel and Hocaoglu [12] propose an analytical method for calculating the loss sensitivity factor and the optimal single DG location and capacity without the use of the admittance matrix. In reference [13], an iterative method has been used for the minimization of the total system losses, voltage drops, and system short circuit levels. This algorithm is based on placing DG at all acceptable buses and the calculation of the cost function. In analytical methods, the process of finding the best candidate location is exhaustive and they sought to optimize only the DG's real power output. Analytical method is appropriate for single DG sizing and placement optimization.

The problem of optimal DG location and sizing is divided into two sub problems, consisting of optimal DG location and suitable capacity. This problem combines discrete, that is, potential bus locations, and continuous, that is, DG sizing, variable, in a single optimization problem. This combination imposes a difficulty to most optimization techniques and it considerably increases the feasible search space size. As mentioned above, some of the analytical methods only consider location for optimization and assume DG capacity to be fixed or propose a single DG system for optimization. Multiple DG systems have good performance in increasing distribution system efficiency. Applied optimization techniques should be capable of handling multiple DG sizing and siting.

Meta-heuristic and evolutionary algorithm techniques, such as the genetic algorithm (GA), and related techniques, such as particle swarm optimization (PSO), ant colony (AC), simulated annealing (SA) and Tabu search (TS) optimization, have been used to solve this type of optimization problem.

Khalesi et al. [9] applied an approach based on dynamic programming to place and size DG in a distribution system in order to minimize power loss of the system and enhance reliability. In reference [15], a hybrid GA and a PSO technique are presented for optimal location and sizing of DG. The cost function is to minimize the distribution system losses, improve the voltage profile, and increase voltage stability. The PSO algorithm has been used in reference [16] for loss minimization by optimal DG placement and sizing.

Abu-Mouti and El-Hawary [17] have implemented the artificial bee colony (ABC) algorithm for multiple and single DG sizing and siting; the objective function is power loss minimization in the distribution system.

According to the above-mentioned research, meta-heuristic and evolutionary algorithms have appropriate performance for multiple and single DG placement and sizing in distribution systems. In this paper, the improved harmony search (IHS) algorithm has been used for this optimization problem.

The harmony search (HS) algorithm is a new algorithm, which is based on using the musical process of searching for a perfect state of harmony. This method uses a stochastic random search that, in this algorithm, the need for derivative information eliminates. The HS algorithm has been successfully applied for various power system optimization problems. Srinivasa Rao et al. [18] implemented the HS algorithm for a large-scale distribution system reconfiguration optimization problem. The results show that the proposed algorithm can converge to the optimum solution quickly with better accuracy compared to other optimization methods. Khazali and Kalantar [19] applied the HS algorithm to an optimal reactive power dispatch problem. In references [20–23], the HS algorithm was used for an economic power dispatch optimization problem. The HS algorithm has good performance and appropriate characteristics for the above mentioned optimization problems. Following this research and the acceptable results of the HS algorithm for optimization problems, in this paper the HS algorithm method is applied to optimal DG sizing and placement problems.

In several of the DG planning studies, the loads are modeled as constant power sinks, that is, independent of the feeder voltage magnitude. The load in the distribution system is divided into three categories, being residential, commercial and industrial. These three load types are voltage dependent, and active and reactive power components respond differently to variations in voltage. Considering the effect of voltage dependent loads has a main impact on distribution system planning studies. In reference [24] it has been shown that the load model has a considerable effect on the total loss of the distribution system, active and reactive intake power at the main substation. Load models are major deciding factors in reconfiguration studies. In references [25, 26], the effect of load models on DG planning has been verified. Singh et al. [25] have shown the effects of different load type models, such as residential, commercial, industrial, and mixed loads, at the presence of the DG on active and reactive intake power and system losses. An iterative method for optimal single DG sizing and placement considering the load model has been applied. The results displayed that the load models significantly affect the DG capacity and location, intake power and system losses.

In reference [26], an exhaustive and GA based multi objective optimization method for DG sizing and siting, considering the load model, has been presented. The objectives are voltage deviation, real power loss, reactive power loss, and line loading. The results show that load model plays an important role in DG siting and sizing, individual indices, and the overall objectives. It has been verified that the GA method has good performance in comparison to the exhaustive method, especially in a large-scale distribution system.

In this paper, optimal DG sizing and placement considering different load models is presented. The IHS algorithm has been applied for optimization. Power loss minimization is a cost function and other system limitations, such as bus voltage magnitude, feeder current capacity, and maximum and minimum DG capacity, have been considered as constraints. The effect of the load model on the distribution system power flow has been respected. According to the influence of these loads on distribution system losses, installed DG capacities and locations are prospected to be dependent on the load model.

The next section of this paper describes the mathematical formulation of the voltage dependent load model, Section 3 highlights the objective function and constraints of the optimization problem, and Section 4 introduces the IHS algorithm and related parameters. The simulation results are presented in Section 5 and the conclusion is given in Section 6.

2. VOLTAGE DEPENDENT LOAD MODEL

Conventionally, in most distribution system planning researches, it is presumed that active and reactive power demands are specified constant values, and loads are voltage independent. In actual distribution systems, different categories and types of loads, such as residential, industrial, and commercial, might be present. The nature of these types of loads is such that their active and reactive powers are voltage dependent. Moreover, load characteristics have considerable effects on load flow solutions and system power losses.

The voltage dependent load models can be mathematically expressed as:

$$P_L = P_{L0}V^{\alpha} \tag{1}$$

$$Q_L = Q_{L0}V^{\alpha} \tag{2}$$

Where α and β are active and reactive power exponents respectively. P_L and Q_L are the values of real and reactive powers, while P_{L0} and Q_{L0} are the values of active and reactive powers at nominal voltages, respectively. V represents the voltage magnitude at each bus. For practical application, the evaluation of coefficients α and β requires field measurement and parameter estimation techniques. In reference [27], common values for the exponents for different static load models have been presented. In practical distribution systems, loads are not explicitly residential, industrial, or commercial. Each busload can be a mix of residential, commercial, and industrial loads. The voltage dependent load model can therefore be expressed as follows:

$$P_L = \rho P_{L0}V^{\alpha} + \sigma P_{L0}V^{\alpha} + \tau P_{L0}V^{\alpha} \tag{3}$$

$$Q_L = \rho Q_{L0}V^{\alpha} + \sigma Q_{L0}V^{\alpha} + \tau Q_{L0}V^{\alpha} \tag{4}$$

ρ, σ and τ are the percentages of residential, commercial and industrial loads at each load bus respectively.

$$\rho + \sigma + \tau = 1 \tag{5}$$

The values of the real and reactive power exponents used in the present work for industrial, residential, and commercial loads are given in Table 1 [26].

Table1: Load types and exponent values

Load type	**α**	**B**
Constant	0	0
Industrial	0.18	6
Residential	0.92	4.04
Commercial	1.51	3.04

According to Table 1, the voltage exponent (β) of the reactive load is quite high in most of the load types when compared to the real power exponent (α), especially for industrial loads; therefore, consideration of the voltage dependency of the reactive load is necessary for DG planning studies.

3.MATHEMATICAL FORMULATION FOR OPTIMIZATION

It is necessary to note the importance of DG allocation and the sizing problem. The non-optimal installation of DG units in the distribution system can result in increasing system losses, increasing system operation costs, and increasing voltage in some load buses and, therefore, an undesirable effect on the distribution system. Therefore, the use of an algorithm that could effectively analyze the influence of DG sizing and siting on system characteristics is necessary for the distribution system planner. The main reason for mal operation of the distribution system in the presence of DG refers to the basic assumption of the distribution system. Traditionally, distribution systems have been designed for radial application. By inserting DG into a traditional distribution system this assumption may be violated. Fig. 1 represents a 3-D diagram of typical power loss versus size of DG at each bus in a distribution system. According to Fig. 1, for an installed DG at a specified bus the size of DG is increased and the system losses are decreased to a minimum value. To achieve further increases in DG capacity, the losses start to increase with the high capacity DG, the losses reach values in excess of the base case. This problem can arise in all distribution systems if the size and location of the DG is not optimal.

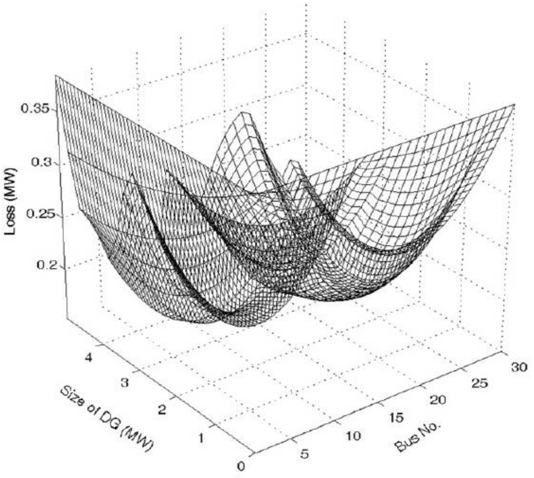

Fig. 1. Effect of size and location of DG on system loss [11]

Another conclusion from Fig. 1 is that a high capacity DG is not advisable in the distribution system and will lead to very high losses. To eliminate this problem, planners tend to use multiple DG systems instead of a single DG system in the distribution system. The reason that a distribution system has high losses for a high capacity DG system is that the distribution system has planned the power flow from the sending bus to the receiving bus, that is, a radial structure. For this reason, the conductor sizes are decreased from the substation downwards. A high capacity DG system can reverse the power flow direction and will lead to excessive power flow through small-sized feeders and, hence, result in higher losses.

3.1. Objective functions

In Fig. 2, a sample two-bus system including a DG unit has been depicted. The objective of this problem is to find the optimal capacity and location for a pre specified number of DG units that minimize the total active power losses of a radial distribution system network. The mathematical formulations of the mixed integer nonlinear optimization problem for the DG unit application are as follows. The objective function is to minimize the total system real power loss:

$$obj.Function = \min .P_{Loss} \tag{6}$$

The real power losses of N_B - bus distribution system is as follows:

$$P_{loss} = \sum_{i=1}^{N_B}\sum_{j=1}^{N_B}[\alpha_{ij}(P_iP_j + Q_iQ_j) + \beta_{ij}(Q_iP_j - P_iQ_j)] \tag{7}$$

Where,

$$\alpha_{ij} = \frac{R_{ij}}{V_iV_j}\cos(\delta_i - \delta_j) \tag{8}$$

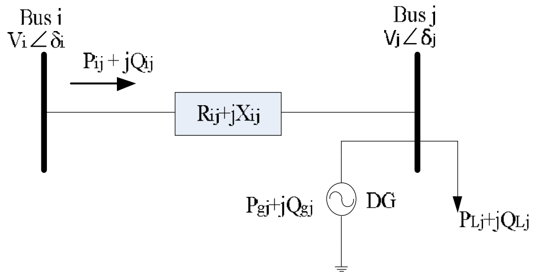

Fig. 2. Single-line diagram of a two-bus system.

$$\beta_{ij} = \frac{R_{ij}}{V_i V_j} \sin(\delta_i - \delta_j) \qquad (9)$$

V_i and δ_i are voltage and voltage angle of bus i, respectively. $Z_{ij} = R_{ij} + jX_{ij}$ are elements of the bus impedance matrix corresponding to buses i and j. The P_i and Q_i are the active and reactive power at bus i, respectively, which is the difference between active and reactive power generation (P_{gi}, Q_{gi}) and the active and reactive power load at that bus (P_{Li}, Q_{Li}):

$$P_i = P_{gi} - P_{Li} \qquad (10)$$

$$Q_i = Q_{gi} - Q_{Li} \qquad (11)$$

3.2. Constraints

Power flow equations in the network must be satisfied throughout the optimization process. These equations can be mathematically expressed as follows:

$$P_{gi} - P_{Li} = \sum_{j=1}^{N_B} |V_i||V_j|[G_{ij}\cos(\delta_i - \delta_j) + B_{ij}\sin(\delta_i - \delta_j)]$$

$$;For\ i=1\ to\ N_B \qquad (12)$$

$$Q_{gi} - Q_{Li} = \sum_{j=1}^{N_B} |V_i||V_j|[G_{ij}\sin(\delta_i - \delta_j) - B_{ij}\cos(\delta_i - \delta_j)]$$

$$;For\ i=1\ to\ N_B \qquad (13)$$

$Y_{ij} = G_{ij} + jB_{ij}$ are elements of the bus admittance matrix corresponding to buses i and j. The delivered active power at the main substation (P_{intake}) to the distribution system can be expressed as the following relation:

$$P_{intake} = \sum_{i=1}^{N_B} P_{oi}(|V_i|)^{\alpha_i} + P_{loss} - \sum_{i=1}^{N_B} \mu_i P_{gi} \qquad (14)$$

Similarly, the total system reactive power (Q_{intake}) can be given by following relation:

$$Q_{intake} = \sum_{i=1}^{N_B} Q_{0i}(|V_i|)^{\alpha_i} + Q_{loss} - \sum_{i=1}^{N_B} \mu_i Q_{gi} \qquad (15)$$

If DG exists at bus i the value of μ_i is 1 else μ_i is zero. All of the equality constraints have been considered in the power flow program. In addition to the equality constraint, this problem has some inequality constraints. These constraints have been considered and added to the algorithm procedure by using penalty factors in the objective function. If these constraints are violated, the value of the penalty factor increases and the related answers removed. The inequality constraints are presented below:

DG penetration level limitation

$$\sum_{i=1}^{N_{DG}} P_{gi} <= \gamma\left(\sum_{i=1}^{N_B} P_{Li}\right) \qquad (16)$$

γ is the penetration level of DG and is a number between 1 and 0. According to this limitation, the installed DG capacity should be less than the sum of the load demand. N_{DG} is the total number of installed DG units.

Bus voltage limitation

$$V^{\min} \le V_i \le V^{\max} ;For\ i=1\ to\ N_B \tag{17}$$

Bus voltage magnitudes of the distribution system should be kept at acceptable levels.

Thermal limit

$$\left|S_{ij}\right| \le S_{ij}^{\max} \tag{18}$$

S_{ij} is the apparent power flow at distribution system lines between bus i and j. Active and reactive power generation constraint of the distributed generator:

$$0 \le P_{gi} \le P_{gi}^{\max} \tag{19}$$

$$Q_{gi}^{\min} \le Q_{gi} \le Q_{gi}^{\max} \tag{20}$$

The operating limits constraints are represented by the generator's capability curves. For a conventional synchronous generator the capability of absorbing or generating reactive power is limited by the minimum excitation limit and by the need to provide a sufficient thermal limit (i.e., field and armature current limits) as showed by the capability curve in Fig. 3. Similar limitations exist for generated active and reactive power, and absorbed reactive power for other types of DG.

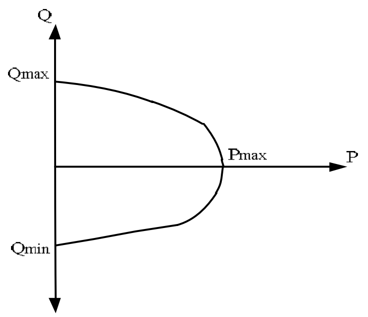

Fig. 3. DG capability curve

4. IHS ALGORITHM

Recently, a new meta-heuristic optimization algorithm, HS, that is conceptualized using the musical improvisation process of searching for a perfect state of harmony, was developed by Geem et al. [28]. In the HS algorithm there is a memory which stores the solution vectors, as shown in Equation (21). Each musician improvises using three possible choices: (1) playing any famous note exactly from his or her memory, known as the harmony memory consideration rate (HMCR); (2) playing a note in the vicinity of the previous selected note, known as pitch adjustment rate (PAR); (3) selecting a note randomly. Geem et al. [28] formalized these three musicians' choices into the HS algorithm's process and the three options respectively became three rules of the algorithm in the generation of a new solution: harmony memory consideration, pitch adjustment, and random selection.

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_D^1 \\ x_1^2 & x_2^2 & \cdots & x_D^2 \\ \vdots & \vdots & \cdots & \vdots \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_D^{HMS} \end{bmatrix} \tag{21}$$

4.1. Harmony memory consideration rule

The harmony memory consideration rule can be considered as elitism, that is, a kind of exploitation or intensification. In fact, this rule makes the algorithm concentrate on potential regions that have already been identified by the exploration component of the algorithm and aims to increase the convergence speed. Algorithms using a harmony memory and HMCR apply this rule. In harmony memory, the algorithm stores the best solutions that have already been identified and, in order to use this solution effectively, the algorithm adopts an HMCR. This should be considered a high degree of elitism as it can lead to a premature convergence and trap the algorithm in the local optimum, but the algorithm, escapes from this premature convergence. The algorithm is generating a new solution, which means that a group of multiple harmonies can be used in parallel to generate a new harmony. In this way the algorithm creates an efficient balance between parallelism (exploration) and elitism (exploitation).

4.2. Random selection rule

The random selection rule is one of the exploration components of the HS algorithm. As is clear from its name, this is not an intelligent rule; in fact, it is used to increase the diversity of the solutions. It can be helpful when the algorithm is trapped in the local optimum because it can help the algorithm to escape from premature convergence but not significantly. A value for each decision variable is selected by the algorithm, either from harmony memory with an HMCR probability or randomly from its domain with a (1-HMCR) probability, and, just for those that have been selected from harmony memory, the algorithm applies the pitch adjustment rule. The random selection rule is applied by Equation (22), where UB_i and LB_i are the upper bound and the lower bound of the i^{th} variable respectively, and rand() is a random number between 0 and 1. The random selection rule is just used for exploration; hence, there is no combination of exploration and exploitation in this rule.

$$x_i^{new} = LB_i + rand() \times (UB_i - LB_i) \qquad (22)$$

4.3. Pitch adjustment rule

The HS algorithm uses PAR and pitch bandwidth (bw) to apply the pitch adjustment rule. By applying this rule, the HS algorithm slightly changes the value that is selected from harmony memory by the harmony memory rule. The PAR is used to control the degree of pitch adjustment and the algorithm with a PAR×HMCR probability adds a small random number (±rand()×bw) to the value that has been already selected from harmony memory. Here rand() is a random number with the range of [0,1]. As mentioned earlier, this rule, which is considered to be an exploration component, makes the algorithm slightly change the values of the decision variables that are sorted in the harmony memory with a PAR×HMCR probability. This act helps the algorithm to search around the good solutions and increases the convergence speed of the algorithm. In fact, this rule in early iterations should work as a global searcher and in the final iterations should work as a local searcher. The serious drawback of the HS algorithm arises from here because Geem et al. [29] have selected a fixed bw for all generations of the algorithm. However, this rule is used as an exploration component in the HS algorithm but it makes the algorithm search in the vicinity of the solutions that have been sorted in harmony memory, in all generations of new solutions. Hence, it can be a kind of exploration that is named local search. To improve the performance of the algorithm and eliminate this serious drawback of the HS algorithm, Mahdavi et al. [30] proposed a new variant of HS, named the IHS algorithm. The IHS dynamically increases the pitch adjustment rate and decreases pitch bandwidth, respectively. IHS tries, by choosing a low PAR and a wide bandwidth in early iterations, to increase the exploration of the algorithm and gradually, by increasing the PAR and decreasing the bw, tries to exploit the global optimum or the closest to it in the vicinity of the best solutions that have been sorted in harmony memory. Therefore, they dynamically update PAR and bw according to the following equations:

$$PAR(t) = PAR_{\min} + \frac{(PAR_{\max} - PAR_{\min})}{Max\_Iter} \times t \quad (23)$$

Where

$PAR(t)$	Pitch adjusting rate for each generation
$PAR_{\min}$	Minimum pitch adjusting rate
$PAR_{\max}$	Maximum pitch adjusting rate
Max_Iter	Number of solution vector generations
t	Iteration number

And

$$bw(t) = bw_{\max} \times e^{\left(\frac{\ln(\frac{bw_{\min}}{bw_{\max}})}{Max\_Iter}\right)} \quad (24)$$

Where

$bw(t)$	Bandwidth for each generation
$bw_{\min}$	Minimum bandwidth

4.4. IHS for optimal DG sizing and placement

As mentioned before, in this paper IHS has been applied in order to solve the addressed problem. Fig. 4 shows the overall procedure of the applied IHS for the optimal DG unit sizing and placement. The steps of the algorithm are presented as follows:

Step 1) Initializing the harmony memory which represents the solutions of the problem, $x^j, j = 1, 2, \ldots, HMS$. x^j consists of two sections. The first section comprises the integer numbers and displays the DG unit's location and the second section comprises a continuous number between 0 and $P_g^{\max}$.

Step 2) Calculating the fitness value of each solution in the HM by using the objective function of the problem $(f(x^j))$. The objective function is the total distribution system losses. A power flow program has been applied for each solution (x^j) in order to compute the losses. As mentioned above, for constraint handling of the problem, in this paper a penalty function, has been used.

Step 3) Improvising a new harmony x^{new} as follows:

```
For $(i = 1 \quad to \quad D)$ Do
    If $(rand() < HMCR)$ The (memory consideration)
        $x_i^{new} = x_i^j$    Where $j \in (1, 2, \ldots, HMS)$
        If $(rand() < PAR)$ Then (pitch adjustment)
            $x_i^{new} = x_i^{new} \pm rand() \times bw$
        End If
    Else (random selection)
        $x_i^{new} = LB_i + rand() \times (UB_i - LB_i)$
    End If
End For
```

Step 4) Updating the HM that means if

$f(x^{new}) < f(x^{end})$ then $x^{new} = x^{end}$ and sort the memory.

Step 5) Updating the algorithm's parameters using (23) and (24)

Step 6) if Max_Iter is reached, returning the best harmony vector found so far; otherwise going to Step 2.

Since meta-heuristic algorithms are very sensitive to the range of parameters, a series of experiments has been carried out to obtain the best values of the parameters. Table.2 shows the values of the applied parameters in the proposed IHS which have been used in all of the experiments in this paper.

Table 2. Applied parameters of proposed IHS

Parameter	Value
HMS	5
Max_Iter	1000
HMCR	0.9
$PAR_{\max}$	0.99
$PAR_{\min}$	.01
$bw_{\max}$	$(UB_i - LB_i)/20$
$bw_{\min}$	0.0001

5. TEST SYSTEM AND SIMULATION RESULTS

The proposed algorithm has been implemented by MATLAB software. In order to verify the performance of the proposed algorithm for DG sizing and siting applications, a 69-bus distribution test system has been applied. Fig. 5 shows a single-line diagram of a 69-bus distribution system. The total active and reactive powers of this system are 3.80 MW and 2.69 MVAR respectively. The technical information of the test system is presented in reference [31]. According to the IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems [32], the application of DG as a P.V. bus is not preferred. DG units normally inject a constant amount of real and reactive power.

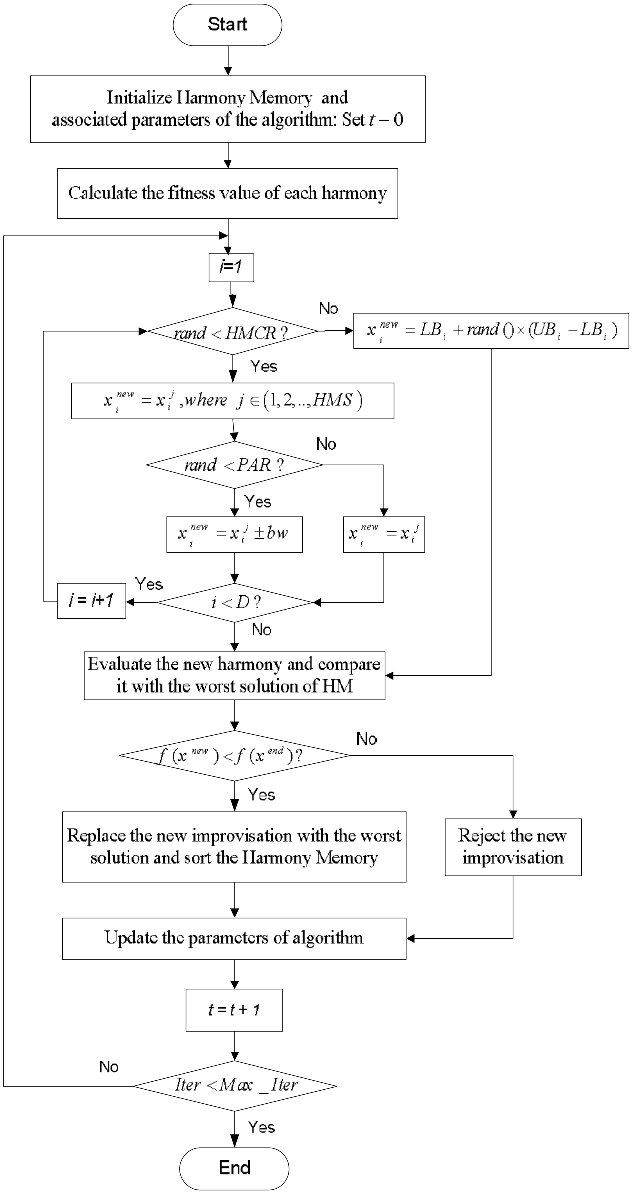

Fig. 4. The IHS algorithm

All DG units are considered with a pre specified power factor and injected power. Two case studies for investigation of the proposed algorithm have been applied. In the first one, the proposed method has been applied in a test system without considering the load model and the results have been compared with other methods in order to verify the capability of the proposed algorithm. In the second one, the proposed algorithm has been applied for DG determination, considering different load type models, that is, residential, commercial, industrial and mixed loads.

5.1. Case1 – DG sizing and siting without considering the load model

In order to verify the performance of the proposed algorithm, this algorithm has been implemented for single and dual DG sizing and placement in a 69-bus test system. Table 3 shows the 69-bus distribution test system specification before inserting the DG unit. System power loss before DG unit installation is 0.225+ 0.1022i and the minimum bus voltage is 0.909185 p.u. at bus number 65. The IHS optimization algorithm has been used for single and multiple (two) DG sizing and allocation. Table 4 shows the optimization results, including the optimal value of the objective function (system losses), DG unit capacity and DG unit location. The results have been compared with two other powerful optimization methods, being, the PSO and ABC methods. The operating power factor of the DG unit is assumed to be 0.85 and the leading and penetration level is 0.7, that is, the total installed DG unit capacity is less than 70% of the total active load. According to Table 4, the system power losses decrease from 0.225 MW to 0.0239 in the case of a single DG unit installation and losses decrease to 0.008 MW in the presence of two DG units. The optimal DG unit location for a single DG unit is bus 61 and for two DG units buses 61 and 17.

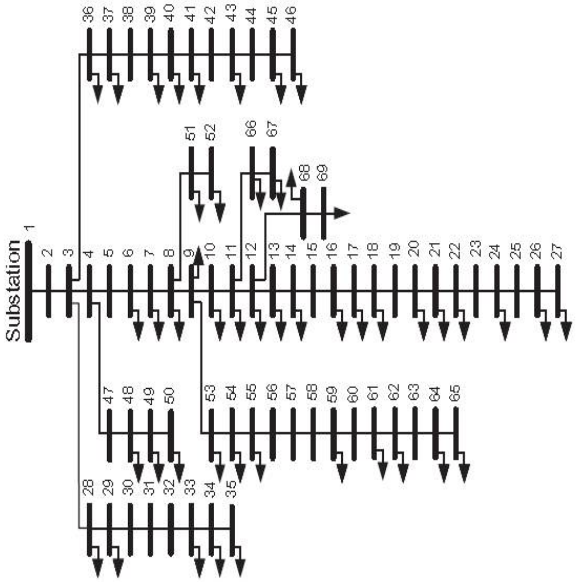

Fig.5. Single-line diagram of a 69-bus distribution system

Installing DG units considerably improves the voltage profile. In the case of a single DG unit installation, the minimum voltage of the bus increases from 0.909 p.u. to 0.9725 p.u. and increases to 0.9936 p.u. in the case of a two DG unit installation.

The results of Table 4 show that proposed method has a good performance in DG sizing and siting applications. With regard to other algorithms, this method also has a good speed for solving this problem. Fig. 6 shows the convergence diagram of this method for single and dual DG units. The proposed optimization algorithm can be used for further numbers of DG units. The voltage profile of a 69-bus distribution system has been depicted in Fig. 7. According to Fig. 7, in the presence of two DG units, the voltage profile of the distribution system considerably improves in comparison to the case of a single DG unit. Generally, it is observed that optimal insertion of DG into a distribution system can significantly decreases the total system losses and improves the voltage profile.

5.2. Case 2 – DG sizing and sitting considering the load model

As mentioned in Section 2-1, the distribution system loads are mainly categorized into residential, industrial, and commercial loads. These types of loads are voltage dependent.

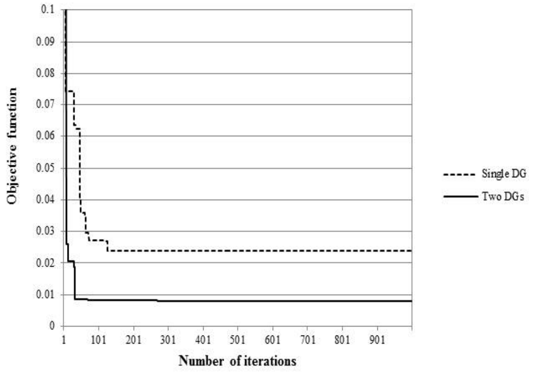

Fig.6. Convergence diagram of proposed algorithm

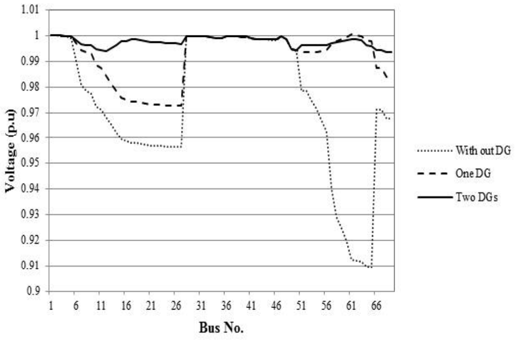

Fig.7. Voltage profile of a 69-bus distribution system

Mathematical expressions of voltage dependent loads have been given in Equations (1) and (2), Table 1 also represents the voltage exponents of different types of load model. Fig. 8 clearly shows the variation of P_{intake}, Q_{intake}, the total active and reactive load and the total active and reactive power losses of the distribution system for different types of load. These variations are due to the voltage dependency of the distribution loads. According to Table 1, the reactive power of an industrial load has the biggest dependency on voltage; this relevance can be seen in Fig. 8 as can other types of load dependency. According to the power flow results of the voltage dependent load model, in this case active and reactive power demand decreases were compared to a constant load. Table 5, shows the detailed results of DG sizing and siting for different types of load models and also the power characteristics of the distribution system. The operating power factor of the DG unit and the penetration level is similar to the previous case study, that is, 0.85 leading and 0.7, respectively.

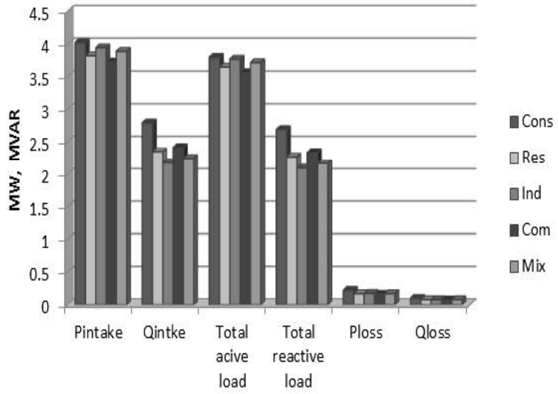

Fig.8. Variation of distribution system characteristics according to different types of load

Table 3. 69-bus system specification without installation of DG unit

System loss (MW, MVAR)	Pintake (MW)	Qintake (MVAR)	Total active load (MW)	Total reactive load (MVAR)	Vmin (p.u)	Vmax (p.u.)
0.225+0.1022i	4.0264	2.7972	3.8014	2.695	0.9091 @ Bus 65	1 @ Bus1

Table 4. Optimization results for a 69-bus distribution system

DG Number	Method	System Losses (MW)	DG Location	DG Capacity (MW)	Vmin (p.u)
Single DG	Proposed method	0.023865	61	1.904308	0.972539 @ Bus 27
	PSO [16]	0.0239	61	1.9042	0.9725 @ Bus 27
	Artificial Bee Colony (ABC)[17]	0.02392	61	1.87	0.972297 @ Bus27
Two DGs	Proposed method	0.008	61, 17	1.768, 0.5121	0.993641 @ Bus 65
	PSO [16]	0.0136	61, 21	1.582, 0.322	0.9862 @ Bus 65
	Artificial Bee Colony (ABC)[17]	0.00799901	61, 17	1.785, 0.51	-

In voltage dependent load models, increasing the voltage of load buses causes an increase in active and reactive power demand. In the case of two DG units, the total active and reactive power of the load is higher than a single DG unit. In this case, voltage increases more than with a single DG unit so that active and reactive power demand is higher. According to Table 5, the maximum difference between the cases without DG and with a single DG unit for total active power load belongs to the commercial load and the maximum difference for reactive load belongs to the industrial load. Referring to Table 1, commercial and industrial loads have the highest dependency on the voltage of the load. The difference in total active load for the commercial load is 0.2 MW. The difference in total reactive load for the industrial load is 0.5 MVAR. According to Tables 4 and 5, considering load models, the optimal capacity of a single DG unit and two DG units differ from the case of a constant load. This implies that the consideration of load model has an important effect on DG capacity and location. For two case studies, one with and one without consideration of the load model, the location of the DG unit is similar but for other case studies or different assumptions, the load model absolutely has an impact on DG location. In the case of installing DG in a distribution system, the DG supply portion of the distribution system loads so that the injected active and reactive power from the main substation to distribution system, that is, P_{intake} and Q_{intake}, decrease.

6. CONCLUSIONS

This paper presented an algorithm using the IHS optimization method for optimal DG sizing and sitting. Optimal DG sizing has important effects on the economic operation and appropriate performance of a distribution system. Improper sizing and sitting of DG can jeopardize the normal operation of the distribution system and cause undesirable effects. This problem is formulated as nonlinear optimization with continuous variables for DG capacity and discrete control variables for DG location. The IHS algorithm has good capability for

Table 5. Optimization results for a 69-bus distribution system for different types of load model

	P_{intake}	**Q_{intake}**	**Total active load**	**Total reactive load**	**P_{loss}**	**Q_{loss}**	**DG capacity**	**DG location**
Const.								
Without DG	4.0264	2.7972	3.8014	2.695	0.225	0.1022	-	-
Res.								
With single DG	1.924	1.4865855	3.78007	2.63155	0.02229	0.01403	1.8701	61
with two DGs	1.521349	1.2673094	3.782929	2.6655	0.00782	0.00827	1.7551, 0.5143	61, 17
Without DG	3.82249	2.3533	3.6517	2.2744	0.17079	0.0789	-	-
Diff.	1.89849	0.8667145	-0.12837	-0.35715	0.1485	0.06487	-	-
Ind.								
With single DG	1.946265	1.4562133	3.79724	2.603149	0.022225	0.01398	1.8732	61
with two DGs	1.529842	1.2428153	3.7993	2.64588	0.007742	0.00823	1.7633, 0.5139	61, 17
Without DG	3.94621	2.183	3.771	2.1023	0.17521	0.0807	-	-
Diff.	1.999945	0.7267867	-0.02624	-0.500849	0.152985	0.06672	-	-
Com.								
With single DG	1.91548	1.4943518	3.766541	2.64131	0.022143	0.01396	1.873204	61
with two DGs	1.521331	1.2676705	3.783294	2.6661	0.007837	0.008279	1.7607, 0.5091	61, 17
Without DG	3.730399	2.41677	3.565438	2.34037	0.164961	0.0764	-	-
Diff.	1.814919	0.9224182	-0.201103	-0.30094	0.142818	0.06244	-	-
Mix.								
With single DG	1.9503	1.4710975	3.79	2.611	0.0222	0.01401	1.8619	61
with two DGs	1.52404	1.2474799	3.79548	2.652	0.00776	0.0082	1.758, 0.5212	61, 17
Without DG	3.8921144	2.250309	3.71948	2.17064	0.1726344	0.079669	-	-
Diff.	1.9418144	0.7792115	-0.07052	-0.44036	0.1504344	0.065659	-	-

Diff.=(without DG)-(with single DG)

most of the continuous optimization problems. The obtained results show appropriate performance of this method compared to other approaches and its implementation is not very hard or complicated.. Mathematical modeling of voltage dependent loads i.e residential, commercial and industrial loads has been presented. Simulation results showed that voltage dependent load models have a significant effect on total active and reactive power losses of a distribution system. Optimal DG sizing and siting considering the load model have been verified and the results have been compared to a constant load model. The obtained results highlight that voltage dependent load models have an impact on the power and voltage characteristics of a distribution system, also that voltage dependent load models influence the optimal capacity and location of installed DG. Consequently, in order to improve DG planning results, assessment of the effects of voltage dependent load models is necessary**.**

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