

An Efficient Hybrid Approach for Optimal Allocation of DG in Radial Distribution Networks

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Abstract— This paper proposes a hybrid method to determine the optimal locations and sizes of renewable Distributed Generation (DG) sources in radial distribution system (RDS). The proposed method is based on Moth-Flame Optimization Algorithm (MFO) and the loss sensitivity factor (LSF). The most candidate locations for incorporating of DG are determined using LSF while MFO algorithm is employed to find the optimal locations and sizes of solar (PV) and wind (WTG) based DG from the candidate buses for minimizing the power loss, improving the voltage profile and enhancing the voltage stability, simultaneously. The proposed method is tested on standard radial distribution system. The obtained results using the proposed method are compared with those obtained from different reported optimization techniques in literature. Numerical results show the superiority of the proposed method over the other reported techniques in term of the objective function. Moreover, incorporating the renewable DG optimally can enhance the system performance.

Keywords— *Distributed Generation; Optimization; Sensitivity; Distribution system.*

I. INTRODUCTION

Power utilities are facing major challenges due to limitation on fossil fuel resources and large power demand. Also conventional electric power stations are discouraged due to high priority of alternative solutions that are used in large power stations to meet the power demand. On the other hand, renewable energy resources have been considered as alternative to traditional fossil fuels. Integration of renewable energy based distributed generation (DG) units provides potential benefits to the distribution system such as power loss minimization, voltage profile enhancement, maximizing the system stability and energy cost reduction. Distributed generation is a small generation units incorporated in distribution systems. The types of DG can be categorized as follows [1]:

Type A: DG produces an active power only.

Type B: DG produces active and reactive powers.

Type C: DG produces reactive power only.

Type D: DG produces an active power and consumes reactive power.

Optimal placement of DGs in electric power system is a crucial task where stochastic inclusion of DGs may increase the system losses [2]. Several techniques are used to determine the optimal locations and sizes of DGs in RDS such as

analytical techniques [3, 4] and meta-heuristic optimization techniques.

Recently, the meta-heuristic optimization algorithms are widely applied for solving many problems in electric power system where these methods have highly searching ability. Several meta-heuristic optimization algorithms have been widely applied to find the optimal sizes and locations of DG in RDS such as artificial bee colony (ABC) [6], genetic algorithms (GA)[7, 8], cuckoo search algorithm(CSA)[9], modified teaching learning based optimization (MTLBO) [10], ant lion optimization (ALO) algorithm [11], backtracking search (BSA)algorithm [12], Differential Evolution (DE) [13], flower pollination algorithm (FPA) [14].

Sensitivity analysis has been performed to determine the most candidate locations for inclusion the compensation devices in RDS to reduce the search space of optimization techniques and simulation time [11, 15].

Moth-Flame Optimization (MFO) algorithm is an efficient optimization algorithm proposed by S. Mirjalili et. al. [16]. MFO algorithm is an inspired from the transverse motion of moth-flame in nature. In this paper an excellent method is presented to assign the optimal locations and sizes of PV and WTG based DG in radial distribution based on MFO algorithm and loss sensitivity factors (LSF) for power loss minimization, voltage profile improvement and voltage stability enhancement.

The remaining of paper is structured as follows: Section II describes the problem formulation that includes the objective functions and the system constraints. Section III explains the sensitivity analysis. Section IV explains MFO algorithm procedures. Section V shows the numerical results and discussion based on standard test systems. Finally, the conclusions of this work are presented in Section VI.

II. PROBLEM FORMULATION

A Single line diagram of a RDS is shown in Fig. 1. The load flow equations at bus $m+1$ can be obtained from Fig. 1 as follows:

$$P_{m+1} = P_m - P_{L,m+1} - R_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) \quad (1)$$

$$Q_{m+1} = Q_m - Q_{L,m+1} - X_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) \quad (2)$$

$$V_{m+1}^2 = V_m^2 - 2(R_{m,m+1}P_n + X_{m,m+1}Q_m) + (R_{m,m+1}^2 + X_{m,m+1}^2) \left(\frac{P_n^2 + jQ_n^2}{|V_m|^2} \right) \quad (3)$$

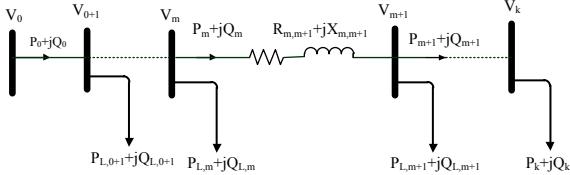


Fig. 1. Single line diagram of a radial distribution system.

where, $R_{m,m+1}$ and $X_{m,m+1}$ are resistance and reactance of the branch between buses m and $m+1$, respectively. P_m and Q_m are the active and reactive powers flow, respectively. V_m and V_{m+1} are the voltage magnitudes of bus m and bus $m+1$, respectively. The active and reactive power flow with incorporating of DG at bus $m+1$ can be give as follows:

$$P_{m+1} = P_m - P_{L,m+1} - R_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) + P_{DG} \quad (4)$$

$$Q_{m+1} = Q_m - Q_{L,m+1} - X_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) + Q_{DG} \quad (5)$$

The active and reactive power losses can be given as follows:

$$P_{loss(m,m+1)} = R_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) \quad (6)$$

$$Q_{loss(m,m+1)} = X_{m,m+1} \left(\frac{P_m^2 + jQ_m^2}{|V_m|^2} \right) \quad (7)$$

The system security level can be assign using the voltage stability index as follows:

$$VSI_{(n+1)} = |V_n|^4 - 4(P_{n+1}X_n - Q_{n+1}R_n)^2 - 4(P_{n+1}X_n + Q_{n+1}R_n)|V_n|^2 \quad (8)$$

where $VSI_{(n+1)}$ is the voltage stability index at bus $n+1$. It should highlight that enhancing the voltage profile depends upon minimizing the voltage deviations as follows:

$$VD = \sum_{n=1}^k (V_n - V_{ref})^2 \quad (9)$$

where k is number of buses and V_{ref} is the reference voltage that commonly equals to 1 p.u. The renewable DG sources are embedded into the radial distribution system for minimizing the total loss, improving the voltage profile and enhancing the voltage stability index simultaneously. The objective functions can be formulated as follows:

$$f_1 = \frac{\sum_{i=1}^{nl} (P_{loss}(i))_{after\ DG}}{\sum_{i=1}^{nl} (P_{loss}(i))_{before\ DG}} \quad (10)$$

$$f_2 = \frac{\sum_{i=1}^{nb} (VD)_{after\ DG}}{\sum_{i=1}^{nl} (VD)_{before\ DG}} \quad (11)$$

$$f_3 = \frac{1}{\sum_{i=1}^{nb} (|VSI(i)|)_{after\ DG}} \quad (12)$$

where, nl is number of branches in RDS while nb is number of buses. The generalized objective function can be

$$f_t = h_1 f_1 + h_2 f_2 + h_3 f_3 \quad (13)$$

where, h_1 , h_2 and h_3 are are weighting factors. Value of any weighting factor is selected based on the relative important on the related objective function with others objective functions. The sum of the absolute values of the weight factors in (13) assigned to all impacts should add up to one as:

$$|h_1| + |h_2| + |h_3| = 1 \quad (14)$$

The operating constraints in RDS must be considered with applying the solution algorithm for inclusion of DG the operating constraints are considered as follows:

A. Equality constraints

The equality constraints represent the active and reactive power flow constraints which can be found as follows:

$$P_{slack} + \sum_{i=1}^{NDG} P_{DG}(i) = \sum_{i=1}^k P_L(i) + \sum_{j=1}^{nb} P_{loss}(j) \quad (15)$$

$$Q_{slack} + \sum_{i=1}^{NDG} Q_{DG}(i) = \sum_{i=1}^k Q_L(i) + \sum_{j=1}^{nb} Q_{loss}(j) \quad (16)$$

where P_{slack} and Q_{slack} are the active power and reactive powers supplied from the slack bus, respectively. P_L and Q_L are the active and reactive load demands respectively. nb is number of branches in electric distribution network. NDG is number of DG units.

B. Inequality constraints

(1) Bus voltage constraints

$$V_{min} \leq V_i \leq V_{max} \quad (17)$$

where, V_{min} and V_{max} are the minimum and the maximum allowable bus voltage limit.

(2) DG sizing limits

$$\sum_{i=1}^{NDG} P_{DG}(i) \leq \frac{3}{4} \times \left(\sum_{i=1}^k P_L(i) + \sum_{j=1}^{nb} P_{loss}(j) \right) \quad (18)$$

$$\sum_{i=1}^{NDG} Q_{DG}(i) = \frac{3}{4} \times \left(\sum_{i=1}^k Q_L(i) + \sum_{j=1}^{nb} Q_{loss}(j) \right) \quad (19)$$

$$P_{DG,min} \leq P_{DG,i} \leq P_{DG,max} \quad (20)$$

$$PF_{DG,min} \leq PF_{DG,i} \leq PF_{DG,max} \quad (21)$$

where $P_{DG,min}$ and $P_{DG,max}$ are the minimum and maximum real outputs of the DG source. $PF_{DG,min}$ and $PF_{DG,max}$ are the minimum and maximum power factor of the DG source.

(3) Line capacity limits

The current flow through network branches must be within their allowable limits as follows:

$$I_{n,i} \leq I_{max,i} \quad i = 1, 2, 3, \dots, nb \quad (22)$$

where, $I_{max,i}$ is the maximum allowable current of branch i .

III. SENSITIVITY ANALYSIS

The loss sensitivity analysis is utilized to find the candidate nodes for DG inclusion in RDS for minimizing the search space of optimization technique and simulation time. The loss sensitivity factor (LSF) is applied to assign the candidate buses. LSF can be deduced from (6) as follows:

$$LSF = \frac{\partial P_{loss(m,m+1)}}{\partial Q_{m+1}} = R_{m,m+1} \left(\frac{2Q_{m+1}}{|V_{m+1}|^2} \right) \quad (23)$$

LSF is calculated for all sending buses using the load flow algorithm and arrange in descending order. The voltages of buses are normalized by dividing their voltage values by 0.95. If the values of the normalized voltages are less than 1.01 and have a high values of LSF they can be considered as the most candidate buses for incorporating the DG.

IV. MOTH-FLAME OPTIMIZATION ALGORITHM

MFO technique is an efficient algorithm that conceptualized from the navigation behavior of moths in natural (transverse orientation) where the moths navigate in straight path with respect to the moon light but these moths are trapped in deadly spiral path around an artificial light. Naturally, straight path movement of moths for long distances are gained by maintaining a fixed angle with respect moon but when moths try keeping the fixed angle with the artificial light it will lead to spiral path around light as shown in Fig. 2.

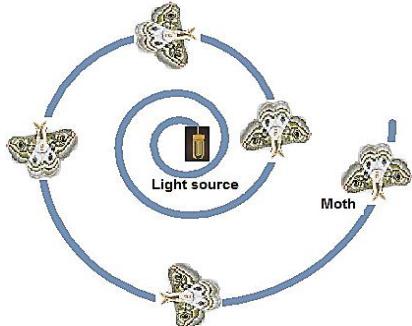


Fig. 2. Spiral navigation of moth around the artificial light.

The MFO algorithm can be considered as a population based technique. Candidate of solutions (search agents) represent the moths and the best moths represent the flames the moth poisons are updated with respect to the flames until the best solution is obtained the procedures of MFO can be summarized as follows:

Step 1 : Initialize the population by generating number of solutions randomly within the upper and lower limits of control variables as follows:

$$X(n, d) = rand * (Up(n, d) - Lp(n, d)) + Lp(n, d) \quad (24)$$

where n is number of moths and d is number of variables (dimension).

Step 2 : The generated solutions are the moths which can be represented as:

$$X = \begin{bmatrix} X_{1,1} & X_{1,2} & \cdots & X_{1,d} \\ X_{2,1} & X_{2,2} & \cdots & X_{2,1} \\ \vdots & \vdots & \ddots & \vdots \\ X_{n,1} & X_{n,2} & \cdots & X_{n,d} \end{bmatrix} \quad (25)$$

Step 3 : Calculate the objective function value in term of moths

$$OA = [OA_1 OA_2 OA_3 \dots \dots OA_N]^T \quad (26)$$

Step 4 : Sort the moths according to their objective function value to obtain flames matrix as:

$$F = \begin{bmatrix} F_{1,1} & F_{1,2} & \cdots & F_{1,d} \\ F_{2,1} & F_{2,2} & \cdots & F_{2,1} \\ \vdots & \vdots & \ddots & \vdots \\ F_{n,1} & F_{n,2} & \cdots & F_{n,d} \end{bmatrix} \quad (27)$$

Step 5 : The fitness values in term of flames can be represented as:

$$OF = [OF_1 OF_2 OF_3 \dots \dots OF_N]^T \quad (28)$$

Step 6 : Update the moth positions with respect to the flame using logarithmic spiral function as follows:

$$D_i = |F_j - A_i| \quad (29)$$

$$X_{i,new} = D_i e^{bt} \cos(2\pi t) + F_j \quad (30)$$

$$t = rand \times (a - 1) + 1 \quad (31)$$

$$a = \left(-1 - \left(\frac{t}{T_{max}} \right) \right) \quad (32)$$

where,

M_i : The i -th moth.

F_i : The j -th flame.

S : The spiral function.

D_i : The distance of the i -th moth for the j -th flame.

b : Constant value.

t : Random number in the range [-1, 1].

T_{max} : Maximum number of iteration.

T : The current iteration.

The flame number are reduced with iteration in the last searching process for enhancing the searching process by the moths and compelling them to focus their searching on the global solution as follows:

$$NO.Flames = round \left(N - T \times \frac{N-1}{T_{max}} \right) \quad (33)$$

where, N is the maximum number of flames. The sensitivity analysis is used to determine the high potential buses for allocation the DG for minimizing the search space of moth flame algorithm. The steps for inclusion of DG source by the proposed method can be summarized as follows:

- (1) : Read the system data.
- (2) : Perform the load flow and calculate LSF then determine the high potential buses for DG inclusion.
- (3) : Define the parameters of MFO includes T_{max} , n , Up , Low , d and the system constraints.
- (4) : Initialize the first population of moths (locations and sizes of DGs), randomly. Run load flow and calculate the objective function of each moth.
- (5) : Sort the moths from best to worst based on their objective functions which represents the flames matrix.
- (6) : Update the moth positions related to flames according to (30).
- (7) : Update the number of flame according to () .

- (8) : Calculate the objective function of the updated moths by running the load flow.
- (9) : Repeat Steps from 5 to 8 until the stopping criteria is achieved.
- (10) : Obtain the best flame (optimal locations and sizes of DGs) and its objective function.

V. SIMULATION RESULTS

To verify the validity and superiority of the proposed method, it is applied on 69-bus RDS. A program code for optimal allocation of renewable DGs by the proposed method is written using MATLAB 2009a and run on a personal computer has core i5 processor, 2.50 GHz and 4 GB RAM. The line and bus data are given in [17].The single line diagram of 69-bus system is shown in Fig. 3. The system active load demand is 3801.490 MW while the reactive load demand is 2694.6 MVAR at 12.66 KV. After load flow, the active power loss without incorporating DG at rated voltage is 224.975 KW while the minimum voltage is 0.90919 p.u at bus NO. 65. The selected parameters of MFO and the constraints are listed in Table I. Fig. 4 shows the LSF for 69-bus distribution system. After normalizing the bus voltage the obtained candidate buses for incorporating the DGs are 57, 58, 61, 60, 59, 15, 64, 19, ,2 16, 63, 20, 62, 25, 24, 23, 26, 27, 18, 27, 18 and 22.

TABLE I. THE USED PARAMETERS.

| | |
|----------------------|-------------------------------|
| Maximum iteration | 100 |
| Search agents No. | 50 |
| Voltage limits | $0.95 \leq V_i \leq 1.05$ p.u |
| DG sizing limits | $0 \leq P_{DG,i} \leq 3$ MW |
| Power factors limits | $0.65 \leq PF_{DG,i} \leq 1$ |

The studied cases are presented as follows:

Case 1: Incorporating single DG

The best locations and sizes of PV and WTG DG types that captured by the proposed method and the obtained results are listed in Table II. The obtained The KW loss, the minimum voltage, the maximum voltage, VD, VSI and the energy cost are also summarized in Table II. With incorporating single PV type, the KW loss is reduced from 225 KW to 83.224 KW and the VD is reduced from 1.8374 p.u to 0.8755 p.u while the voltage stability is enhanced 61.2181 p.u to 64.61156 p.u. The optimal size of PV is 1867.336 KW at bus No. 61. In Case of inclusion WT type, the KW loss is reduced to 23.171 KW and the VD is enhanced to be 0.591456 p.u while the voltage stability is also enhanced to be 64.61156 p.u. Hence, superior

results are obtained with WTG type compared with PV type. A comprehensive comparison is introduced in Table III including the power losses obtained by other techniques. From Table III, it is clear that the obtained KW losses with inclusion the PV type or WTG type are better than those obtained by other techniques. The voltage profile of 69-bus system with incorporating DGs is depicted in Fig. 5. The voltage profile is enhanced considerably with incorporating WTG compared to PV type as shown in Fig.5.

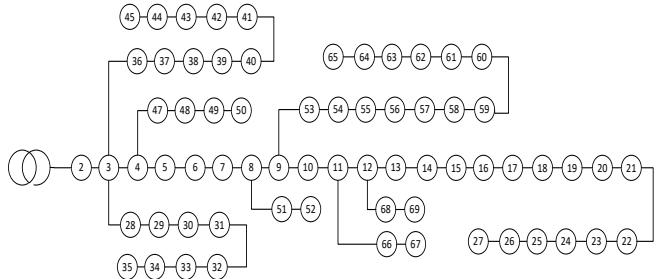


Fig. 3. The 69-bus system diagram.

Case2: Incorporating two DGs

To verify the effectiveness of the proposed method, it has been applied to assign the best locations of two DGs, simultaneously. In case of inclusion two PV DGs, the KW loss is reduced to 71.679 KW and the VD is enhanced to be 0.5091 p.u while the voltage stability is also enhanced to be 65.9954 p.u. Buses No. 17 and 61 are optimal location for inclusion PV DGs and the selected sizes at these buses are 522.74 KW 1776.9 and KW, respectively. In case of incorporating two WTG DGs, the KW loss is reduced to 21.42 KW and the VD is enhanced to be 0.471529 p.u while the voltage stability is also enhanced to be 66.1533 p.u. Buses No. 17 and 61 are optimal location for inclusion PV DGs and the selected sizes at these buses are 624.9 KVA and 1499.9 KVA with 0.8 power factor, respectively. From Table II, it is noticed that superior results have been yielded with incorporating two WTG DGs compared with two PV DGs. Referring to Fig. 6, the voltage profile is enhanced significantly with inclusion the WTG DGs type and the PV DGs type. Table IV presents a comprehensive comparison for power loss which obtained by the proposed method and other reported evolutionary techniques by inclusion PV and WTG based DG. It is clear that the yielded results by the propose method are better than those obtained by other optimization methods.

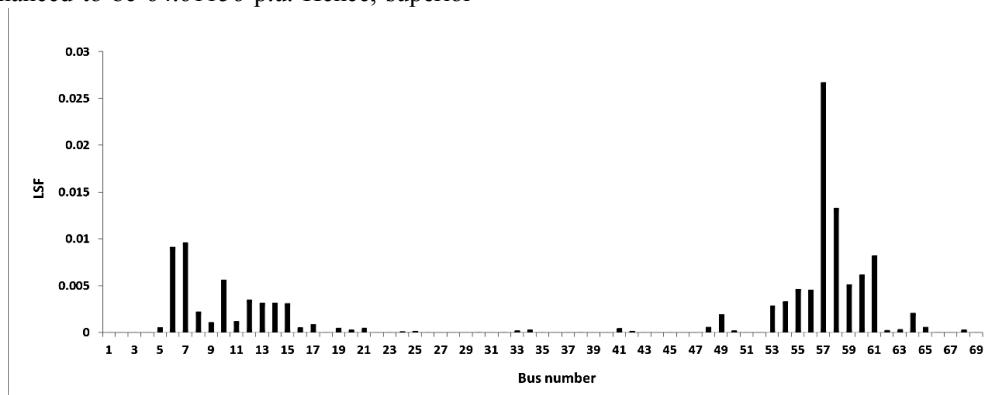


Fig. 4. LSF value for the 69-bus network

TABLE II. OPTIMAL SIZES AND LOCATIONS OF RENEWABLE DGs AND CORRESPONDING KW LOSS, VD, VSI AND THE ENERGY COST FOR 69-BUS SYSTEM

| Item | | P _{loss} (KW) | Loss reduction | V _{min(p.u)} | V _{max(p.u)} | VSI(p.u) | VD(p.u) | Location(KVA/PF) |
|-------------------|--------------|------------------------|----------------|-----------------------|-----------------------|----------|----------|-----------------------------------|
| Without DG | | 225.000 | - | 0.90919 | 0.99997 | 61.2181 | 1.8374 | - |
| Single DG | 1 PV | 83.224 | 63.01171 | 0.96826 | 0.99997 | 64.61156 | 0.8755 | 61 (1867.336/1) |
| | 1 WTG | 23.171 | 89.70182 | 0.97242 | 0.99998 | 65.70429 | 0.591456 | 61(2235.92/0.81) |
| Two DGs | 2 PV | 71.679 | 68.14281 | 0.97872 | 0.99997 | 65.9954 | 0.5091 | 61 (1776.9/1) 17 (522.74/1) |
| | 2 WTG | 21.4177 | 90.48106 | 0.97347 | 0.99998 | 66.1533 | 0.471529 | 61 (1499.9/0.8) 17 (624.9/0.8) |

TABLE III. COMPARATIVE RESULTS FOR INCORPORATING SINGLE DG IN 69-BUS SYSTEM

| | Technique | Proposed method | MTLBO [10] | SGA[9] | CSA[9] | GA[8] | Analytical [5] | ABC [31] | WOA[18] | GWO[19] |
|------------|------------------------|------------------|------------|---------|---------|-----------|----------------|----------|-----------|-----------|
| Single PV | P _{loss} (KW) | 83.224 | 83.323 | 89.4 | 83.8 | 83.4252 | 92 | 83.31 | 83.2279 | 83.24 |
| | Location | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 |
| | Size (kVA/PF) | 1867.3357/1 | 1819.691/1 | 2300/1 | 2000/1 | 1794/1 | 1807.8/1 | 1900/1 | 1872.82/1 | 1928.67/1 |
| Single WTG | Technique | Proposed method | CSA [9] | SGA [9] | PSO [9] | GA [7] | WOA[18] | | | |
| | P _{loss} (KW) | 23.171 | 52.6 | 64.4 | 52.6 | 38.458 | 27.9649 | | | |
| | Location | 61 | 61 | 61 | 61 | 61 | 61 | | | |
| Two PV | Size (kVA/PF) | 2235.9149/0.8144 | 2300/NR | 2600/NR | 2300/NR | 2155.6/NR | 2217.39/0.9 | | | |

TABLE IV. COMPARATIVE RESULTS FOR INCORPORATING TWO DGs IN 69-BUS SYSTEM

| | Technique | Proposed method | CSA [9] | SGA [9] | PSO [9] | GA [7] | GA [8] | MTLBO [10] | GWO[19] |
|---------|------------------------|-----------------|---------|---------|---------|---------|------------|------------|---------|
| Two PV | P _{loss} (KW) | 71.679 | 76.4 | 82.9 | 78.8 | 71.7912 | 84.233 | 71.776 | 71.74 |
| | Location | 17 | 22 | 17 | 14 | 11 | 1 | 17 | 17 |
| | Size (kVA/PF) | 61 | 61 | 61 | 62 | 61 | 62 | 61 | 61 |
| Two WTG | 522.7424/1 | 600/1 | 1000/1 | 700/1 | 555/1 | 6/1 | 519.705/1 | 566.08/1 | |
| | 1776.9/1 | 2100/1 | 2400/1 | 2100/1 | 1777/1 | 1794/1 | 1732.004/1 | 1816.42/1 | |
| | Technique | Proposed method | CSA [9] | SGA [9] | PSO [9] | | | | |
| Two WTG | P _{loss} (KW) | 21.4177 | 39.9 | 44 | 42.4 | | | | |
| | Location | 17 | 18 | 18 | 18 | | | | |
| | Size (kVA/PF) | 61 | 61 | 62 | 62 | | | | |

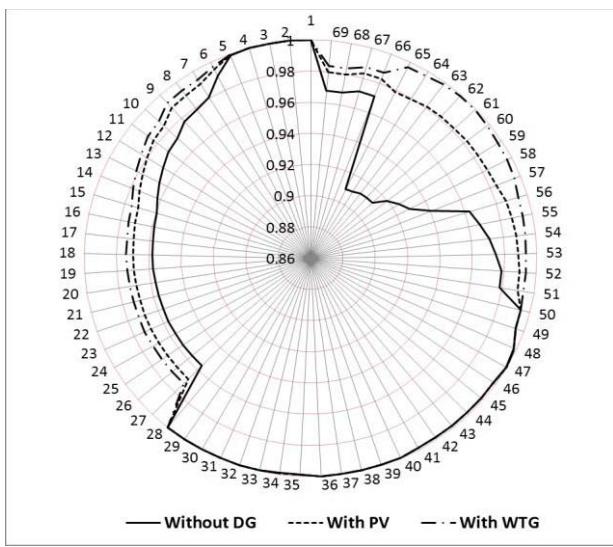


Fig. 5. Bus voltage profile level with single DG.

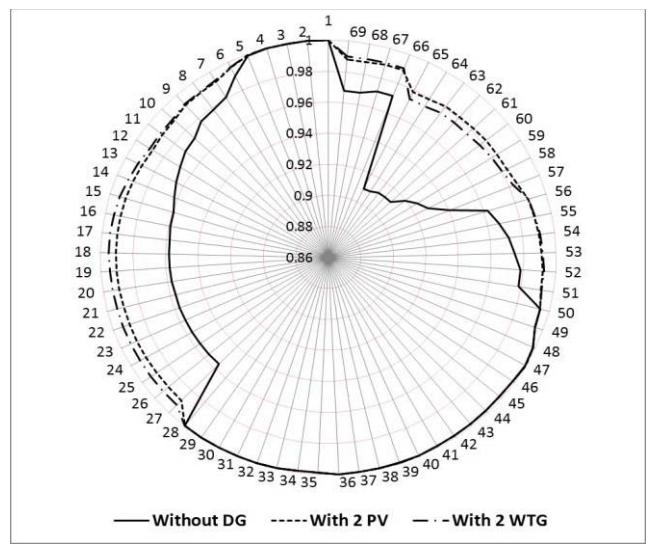


Fig. 6. Bus voltage profile level with two DGs.

VI. CONCLUSIONS

In this paper, an efficient hybrid method was proposed for optimal installations of the solar (PV) and wind turbine (WTG) based distributed generation types. The hybrid method is based on loss sensitivity factor (LSF) and moth flame algorithm (MFO) where the high potential buses for incorporating the DGs were determined by LSF while the final sizes and locations were founded by MFO algorithm. The optimal PV and WTG installation problem was solved for multi-objective function including the power loss minimization, voltage stability enhancement and voltage profile improvement. The proposed method has been tested on slandered distribution network. Moreover, its results have been compared with those founded by other optimization methods. From obtained results, it can be concluded that the proposed method is giving better results than the other reported methods in term of the required objective function. In addition, inclusion two DGs (PV type or WTG type) give a superior results compared with inclusion single DG.

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