Optimal Energy Saving of Photovoltaic Distributed Generation System with Considering Environment Condition via Hyper-Spherical Search Algorithm

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Abstract: Hyper-spherical search algorithm (HSSA) is proposed for optimal allocation and sizing of Photovoltaic Distributed Generation System (PVDGS) in the distribution network. Firstly, Power Loss Index (PLI) technique is presented to get the highest candidate buses for installing PVDGS. Secondly, the proposed HSSA is developed to decide the most optimal locations of PVDGS and their economic sizing at the elected buses by PLI. Herein, the cost objective function is designed to diminish the total cost of the system losses, and subsequently increase the annual net saving. Hourly variation of solar radiation, and temperature is taken into account in cost calculation of the PV system. In addition, the present worth value for the costs of the maintenance and the PV system components is estimated as function of interest and inflation rates. The proposed algorithm is tested on 69- IEEE and 118 IEEE radial distribution systems to ensure the effectiveness of the proposed algorithm in increasing the net saving via precise cost calculation

Keywords: PV generator, HSSA, distribution network, cost objective function

1 Introduction

In recent years, the use of solar PV system as integrated with distribution power networks has developed. This development has been accelerated due to the evolution of the materials used as well as the techniques of control and the economic and environmental profits.

The integration between the distribution networks and solar PV power generation system may have a negative impact on the electrical distribution system in case of connecting all solar PV power generation systems at one bus in the distribution network. In the other hand, positive impacts on the distribution network in terms of losses, voltage steadiness and the voltage levels is achieved in case of distributing PV power generation systems at optimal locations in distribution network [1-4].

The development of optimal distribution techniques depends on various objectives. Some of these objectives targeting the minimization of losses [5-11], and other focused on enhancing the voltage levels [12]. Whereas, some authors studied the combined objective functions of minimization of losses and improving voltage levels [13-23]. Some articles [24-30] focused on the economic aspect as a goal. Numerous optimization algorithms have been utilized for sizing and allocating of DG sources in distribution networks.

Optimization algorithms have been characterized into two assortments. First assortment is including classical optimization algorithms such as analytical algorithms [31], linear programming [32], nonlinear programming [33], mixed integer linear programing [34], mixed integer nonlinear programming [35], optimal power flow [36], continuation power flow [37] and load concentration [38]. Second assortment is the artificial intelligent algorithms. Ref. [39] developed a combined heuristic method from simulated annealing and genetic algorithm to solve the problem of placing and sizing of energy storage facilities in distribution network. Ref. [40] presented a new technique for allocating distributed generator in radial power distribution network via harmony search (HS). Ref. [41] proposed an innovative optimization algorithm based on combination of tabu search methods and genetic algorithms to find optimal location of distributed generation sources in power distribution networks.

A novel methodology mixing amongst Particle Swarm Optimization (PSO) and fuzzy for distribution of DG in the radial distribution network was presented. The objective of this research focused on reducing power losses and enhancing the voltage profiles in the redial feeder network [42]. Ref. [43] introduced an optimization technique merging between genetic algorithm (GA) and particle swarm optimization (PSO) for convenient size and best location of DG in distribution network. The goal of this research was to enhance voltage profile, and minimize network losses. A combined optimal power flow and discrete PSO techniques was presented in [44]. Ref. [45] developed an innovative study and efficient combined PSO-GSA optimization mathematical algorithm. This method was employed to discover the optimum place with suitable size of DG for diminishing power losses and operation costs further improving voltage levels of distribution system. The validation of HSSA algorithm for solving some mathematical problems is proved in [46], few works use HSSA to solve some engineering problems [48, 49]. In [47], the effectiveness of HSSA is demonstrated through different radial distribution systems in order to maximize net annual saving by detecting the optimal size and location of shunt capacitor. Moreover, it is obvious from the literature review that the utilization of HSSA to solve PV allocation and sizing problem has not been investigated. This encourages the authors to utilize the HSSA to solve this problem.

In addition, the investigation of the work which deals with economic aspects [24-30] reveals that most studies didn't involve hourly variation in solar irradiance and temperature in estimating PV capacity, which have a significant impact on the output power of PV modules. However, this may lead to misleading conclusion. This encourage the authors to develop a cost objective function of PV system components which takes the effect of temperature and solar irradiance variation on the rated output power of the PV system into account based on the geographical location. In addition, the operating and maintenance cost of PV modules and inflation and interest rates have been considered in assessing the cost function of PV system. However, the pervious methods can result in an acceptable solution, but they are not applicable for large networks. So, the proposed method in this paper is applied on a large network.

2 Output power of PV module

The output power (kW) delivered from PV array system depending on available hourly solar radiation (S) and ambient temperature (T_a) is calculated from the following formula [50]:

$$P_{PV\_out}(t) = P_{PV\_rat} * \frac{S(t)}{S_{ref}}\left[1 + \beta_{ref}\left(T_c(t) - T_{ref}\right)\right] \quad (1)$$

Where the surface temperature ($T_c(t)$) of PV array as function in ambient temperature and solar radiation is expressed as fellow:

$$T_c(t) = T_a(t) + \frac{NOCT-20}{0.8} * S(t) \quad (2)$$

Total rated output power of PV array system, P_{PV_rat} is evaluated according to load profile of the load demand.

where NOCT (Normal Operating Cell Temperature) is defined as the cell temperature when the PV module operates under $S_{ref} = 1000$ W/m² of solar irradiation and $T_{ref} = 25$°C of ambient temperature, NOCT is usually between 42°C and 46°C. The thermal power coefficient is β_{ref} (= -0.00311/oC) to express the degradation of the output of PV module per degree of temperature.

The hourly solar radiation (S) and ambient temperature (T_a) are obtained from NASA for IEEE system location [51]. Figure 1 shows hourly solar radiation and temperature of one year in IEEE system location.

2.2 Methodology of total annual cost calculation

2.2.1 Cost equation of PV system

Two factors affect the value of money over time period. The inflation rate, i, is a measure of the decline in value of money. The discount rate, d, relates to the amount of interest that can be earned on principal that is saved. The real challenge, then, in investing money, is to invest at a discount rate that is greater than the inflation rate [52].

The proposed PV system to use in distributed power network for power losses reduction consists of PV array and inverter. Total annual cost of the PV system solely is including the initial ($C_{int.PV}$ and $C_{int.inv}$), operating and maintenance ($C_{OM,PV}$ and $C_{OM,inv}$) and replacement ($C_{rep,PV}$ and $C_{rep,inv}$) costs of PV array and inverter as illustrated in Eq. (3):

$$C_{pv\,sys_{ta}} = (C_{int.PV} + C_{int.inv}) * CRF + (C_{M.PV} + C_{M.inv}) * \mathrm{MF} + (C_{rep.PV} + C_{rep.inv}) * RF \quad (3)$$

here CRF, MF and RF are the capital recovery, present worth maintenance and replacement factors, respectively. CRF, MF and RF are presented in Eqns. (4-6) as function in interest rate (d) and inflation rate (i) to give the current value of the hybrid system components at given time period (N) [52].

$$CRF = \frac{d(1+d)^N}{(1+d)^N - 1} \quad (4)$$

$$\mathrm{MF} = \left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right) * \left\{\frac{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{N}}}{1-\left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)}\right\} \quad (5)$$

$$RF = \left(\frac{1+\mathrm{i}}{1+\mathrm{d}}\right)^{\mathrm{N}} \quad (6)$$

The average annual inflation rate (i=3%), average annual discount (interest) rate (d=6%), N, lifetime (20 years).

Initial and annual maintenance costs of PV array system is calculated from Eqns.(7 and 8):

$$C_{int.PV} = P_{PV\_rat} * C_{PV} \quad (7)$$

$$C_{M.PV} = \left(C_{PV}^{m} * \sum_{t=1}^{8640} P_{PV\_out}(t) * \Delta t\right) \quad (8)$$

where, $P_{PV\_out}(t)$ is output power of PV array at time t (Eq. 1); CPV (=600$/kW) is the initial cost of PV array per kW; C_{PV}^{m} (=0.05$/kWh) is the maintenance cost of PV array per kWh; Δt (=1hour) is the increment in time used for calculation.

No replacement cost of both PV array and inverter because of both have lifetime equal to project life time (N=20 year).

It is worth noting that inverter rating is higher than peak load demand ($E_{l,peak}$) by 20% and initial cost of inverter per kW is C_{inv} (=513$/kW). Thus, total initial cost of inverter is determined from Eq. (9):

$$C_{int.inv} = 1.2 * C_{inv} * E_{l.peak} \quad (9)$$

Assuming no maintenance cost of inverter. Economic parameters of PV system is illustrated in Table 1.

Table 1 Economic parameters of PV system

Parameter	Value	Unit
PV		
Life time	20	year
Initial cost	600[53]	$/kW
O&M cost	0.05[54]	$/kWh
Converter		
Initial cost	515[53]	$/kW
Life time	20	year
Efficiency	95[50]	%
Other		
Project life time	20	year
Interest rate	6	%
Inflation rate	3	%

3 Problem formulation

The purpose of the problem is to minimize total yearly operational and conventional generation cost for PVDGS. This section introduces the problem formulation.

3.1 Power loss index (PLI)

In this paper, PLI is used to appoint the candidate buses p. The highest buses in terms of PLI [24, 25] index are the highest affected buses on power loss due to variation of its power. The PLI is calculated by the following expression.

$$PLI(i) = \frac{P_{loss}(i) - P_{loss-\min}}{P_{loss-\max} - P_{loss-\min}} \quad (10)$$

Where all values of power losses are calculated at unity power factor at any specified bus.

The highest buses in terms of PLI index will be given to the HSSA to optimally fix PV system placement and sizing.

3.2 Objective (fitness) function

The objective of PV allocation and sizing is to minimize the annual energy losses with consideration of PVDGS installation and size costs. The objective function can be tailored as follows.

$$J = \min\left[K_P TP_{slack} + \sum_{i=1}^{Npv} C_{pv,i}\right] \quad (11)$$

Where, the parameters are given in Table 1. The PV costs discussed in pervious section and conventional generation costs are considered.

Constraints

3.3.1 Active and reactive power constrains

The power and reactive power constraints are given in the quality and inequality functions in Eq. (12).

$$P_{slack} + \sum_{i=1}^{Npv} P_{pv,i} = \sum_{i=1}^{N} P_{ld,i} + \sum_{j=1}^{N_L} P_{losses,i} \quad (12)$$

In addition, the PV power should be less than 3/4 the total power demand as in Eq. (13).

$$\sum_{i=1}^{N_{cb}} P_{PV,i} \le 0.75\left(\sum_{i=1}^{N} P_{ld,i} + \sum_{i=1}^{N} P_{loss,i}\right) \quad (13)$$

3.3.2 Voltage magnitude constraints

The voltage magnitude constraints at each bus are restricted by the following inequality, in which the minimum and maximum voltage limits lie in the interval [0.9, 1.05].

$$V_{\min} \le V_i \le V_{\max} \quad \forall i \in N \tag{14}$$

3.3.3 Current constrains

In order to keep transmission line complex power capacities within their constraints, the current through any line is limited by the inequality as in illustrated in Eq. (15).

$$I_{l,\min} \le I_{l,i} \le I_{l,\max} \quad \forall i \in N_L \tag{15}$$

3.3.4 Thermal/loss constraints of the line

The maximum capacity of a feeder is defined by considering lines thermal and stability limitations. The Line Thermal Limitations (LTL) constraint limits the feeder capacity in MVA into the maximum power, which can flow through the line. The objective of maximizing the PVDG units' capacity is by focusing on the Total Line Loss Limitation (TLLL) with and without PVDG units installation. According to this constraint, total line loss after DG installation should not exceed the total line loss before PVDG installation

4 Employing HSSA for optimal allocation and sizing problem

One of the promising optimization methods in optimal dispatch problems is the HSSA [55]. The analysis of HSSA technique divided to five stages based on a certain constraints on the decision variables as follows:

4.1 Initialization of particles in HSSA.

The process of initiation of HSSA is conducted in four steps. First step is related to identification of some parameters via the user. These parameters such as number of hyper-sphere centers (Nsc), number of initial population (Npop), the minimum and maximum distances between the particle and sphere center (rmin, rmax,), the probability of changing the angle of the particle (Prangle) and new group of particles (Nnewpar). Second step is the generation of randomly solution N_{pop} of variables Xi, which are randomly nominated within the range ($X_{i,\min} < X_i < X_{i,\max}$). The objective function has been estimated at each solution. Third step, based on the estimation of the objective function, the particles care sorted in ascending order. The nomination of the optimal Nsc particles to be assigned as sphere centres (SCs) is defined. Fourth step, the remaining particles after excluding the selected Nsc particles as the SCs are distributed among SCs as considering the domination of SCs. The objective function difference (OFDsc) of each SC is specified to allocate particles in proportional way as indicated in Eq. 16.

$$OFD_{sc,i} = F_{sc}(X_i) - \max\{f(X_i)\} \tag{16}$$

The dominant SC (Dsc) as function of OFDsc,I can be calculated from following formula.

$$D_{sc} = \left| \frac{OFD_{sc,i}}{\sum_{i=1}^{N_{sc}} OFD_{sc,i}} \right| \tag{17}$$

The initial particles number of the SCs that is selected randomly among the residues particles is divided based on Eq. 18.

$$n = round\{D_{sc}(N_{pop} - N_{sc})\} \tag{18}$$

4.2 Optimal solution searching

The particle goes to the best solution at an identified level restricted a sphere with radius of r, the gap between the SC and position of the particle. The searching process has been conducted via variation of the particle parameters on surface of sphere with radius r and angles θ and φ.

For each particle position in N-dimensional spherical space, there are N−1 angles. Thus, varying these angles give rise to new particle's position in the searching space. The variation of the particle position angle is done randomly based on the probability function Prangle. The value of angle variation is in radian and uniformly selected between [0, 2π] at each iteration. Herein, the distance between the SC and the particle position is determined randomly within the range of ($r_{\min} \times r$, $r_{\max} \times r$) where r is defined in the following equation.

$$r = \sqrt{\sum_{i=1}^{N} (P_{i,center} - P_{i,particle})^2} \tag{19}$$

In the HSSA, each particle seeks its hyper-sphere take into account its SC. The parameters of the search process is specified by Q[rmin, rmax, Prangle, SC]. Throughout searching in its spherical coordinate space, a certain particle may discover a position has an objective function value lower than its SC. In this situation, the SC and the position of this particle are switched.

4.3 Reallocation of dummy particles

Particle's position and its SC are called as set. Some set include particles have abnormal objective function (i.e. so high objective function) are not predictable to get a universal minimum solution due to their unsuitable position. These undesirable particles are named by dummy particles. Dummy particles should be assigned to different hyper sphere as depicted in Fig. 2.

To define the worst set as including dummy particles, the set objective function (SOF) is evaluated from Eq. (20). Then, the values of SOF are sported in ascending way to determine the worst set.

$$SOF = f_{sc} + \gamma \; mean(f_{particles \;\; of \; SC}) \qquad (20)$$

Where γ is constant affected the role of particles in calculating SOF.

Some of dummy particles (or one particle) with the highest SOF is assigned to other SCs. Thus, the difference in SOF (DSOF) of every set is indicated in Eq. (21). Herein, the particle is transfer to other SCs according to the assigning probability (AP), which formulated in Eq. (22).

The dummy particles are classified with their SCs according to their APs whereas the worst set that has the highest SOF will leave its dummy particle. Based on the value of AP, the dummy particle finds a new SC.

$$DSOF = SOF - max_{group}\,\{SOF\ groups\} \qquad (21)$$

$$AP = \left|\frac{DSOF}{\sum_{i=1}^{N_{SC}} DSOF_i}\right| \qquad (22)$$

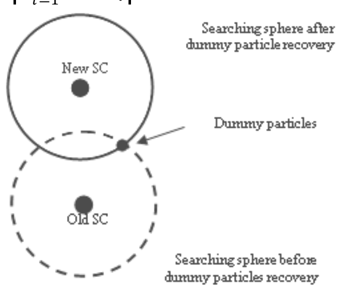

Fig. 2 Reallocation of dummy particles

4.4 Substitution of worst particle with new particles

During the search process, the particle may find position with lower OF value than its related SC. Therefore, for more efficient and effective HSSA, the worst particles (Nnewpar) that not predictable to find optimal minimum value of OF are replaced with new particles which are generated randomly as illustrated in the fourth step of initialization particles stage.

4.5 Examination of Convergence

Final stage is the termination of all worst sets, that including the worst particles which assigned to worst SCs. The remaining are the best sets which have approximately the same position and OF value. Thus, the researching process will stop if the algorithm finds the minimum OF value and the variation of the solution between two sequentially iterations is less than the defined threshold. All the above four stages of HSSA are reformulated in shape of flow chart as depicted in Fig. 3.

5 Results and discussion

In this section, the proposed method is tested on different distribution systems IEEE-118 and IEEE-69 to demonstrate the effectiveness of the HSSA method as is compared with the latest modern methods to approve the distinguish of the proposed HSSA technique.

5.1 IEEE-69 distribution system test

Herein, the suggested technique is applied on the 69-bus system. The schematic diagram of system which including 7 branches are branched of main feeders is depicted in Fig. 4. The input variables of the 69-bus distribution network are the same weather condition (see Fig. 1), technical economic data of the PV generator (see Table 1) of the previous 118-bus. The technical data of the 69-bus distribution network is introduced in [61].

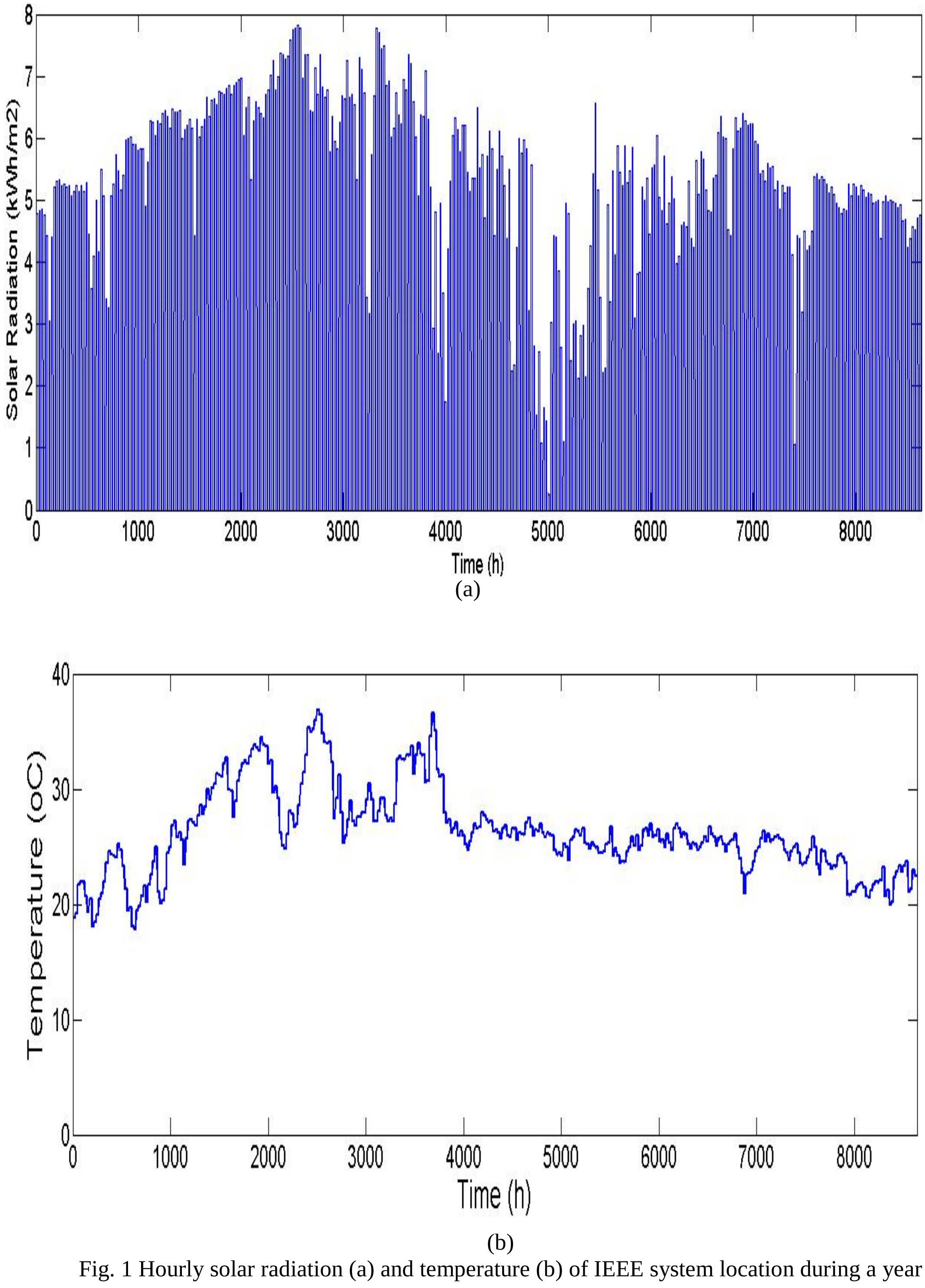

Fig. 1 Hourly solar radiation (a) and temperature (b) of IEEE system location during a year

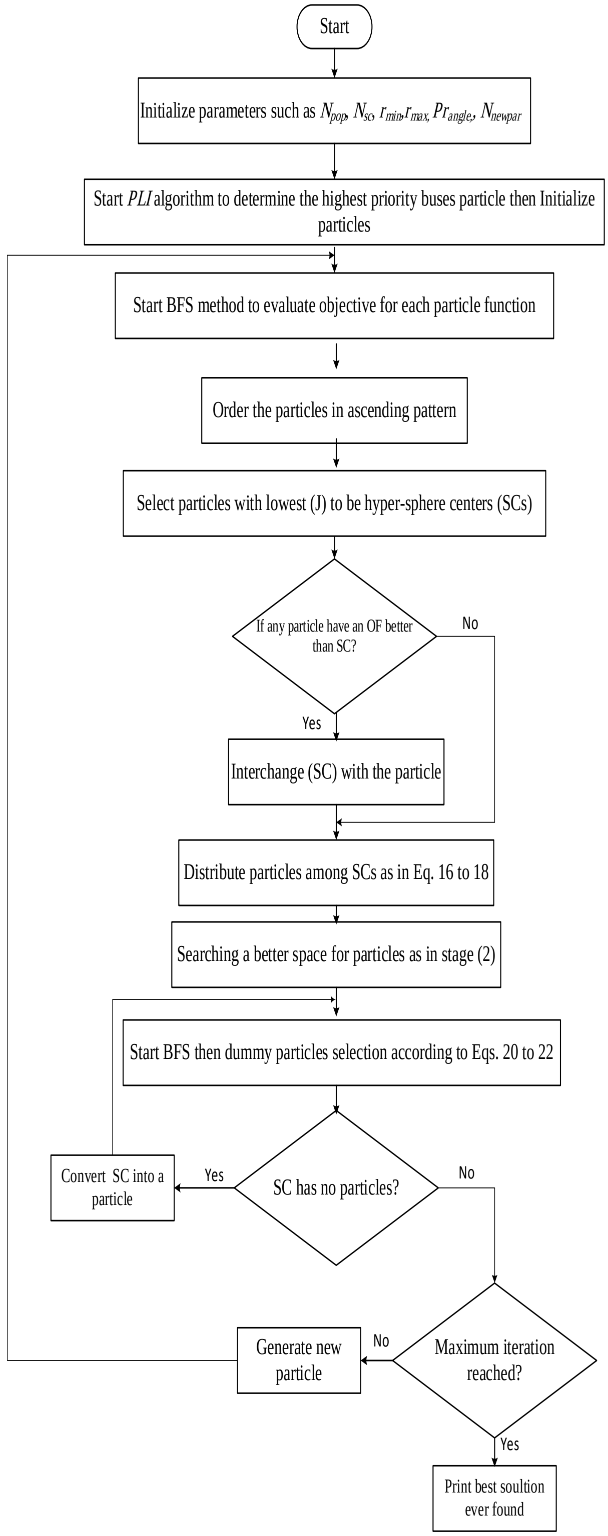

Fig. 3 Flow chart of HSSA

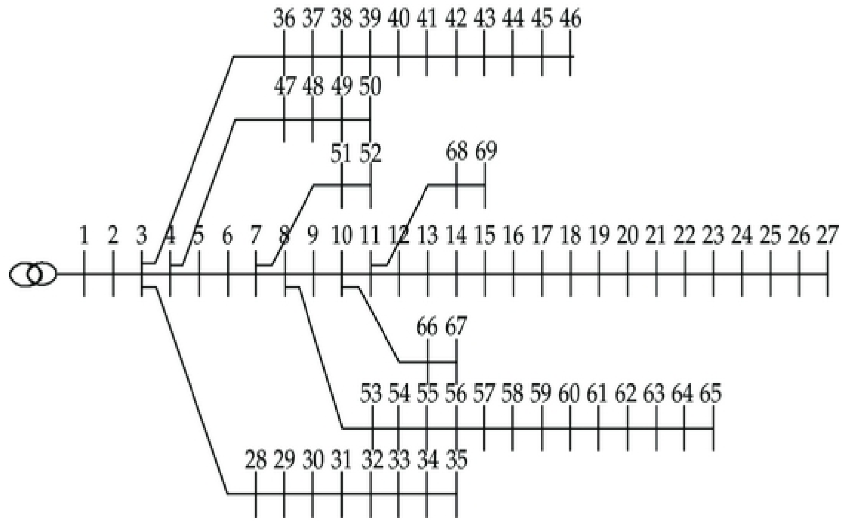

Fig. 4 Schematic diagram of IEEE 69-bus system

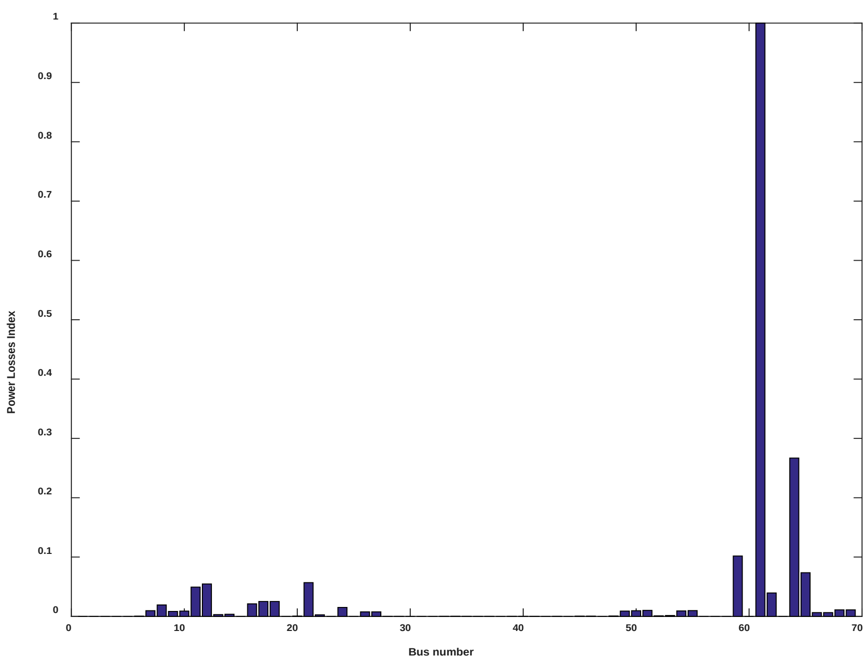

Fig. 5 PLI at all buses of IEEE-69 bus system

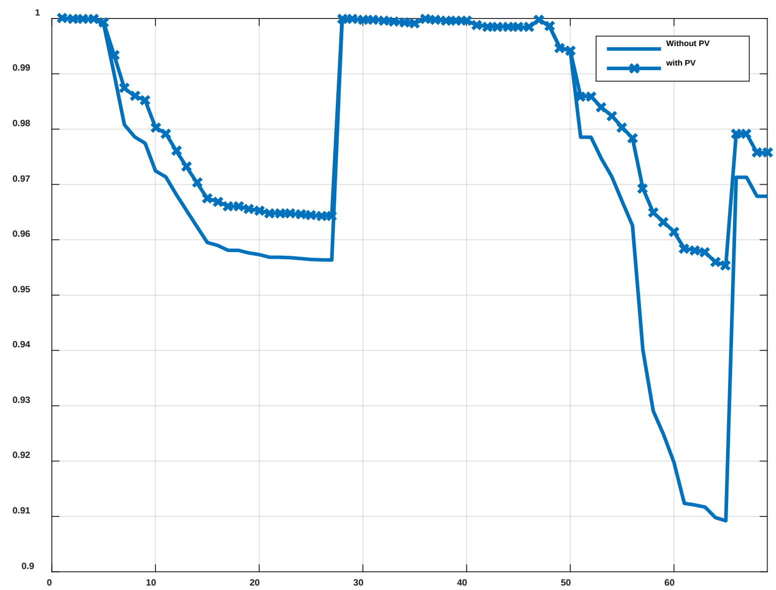

Fig. 6 The effect of installing PV on VSI of IEEE-69 bus system [61]

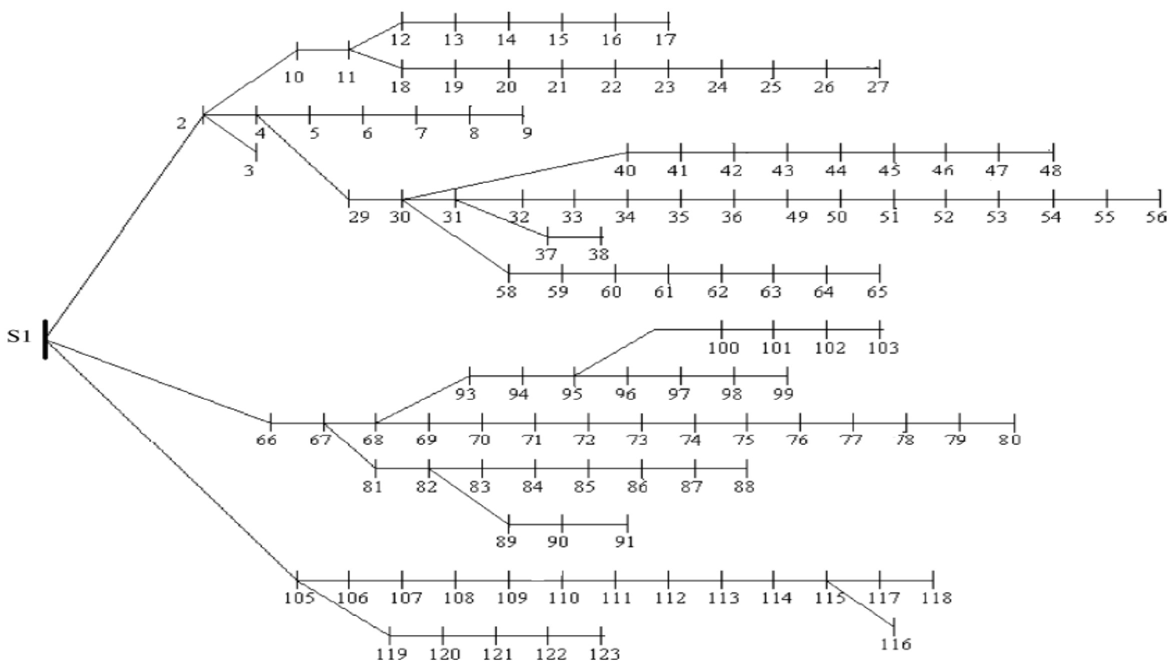

Fig. 7 Schematic diagram of 118-bus system

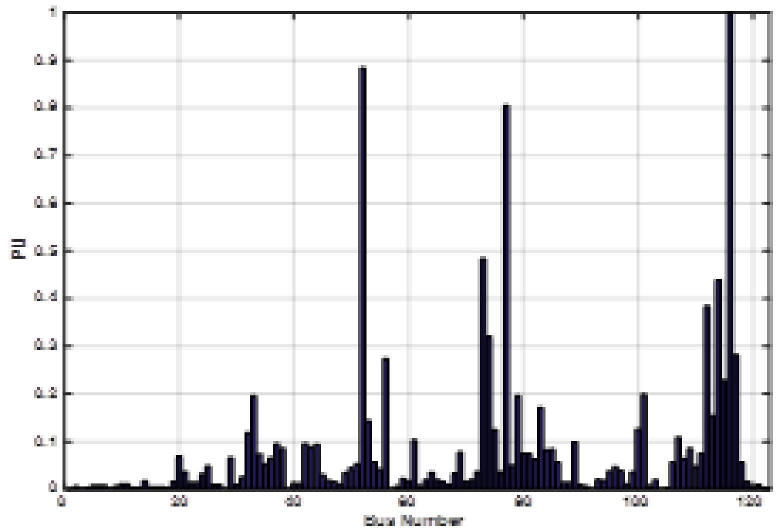

Fig. 8 PLI of 118-bus system

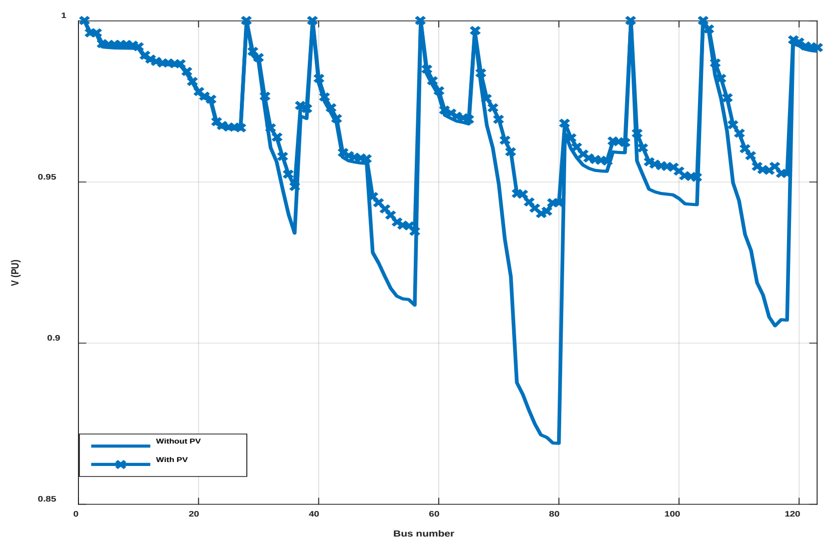

Fig. 9 The effect of installing PV on VSI of IEEE-118 bus system [56]

Table 2 Results for PV in IEEE-69 bus system

	Optimal location (l) And size(s)	Total load (kW)	Total swing power (kW)	Total PV Power (kW)	Total losses (kW)	Saving ($/year) with PV cost	Apparent Saving ($/year) Without PV cost	Max Voltage	Min
WITHOUT	-----------------	3887.9	4016.8	-------	224.89	0	0	1	0.91
ABC [57]	L 61 S 1900	3887.9	1975.1	1900	83.187	24527	74505	1	0.9685
ALOA [60]	L 61 S 1800	3887.9	2075.2	1800	83.346	27072	74422	1	0.96791
CSA [58]	L 61 S 2000	3887.9	1875.6	2000	83.723	21618	74224	1	0.96908
BB-BC [59]	L 61 S 1872	3887.9	2003.1	1872	83.161	25277	74519	1	0.96834
ALOA [60]	L 61 S 1700 L 17 S 538	3887.9	1625.8	2238	70.737	21598	80523	1	0.97708
TEST1 HSSA-no PV cost	L 61 S 1714 L 11 S 344	3887.9	1239	2622.3	69.405	12790	81749	1	0.97884
Proposed HSSA	L 61 S 1207	3887.9	2684.3	1207	99.397	34220	65985	1	0.95541

Via the power flow program, the PLI of all the buses in 69-bus system is calculated and illustrated in Fig. 5. Thus, the most significant buses to add PV generator can be identified. The candidate buses are arranged as follows:

61, 64, 59, 65, 21, 12, 11, 62, 18, 17, ...,

Herein, the proposed technique is executed to obtain optimal location and size of PV generator in the tested system as described in Table 2. In addition, the output results of the proposed technique are compared and analysed with the best results of other previous studies as clarified in Table 2.

1- The proposed technique has been applied on the distribution network via considering the power losses as the objective function without including the cost of the PV generator (Test-1). Active power loss is dropped to 69.405kW, which is corresponding to a 69.14% reduction in power losses. The HSSA technique achieves energy saving about 81749$ is annually. The low level of the voltage at the buses is enhanced from 0.91 p.u to 0.97884 p.u. In addition, the outcomes indicate that the proposed technique presents the best results in terms of power losses, voltage profile and energy saving as compared with the best results of the previous studies [57,58,59 and 60] as revealed in Table 2.

2- Using the proposed technique based on economic objective and technical requirements, it is shown from Table 2 that the actual value of the total saving (34220$) achieved by applying the proposed technique is the best as compared with the other techniques. In addition, the most important technical index is the voltage level, which is improved at most buses as depicted in Fig. 6. From Table 2, it is clear that the minimum voltage is enhanced from 0.91 to 0.95541 p.u. with the stability of the maximum voltage at 1p.u.

5.2 IEEE-118 distribution system test

Despite of the pervious methods can result in an acceptable solution, but they are not applicable for large networks. So, large network such as IEEE-118-bus distribution system is employed to investigate the effectiveness of the proposed optimization technique. Despite the multiplicity of techniques, which are used in determining the size and location of PV generator in distribution system, it has not been applied to these large-scale redial systems in distribution network. The schematic diagram of the 118-bus system is depicted in Fig. 7 and its specific data is given in [56].

Through the integration of the power flow program, the power loss coefficient (PLI) is calculated. Thus, the buses are classified according to the most effective buses with adding PV generator. This arrangement of the buses is illustrated in Fig. 8 as follows:
116, 52, 77, 73, 114, 112, 74, 117, 56, 115, 101, 79, 33, 83, 113, 53
The next step is to apply the proposed technique to complete the process of selecting the optimal locations of the PV generator at optimal buses, which fulfil the minimum value of the cost objective function. The optimal location and the corresponding capacity of the PV generator in kW are specified in Table 3.

Table 3 Optimal location and sizing of PV for IEEE 118 bus

Optimal location	PV Power (kW)
116	1879.80
52	1435.50
112	1311.50
79	800.00

From the economic and technical point of view, which achieves all the pre-determined conditions, and through the results shown in the Table 4, it is clear that one of the target of this study has been achieved and losses has been decreased by 56.56%.
It is worth noting that the total saving in the cost is 152852 USD with considering the cost of PV generator based on hourly variation of the metrological conditions. Despite of the total saving with ignoring the PV generator cost is 295321 USD, which is higher than the previous value it is considered as misleading result because of the saving in cost should be considered from both sides the technical side (reduction of losses) and economic side (cost of PV generator).
It is also clear that a significant improvement has been achieved by using PV generator on the voltage profile as shown in Fig. 9. The voltage level has been increased at most buses whereas the minimum voltage reached 0.9355 and the maximum voltage limit is 1. Thus, another technical goal of this research has been attained by enhancing voltage profile.
Therefore, the results confirm the relative discrimination of the proposed technique in its ability of reaching the optimal location and size of PV generators in the large-scale distribution network under test. In the next section, the proposed technique is applied to medium-scale distribution network to conduct a comparison among different scale network via using different optimization technique such as ABC [57], CSA [58], BB-BC [59] and ALOA [60].

Table 4 Results for IEEE 118-bus system using HSSA.

Items	Without -PV	With PV
Total load (kW)	22710.00	22710.00
Total swing power (kW)	24004.06	18015.05
Total PV Power (kW)	0	5426.80
Total losses (kW)	1294.34	732.13
Total losses (kW) (%)	-	43.43
Saving ($/year) with PV cost	0	152852.32
Apparent Saving ($/year)Without PV cost	0	295321.42
Maximum Voltage	1.00	1.00
Minimum Voltage	0.87	0.9355

6 Conclusions

In this research, a novel technique has been proposed to determine the optimal location and size of the PV generators in distribution power network. This technique was verified by applying it to different distribution systems. The mathematical analysis and the results have been presented and the following conclusions have been drawn:
1- The proposed technique was investigated via targeting the cost objective function. The hourly variation of the weather condition is taken into account in estimation of the objective function. Therefore, the proposed technique is considered valid for application at any geographical point around world.
2- Recent global prices of PV generator components have been taken into account for the implementation of PV generator, which led to the emergence of a mutation in possible sizes in PV generators and reduction in the actual cost of the energy that generated via PV generator.
3- The proposed method is applicable for large networks such as IEEE-118 bus and also gives an accurate solution.
4- The obtained results proved the effectiveness of the proposed technique in optimizing the power losses and energy saving and enhancing the voltage levels at the most buses in the distribution network.
5- The results showed significant improvement in the voltage levels with achieving the economic targets.

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