Sizing and Allocation of Distributed Energy Resources for Loss Reduction using Heuristic Algorithms

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Abstract—Loss minimization in distribution networks (DN) is of great significance since the trend to the distributed generation (DG) requires the most efficient operating scenario possible for economic viability variations. Moreover, voltage instability in DN is a critical phenomenon and can lead to a major blackout in the system. The decreasing voltage stability level restricts the increase of load served by distribution companies. DG can be used to improve DN capabilities and brings new opportunities to traditional DNs. However, installation of DG in non-optimal place can result in an increase in system losses, voltage problems, etc. In this paper, genetic algorithm (GA), harmony search algorithm (HSA) and improvement HSA have been applied to determine the optimal location of DGs. Simulation results for an IEEE 33 bus network are compared for different algorithms, and the best algorithm is stated for minimum losses.

Index Terms—Distributed Energy Resources, Genetic Algorithm, Harmony Search Algorithm, Loss Reduction, Radial Distribution System.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| \(P_i, Q_i\) | The injected active/reactive powers to \(i\)th bus |
| \(V_i, \delta\) | The voltage/magnitude/phase angle at bus \(i\) |
| \(Y_{ij}, \theta_{ij}\) | The magnitude/argument of the \(ij\)th element of \(Y_{bus}\) matrix |
| \(N\) | Number of Buses |
| \([P]_{abc}, [Q]_{abc}\) | Three phase real/reactive powers vectors |
| \([V]_{abc}\) | Three-phase voltage magnitude vector |
| \([\delta]_{abc}\) | Three-phase voltage angle vector |
| \(Y_{abc}\) | The elementary three-phase \(YBUS\) matrix |
| \([P]_{abc}, [Q]_{abc}\) | Three phase real/reactive power vectors |
| \(PL\) | Total power losses of DN |
| \(m\) | Number of lines in the DN |
| \(R_j\) | Resistance of \(j\)th line |
| \(|I_j|\) | Magnitude of \(j\)th line current |
| \(PG_i\) | Generated power at \(i\)th bus including DER units |
| \(PD_i\) | Power demand at \(i\)th bus including DER units |
| \(V_{r}, W_{r}\) | Voltage amplitude and associated weighting factor for the \(r\)th bus, respectively |
| \(V_{refj}\) | Nominal voltage magnitude which is assumed to be 1 for all load buses (i.e., PQ buses) and to be equal to the specified value for generation buses (i.e., PV buses) |
| \(NB, NL\) | Number of system buses and lines, respectively |
| \(HMS\) | 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 |
| \(bw\) | An arbitrary distance bandwidth for the continuous design variable |
| \(U(-1,1)\) | Uniform distribution from \(-1\) to \(1\) |
| \(PAR_{gn}\) | Pitch adjusting rate for each generation |
| \(PAR_{min}, PAR_{max}\) | Minimum and maximum pitch adjusting rate, respectively |
| \(NI\) | Number of solution vector generations |
| \(gn\) | Generation number |
| \(bw_{(gn)}\) | Bandwidth for each generation |
| \(c\) | Constant parameter |

I. INTRODUCTION

Distributed/dispersed generation (DG) is an electrical power generation resource that is placed close to the load being served, usually at the customer site. DG may range from a few kilowatts to over 100 Megawatts and can be renewable-based micro-hydro, wind turbines, photovoltaic, etc. or fuel-based fuel cells, reciprocating engines, micro-turbines, etc. [1]-[2]. On one hand, the installation of distributed/renewable energy resources (DERs/RERs) in low-voltage (LV) and medium voltage (MV) grids can provide some advantages such as loss reduction, voltage control, power stress reduction in distribution lines, power quality enhancement, and the reduction of costs and pollution caused by conventional fossil fuel power [3]-[8]. On the other hand, these resources may lead to some undesirable issues such as voltage profile fluctuations, increased short-circuit (SC) current, inversion in the power-flow direction, readjustment of control and protection systems, etc. [9]-[16]. Before installing DG, its effects on voltage profile, line losses, short circuit current, and the amounts of injected harmonic and reliability must be evaluated separately [2], [4]-[5]. Different factors such as choosing the best technology, size, location of DGs, type of network (radial, meshed), and other factors are considered in the planning of DNs. Based on this issue, the effects of DERs in DN, including the voltage profile, stability, cost, total harmonic distortion and reliability should be taken into account [2], [4].
The problem of allocation and sizing of DER units is of great importance. The inappropriate selection of location and capacity of DERs may lead to more system losses comparing to the normal system without DER units. Thus, the use of an optimization algorithm having the capability of indicating the best solution (location and size of units) as well as modeling of DG system (i.e., wind, Solar, etc.) for a given DN can be beneficial for the engineering analysis [2], [6], [17]-[31]. The selection of the best places for installation and the preferable size of the DG units in large DNs is a complex, combinatorial optimization problem. In the planning process, a cost function is typically constructed to represent the overall operating, maintenance, and investment costs. Moreover, other objectives such as size, power losses, voltage regulation, stability, security, power quality and load demand, can be considered [17]-[18]. Consequently, a generalized procedure is required for the optimal allocation and sizing of DERs to indicate positive effects on the DNs, and thus, minimize electrical grid losses and keep an acceptable voltage profile [2].

Keeping these issues in mind, various methods for optimal siting and sizing of DGS/DERs have been discussed in the literature [2], [6], [17]-[34]. An analytical approach has been presented for optimal siting and sizing of DGs in order to minimize power losses [6]. In addition to power losses, some other factors, such as the costs of DG investment, total power operation, power supply quality [18], and reliability [32]-[33], have been considered. In this kind of algorithm, the most critical point is employing a robust and accurate power flow solution method, such as one of the efficient approaches discussed in [35], for DNs and micro-grid systems based on nonlinear mapping and the parallel processing capability of radial basis function neural networks (RBFNNs). This ability has been extended to application in a micro-grid hierarchical control structure in [35]-[36]. When wind and solar power generation units are added to the DNs, and the statistical pattern of load variation is also considered (such as the mode of plugged-in hybrid electric vehicle (PHEVs)), statistical approaches are used [37]-[39]. In these kinds of approaches, the extension of the power-flow method of [35], for possibilistic/probabilistic power flow is usually useful [40].

The DG/DER sizing and allocation is performed based on an optimization algorithm. In this way, various single-objective and multi-objective optimization (SOO/MOO) algorithms are used such as, the genetic algorithm (GA) [41]-[42], particle swarm optimization (PSO) [42]-[43], [60]-[69], harmony search algorithm (HSA) [44]-[49], differential evolution algorithm (DEA) [50]-[51], and bacteria foraging algorithm [52]. MOO DG sizing and allocation problem has been presented in [53]-[58]. In [53], based on a double trade-off solution method, operation of power quality indicators like voltage quality and harmonic distortion has also been considered in the DN performance. In [54], in addition to the power losses, expected energy not supplied (EENS), the energy required by the served customers, and moreover, the cost of network upgrading have also been considered, and the optimization problem has been solved using a GA-based ε-constrained method.

In this paper, a new harmony search algorithm (HSA) is implemented as the optimization technique for DG placement in order to reduce power losses. The results of this method are compared with well-known, reported optimization techniques. The objective function is power losses. The rest of this paper is organized as follows: Section II describes the problem formulation. Details of heuristic optimization algorithms are provided in section III. Verification of the performance of the proposed algorithm, based on testing on the 33 bus distribution system is presented in section IV. Finally, conclusions are stated in section V.

II. PROBLEM FORMULATION

A. Power-Flow Analysis

The load-flow equation can be expressed as [35]:

\[ P_i = \sum_{j=1}^{N} \left| V_j \right| \left| V_i \right| \cos(\delta_i - \delta_j - \theta_j) \]

(1)

\[ Q_i = \sum_{j=1}^{N} \left| V_j \right| \left| V_i \right| \sin(\delta_i - \delta_j - \theta_j) \]

(2)

in the balanced/ unbalanced DNs, it is given by:

\[ P_i = [P_{DG,abc} - P_{PD,abc}] = \sum_{j=1}^{N} \left| V_j \right| \left| V_i \right| \cos(\delta_i - \delta_j - \theta_j) \]

(3)

\[ Q_i = [Q_{DG,abc} - Q_{OD,abc}] = \sum_{j=1}^{N} \left| V_j \right| \left| V_i \right| \sin(\delta_i - \delta_j - \theta_j) \]

(4)

B. Power Losses

The large-scale integration of DERs/RERs transforms DNs from what were traditionally energy delivery networks to networks that both deliver and harvest energy. Installing of DER units close to the loads and introducing the concept of DG will change the losses. Based on this idea, the power losses initially decreasing until the load at the bus is satisfied and then increasing as the excess power-flows back up the line in the opposite direction [55]-[56]. The power losses are given by:

\[ P_L = \sum_{j=1}^{n} R_j |I_j|^2 \]

(5)

With the fixed line resistance value, the line current is a function of DN topology and the location of DER units. Here, only the active power losses are considered, which are calculated as:

\[ P_L = \sum_{i=1}^{n} P_{DG,i} - \sum_{i=1}^{n} P_{DG,i} \]

(6)

C. Problem Formulation

The objective function is to minimize the total real power loss as follows:

\[ \min P_{loss} \]

\[ \text{st.} \]

\[ V_{i,\text{min}} \leq V_i \leq V_{i,\text{max}} \]

(8)

\[ P_{DG,i,\text{min}} \leq P_{DG,i} \leq P_{DG,i,\text{max}} \]

\[ Q_{DG,i,\text{min}} \leq Q_{DG,i} \leq Q_{DG,i,\text{max}} \]

where \( V_i \), \( P_{DG,i,\text{min}} \), and \( Q_{DG,i,\text{max}} \) are the voltage of \( i \)th bus, active and reactive power generation limits, respectively.
III. HEURISTIC OPTIMIZATION ALGORITHMS

A. Genetic Algorithm

GA is an adaptive heuristic method based on natural selection and genetics. To solve the optimization problem, intelligent exploitation of random genes is employed. In each generation, randomized solutions are generated and evaluated in the objective function to find the fitness value. A higher fitness value (i.e., the best solutions), can survive and go to the next iteration (Reproduction). Also, "Crossover" is employed to innovate the solutions and "Mutation" can increase the area of feasible solutions. Based on this issue, the algorithm can explore all possible areas in the set. After these three steps, the new generations are generated, and the algorithm continues iteratively to find a feasible solution [41], [59]-[69].

B. Harmony Search Algorithm

B.1) Simple Harmony Search

In this paper, HSA is employed to find the optimal solution. Harmony search (HS) is a meta-heuristic optimization technique based on the music improvisation concept [45]-[49]. To find harmony in musical performances, musicians search for a pleasing harmony with an artistic standard. In the same way, to find a global solution to optimization problems, objective functions are defined to explore the best results. This comparison between music improvisation and engineering optimization is depicted in Figure 2.

The methodology of harmony search is as follows:

1) An n-dimensional search space showing the size of decision variables is selected. The design variable is limited between specific boundaries as follows:

\[
X_i = (x_{i1}, x_{i2}, \ldots, x_{in}) \; | \; L_X, X \leq X_i \leq U_X \tag{10}
\]

2) All the solution vectors (decision variables) are stored in the Harmony Memory (HM), filled by randomly produced solution vectors.

\[
HM = \begin{bmatrix}
    x_1^1 & x_1^2 & \ldots & x_1^{NMS-1} & x_1^N \\
    x_2^1 & x_2^2 & \ldots & x_2^{NMS-1} & x_2^N \\
    \vdots & \vdots & \ddots & \vdots & \vdots \\
    x_n^1 & x_n^2 & \ldots & x_n^{NMS-1} & x_n^N \\
\end{bmatrix}
\tag{11}
\]

3) In this step, a new harmony is improvised. This new vector is produced according to memory consideration, pitch adjustment, and random selection. The first decision variable \(x_1^\prime\) can be selected from HM range. The HMCN is the probability of selecting a value from HM and varies between 0 and 1.

\[
x_1^\prime \left\{ \begin{array}{ll}
    \text{Yes with probability } & PAR \\
    \text{No with probability } & (1 - PAR)
\end{array} \right.
\tag{13}
\]

The value of \((1-PAR)\) indicates whether an adjustment should be employed or not. If the pitch adjustment decision for \(x_1^\prime\) is yes, \(x_i^\prime\) can be substituted by:

\[
x_i^\prime = x_i^\prime \pm \text{rand()}\cdot b_w
\tag{14}
\]

5) If the new harmony vector can dominate another harmony vector in the HM from an objective point of view, then it can be replaced by the worst harmony vector in the HM. If the stopping is satisfied, then the computation is terminated. Otherwise, the process repeats.

B.2) Improved Harmony Search Algorithm (IHSA)

In the simple HSA, PAR and \(b_w\) play key roles in the optimization process. To increase the speed and accuracy of the algorithm, these parameters should be changed during the iterative process. Based on this issue, at the beginning of process the amount of PAR and \(b_w\) should be large so that it is possible to explore all of the feasible search space. Therefore, PAR and \(b_w\) are dynamically varied to enhance the performance of HSA as:

\[
PAR(gn) = PAR_{\min} + \left( \frac{PAR_{\max} - PAR_{\min}}{NI} \right) gn,
\tag{15}
\]

\[
b_w(gn) = b_{w_{\max}} + e^{\gamma gn}.
\tag{16}
\]
IV. SIMULATION RESULTS

A software program is developed for the proposed sitting and sizing algorithm in the MATLAB programming environment and then tested on an IEEE 33-bus distribution system (Figure 3.).

![Figure 3. IEEE 33-bus Test System](image)

A. 33-Bus Radial System Before DG Installation

In the 33-bus system, the active and reactive powers are 3715 kW and 2300 kVar, respectively. The initial system loss is 210.87, and the minimum magnitude of the voltage is 0.9075 Pu at bus 18. The voltage profile of buses before the placement of DG is illustrated in Figure 4.

![Figure 4. Voltage profile before DG placement in the 33-Bus radial system.](image)

B. Sitting and Sizing of DER units using Heuristic Algorithms.

In order to precisely examine the challenge and to reduce losses in the system, the following scenarios with different numbers of DER units are considered for the IEEE 33-Bus test system. Based on the modeling described in section 0, the proposed DG allocation algorithm is implemented based on the GA, HSA and IHSA methods. The results have been depicted in Figure 5., Figure 6., and Tables I and II, respectively. Figure 5. and Figure 6. illustrate the voltage profile of DN after optimal DG allocation and the convergence trend of two optimization algorithms, respectively. Based on these results, HSA shows better performance for the convergence and optimality of results.

![Figure 6. Comparing the convergence of HSA and IHSA.](image)

| Algorithm | Optimum Bus Numbers | Losses [KW] | Optimum rate value [MW] |
|-----------|---------------------|-------------|-------------------------|
| GA        | 6                   | 111.481     | 2.6006                  |
| HSA       | 6                   | 111.481     | 2.5944                  |
| IHSA      | 6                   | 111.479     | 2.6008                  |

C. Sitting and Sizing of One and Two DGs in the 33-Bus System Considering Reactive Power is not equal to Zero

In the previous section, siting and sizing has been determined in case DG only generates active power. In this section, it is assumed that DG can generate reactive power as well as active power. Three explained algorithms, i.e., GA, HSA, and IHSA, are employed to determine the optimum bus and reduce losses. Figure 7., Figure 8., and Figure 9. illustrate the voltage profile of DN after optimal DG allocation and the convergence trend of two optimization algorithms for the installation of one and two DG(s), respectively. The results are summarized in Tables III, IV, and V for installation of one, two, and three DG units. The results reveal that compared to the condition that reactive power is zero, the losses is diminished to 69489 kW in IHSA, which is a significant reduction. The corresponding loss when the reactive power is considered to be zero is 111.479 kW. Also, the results show that compared to the condition in which reactive power are zero the losses is diminished to 29.66 kW in IHSA, which is a significant reduction. The corresponding loss when the reactive power is not considered is 87.88 kW.
In this paper, heuristic algorithms have been evaluated to determine the optimal location and size of DG units in a distribution system in order to minimize total power losses. The optimal size and location of the DG are evaluated by the genetic algorithm, harmony search algorithm, and improved harmony search algorithms based on the problem formulation explained in section II and III. The results of the proposed algorithm on the IEEE 33 bus test distribution system show the advantage of the improved harmony search method and its superiority compared to the other two algorithms in the optimal and fast placement of DG. The results showed the efficiency of this method for the improvement of the voltage profile as well as power loss reduction.

V. CONCLUSION

In this paper, heuristic algorithms have been evaluated to determine the optimal location and size of DG units in a distribution system in order to minimize total power losses. The optimal size and location of the DG are evaluated by the genetic algorithm, harmony search algorithm, and improved harmony search algorithms based on the problem formulation explained in section II and III. The results of the proposed algorithm on the IEEE 33 bus test distribution system show the advantage of the improved harmony search method and its superiority compared to the other two algorithms in the optimal and fast placement of DG. The results showed the efficiency of this method for the improvement of the voltage profile as well as power loss reduction.

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