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POWER SYSTEMS AND POWER ELECTRONICS

Economic based evaluation of DGs in capacitor allocated optimal distribution network

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Abstract. Feeder reconfiguration (FR), capacitor placement and sizing (CPS) are the two renowned methods widely applied by the researchers for loss minimization with node voltage enrichment in the electrical distribution network (EDN), which has an immense impact on economic savings. In recent years, optimization of FR and CPS together can proficiently yield better power loss minimization and save costs compared to the individual optimization of FR and CPS. This work proposes an application of an improved salp swarm optimization technique based on weight factor (ISSOT-WF) to solve the cost-based objective function using CPS with and without FR for five different cases and three load levels, subject to satisfying operating constraints. In addition, to ascertain the impact of real power injection on additional power loss reduction, this work considers the integration of dispersed generation units at three optimal locations in capacitive compensated optimal EDN. The effectiveness of ISSOT-WF has been demonstrated on the standard PG&E 69-bus system and the outcomes of the 69-bus test case have been validated by comparing with other competing algorithms. Using FR and CPS at three optimal nodes and due to power loss reduction, cost-saving reached up to a maximum of 71%, and a maximum APLR of 26% was achieved after the installation of DGs at three optimal locations with the significant improvement in the bus voltage profile.

Key words: ISSOT-WF; capacitor placement and sizing; feeder reconfiguration; dispersed generation; electrical distribution network; additional power loss reduction

1. INTRODUCTION

The primary objective of the electrical distribution network (EDN) is to feed the required electrical energy to the end-user consistently, which depends on the quality and efficacy of the EDN. Due to the rapid growth in power demand, the power generation capacities need to be expanded to avoid blackouts which create severe financial problems in developing countries [1]. In India, the T&D losses are nearly 20% of the total power generation, which is almost three times compared to the United States. Therefore, to be more competitive, distribution companies (DISCOs) presently receive more attention in minimizing the I^2R loss as it reflects the cost of electricity. Feeder reconfiguration (FR), real and reactive power compensation are the most proficient techniques applied to EDN to suppress real and reactive power loss (P_{Loss} & Q_{Loss}) and bus voltage enrichment [2].

The importance of FR has been recognized from 1988 onwards. Hence, many types of research on optimal FR-based optimization problems are being focused [3–6]. By using FR, the merits such as a decrease in P_{Loss}, enrichment in bus voltage profile, load congestion management, and reliability of the EDN get improved and this will reflect in the performance improvement of the EDN. Although the EDN is set as a weak mesh network, its operation is radial for effective coordination with protection schemes and to reduce the fault level.

Since the 1960s, the application of shunt capacitors has been one type of imperative research in radial EDN. However, a part of a reduction in power loss could be done by capacitor placement and sizing (CPS), which feed a part of reactive power demand. It is well known that by the addition of capacitors in radial EDN, the benefits such as reduction in branch real & reactive power loss, increase in feeder capacity release, reduction in total KVA demand, reduced loading of thermally limited apparatus, bus voltage and power factor improvement can be obtained. Since capacitors lower the reactive power requirement from the main source (MS), more real-power output is available. In recent times, a lot of research has been focused on CPS problems [7–10] in EDN.

Combined optimization of FR and CPS will yield more reduction in P_{Loss}, Q_{Loss}, and enrichment in bus voltage profile compared to individual optimization of FR / CPS problems. Optimal CPS along the EDN with FR is a non-linear, complex, combinatorial, and mixed-integer optimization problem, which includes both integer and discrete variables that correspond to the optimal locations at which capacitors are required to be placed and the number of capacitor banks that are installed at each bus. It is also a computationally in-depth problem whose dimension increases extremely with network size. Only a few research papers are available in the literature for optimization of capacitor allocation and sizing together with FR [11–17].

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P_{Loss} minimization, bus voltage enrichment, and yearly cost savings increase as objective, optimal allocation, and sizing using individual CPS and dual CPS-FR have been proposed in [11]. In this paper, four optimization methods such as MBBO/ CS / MIC / MBFBO are engaged to solve the multi-objective functions. Self-adaptive harmony search algorithm (SAHSA) as optimization method, FR simultaneous with CPS under five different scenarios considering 100% and 120% loading conditions to suppress the P_{Loss} and to enhance the bus voltage has been reported in [12]. Distribution system reconfiguration, i.e. FR/dual DSR-optimal capacitor placement, i.e. dual FR-CPS-based optimization considering IEEE 33- & 69-bus test system have been presented in [13]. To find the optimal solution for significant P_{Loss} reduction and voltage profile enrichment, modified biogeography-based optimization (MBBO), binary teaching-learning-based optimization (BTLBO), and discrete dolphin echolocation (DDE) algorithm have been adopted. FR and CPS problem under three different cases using BAT algorithm has been suggested in [14]. In this work, the cost of the capacitor and energy loss has been taken as objective and PEM has been proposed to model the uncertainties of the problem. Both deterministic and stochastic frameworks are considered. Optimal allocation and sizing of type I (real power injection) and type II (reactive power injection) dispersed generations (DGs) in the reconfigured radial EDN using an analytical approach has been suggested in [15]. Power voltage sensitivity constant (PVSC) and DG penetration index have been engaged to decide the location and optimal size of both types I and II DGs. Considering the voltage limits of all the buses and P_{Loss}, optimal nodes for DG placement has been suggested by PVSC. P_{Loss} minimization as objective, optimal CPS and DG simultaneous with FR under seven different cases considering PG&E 69-bus using AGPSO as optimization method has been discussed in [16]. Adaptive whale optimization algorithm (AWOA) as an optimization tool, Cost-based P_{Loss} minimization using FR and CPS under three cases has been presented in [17]. In this paper power loss sensitivity index (PLSI) has been utilized to identify the optimal nodes for capacitor placement.

Owing to the liberalization of the electricity market, the share of dispersed generations in EDN has been increasing slowly in the last two decades. The increase in power demand must be satisfied by the utility DGs due to the terrific load growth. To improve the network performance such as reduction in P_{Loss} and the bus voltage profile enrichment, DGs must be placed optimally with appropriate size while maintaining the system stability which is a complex, combinatorial, and non-linear optimization problem. Optimal DG allocation and sizing (DGAS) problems solved using various algorithms have been reported for the past two decades [18]. Recently, to reduce P_{Loss} and bus voltage enrichment in the EDN, optimal allocation of all the three techniques such as FR, DGAS, and CPS has been adopted [19–21].

A fast and novel computation method has been suggested in this work to solve the CBOF. CPS with and without FR under five different combinations has been considered to solve the CBOF considering 50%, 100%, and 160% load levels. This is the first level of cost based P_{Loss} minimization. In addition, this work also considers a real power injection at three optimal nodes after CPS with FR intending to achieve additional power loss reduction (APLR) as well as operational cost minimization. In other words, the impact of DGAS in the reactive power compensated optimal EDN intending to achieve APLR which considered the DG operational cost has been discussed subject to fulfilling all the equality and inequality constraints; it has been projected as the next stage of optimization. In this paper, no sensitivity factor (SF) has been utilized to identify the most sensitive buses for reactive power compensation and the algorithm must search for both optimal nodes and sizing of capacitors to avoid poor quality solutions and to maximize the utilization property of the optimization technique. The newness of this work is that this work suggests an improved salp swarm optimization technique based on weight factor (ISSOT-WF) to solve the FR together with CPS and DGAS in PG&E 69-bus radial EDN to solve the CBOFs under three different load levels. In the light of the above-discussed features, the contributions of this work include:

- A novel optimization algorithm has been applied to solve the objective functions.
- Apart from the above, this work also considers the study of the impact of APLR by DGAS considering the DG operational cost in capacitive compensated optimal EDN under three different load levels.

The entire work has been set in five sections. The problem formulations of the proposed work along with EDN load flow (EDNLF) have been discussed in Section 2. SSOT and ISSOT-WF with their capability to solve the CBOFs with their pseudocode have been explained in Section 3. Discussions on the simulation and the outcomes of the proposed methodology with the comparisons have been shown in Section 4 and finally, the work carried out in this research paper has been discussed in short in the conclusion followed by the references.

2. PROBLEM FORMULATION AND EDN LOAD FLOW

In this work, a sturdy, fast, flexible, and proficient method of EDNLF is used which is based on recursive function and a linked-list data structure designed power flow study [22]. A tree-like structure of EDN with efficient use of dynamic data structure has been exploited by the author. Total P_{Loss} (TP_{Loss}) and total Q_{Loss} (TQ_{Loss}) incurred in the whole network which includes all feeders (laterals and sub-laterals), may be obtained by summing up all the branches of the radial EDN as given below:

$$TP_{\text{Loss}} = \sum_{m=1}^{NTB} P_{\text{LOSS}(m)}, \tag{1}$$

$$TQ_{\text{Loss}} = \sum_{m=1}^{NTB} Q_{\text{LOSS}(m)}, \tag{2}$$

where m is a branch connecting sending end and receiving end buses and NTB indicates the total number of branches.

2.1. Problem formulation

The purpose of CPS with FR and DGAS in the EDN is to minimize P_{Loss}, reduce capacitor purchase cost, and DG power purchase cost subject to the satisfaction of power balance constraints & inequality constraints. The problem has been mathematically formulated as given in (3)–(5)

Minimize

$$\text{Cost saving} = (\text{Cost}_1 + \text{Cost}_2). \tag{3}$$

Cost_1 is applicable for CPS with and without FR and Cost_2 is applicable for DG energy purchase (DGEP) based on P_{Loss} reduction after CPS with FR.

$$\text{Cost}_1 = \left(K_{PL} \times TP_{\text{Loss}(ACP)}\right) + \left(K_{CP} \times \sum_i^{NCN} Q_{c(i)}\right), \tag{4}$$

where K_{PL}, K_{CP}, and $Q_{c(i)}$ refers to the P_{Loss} cost, capacitor purchase cost, and i-th node capacitor size, respectively.

$$\text{Cost}_2 = \left(K_{PL} \times TP_{\text{Loss}(ADGI)}\right) + \left(K_{DGP} \times \sum_i^{NDG} P_{DG(i)}\right), \tag{5}$$

where K_{DGP} and $P_{DG(i)}$ refer to the DG power purchase cost and power injected by the i-th DG.

2.2. Power balance constraints

Equality constraints

$$Q_{MS} - \sum Q_D + \sum_i^{NCN} Q_{C(i)} - TQ_{\text{Loss}} = 0, \tag{6}$$

$$P_{MS} - \sum P_D + \sum_i^{NDG} P_{DG(i)} - TP_{\text{Loss}} = 0, \tag{7}$$

where P_{MS}, Q_{MS}, P_D, and Q_D indicates the real and reactive power supplied by the MS and demand, respectively.

Inequality constraints

$$\sum_i^{NCN} Q_{C(i)} \leq \left[(\mu) \times \left(\sum Q_D + TQ_{\text{LOSS}(ACP)}\right)\right], \tag{8}$$

$$\sum_i^{NDG} P_{DG(i)} \leq (\lambda) \times \left(\sum P_D + TP_{\text{LOSS}(ADGI)}\right), \tag{9}$$

where μ and λ are the penetration limit of the capacitor and DG outputs which have been taken as 0.7 and 0.6, respectively.

The real and reactive power injection limit for the i-th capacitor and DG nodes can be stated as

$$\begin{cases} P_{DG(i)}^{\min} \leq P_{DG(i)} \leq P_{DG(i)}^{\max}, \\ Q_{C(i)}^{\min} \leq Q_{C(i)} \leq Q_{C(i)}^{\max}. \end{cases} \tag{10}$$

Bus voltage range for the i-th node can be stated as

$$V_i^{\min} \leq V_i \leq V_i^{\max}. \tag{11}$$

After compensation, the bus voltage magnitudes of the EDN should be well within the limit of the acceptable values.

$$Q_c^{\max} = U \times Q_C^0, \tag{12}$$

where U is the multiplies of integer values of the smallest size denoted as Q_C^0. The value of U lies between 1 and 14 for all three load levels.

2.3. Isolation constraints

During the optimization process of altering the topological structure, all the nodes must be energized and no end-user should be isolated from the main power supply by maintaining the radiality structure of the EDN.

3. EXISTING METHODOLOGY (SSOT) [23]

Salp swarm optimization technique (SSOT) is a population-based meta-heuristic optimization technique presented in [23] to solve all problems, which has been acknowledged as an efficient one. SSOT has been developed from the navigation and search behaviour of salps in oceans. Salps normally form a swarm called salp string which resembles its behaviour. Salps can be categorized as leaders or followers depending upon their arrangement in the string. The one which is positioned first is the leader (leader of the salp string) and the remaining salps are followers which follows the leader salp and each other in the string.

3.1. The mathematical model for salp chains

The position of salps has been effectively formed as an m-dimensional (number of variables) search space like other swarm-based algorithms. Hence, all the positions of the salps are organized and stored in a two-dimensional matrix which is termed as X. It has been understood that there is a source for the best food “F” in the search space which is the ultimate target of the swarm. During the searching process, follower salps follow the leading salp and the leader salp also moves in the direction of the best food source (F). If “F” be replaced by the global optimum, each salp location has been updated to attain a superior solution. As a result, the salp chain will move automatically in the right direction to achieve global optimum which changes over the range of iterations. The mathematical model to move the salps chain can be written as follows:

$$\begin{aligned} x_j^1 &= F_j + C_1\left((ub_j - lb_j)c_2 + lb_j\right)c_3 \geq 0 \quad \text{and} \\ x_j^1 &= F_j - C_1\left((ub_j - lb_j)C_2 + lb_j\right)c_3 < 0 \end{aligned} \tag{13}$$

where x_j^1 is the location of the initial salp, i.e. leader in the j-th dimension. F_j is the position of the food source (F) in the j-th dimension. ub_j and lb_j indicate the upper and lower bound of j-th dimension respectively. C_1 to C_3 are the arbitrary numbers uniformly generated in the interval of [0, 1] and the coefficient C_1 is the main controlling parameter of the SSOT and is defined by

$$C_1 = 2e^{-\left(\frac{4l}{L}\right)^2}, \tag{14}$$

where l is the current iteration and L is the maximum number of iterations. The position of the followers are updated using the equation

$$x_j^i = \frac{1}{2}\left(x_j^i + x_j^{i=1}\right), \tag{15}$$

where $i \geq 2$ and x_j^i is the position of the i-th follower salp in the j-th dimension.

3.2. Improved salp swarm optimization technique based on weight factor (ISSOT-WF) [24]

In general, while solving the objective functions, the problems such as falling into local optima and evolutionary stagnation have been experienced by the swarm-based algorithms with multiple local extrema. Although conventional SSOT is an effective optimization technique due to its high sturdiness, uncomplicated parameters, and simple execution, it also faces the above-mentioned problems. To balance the potential of global exploration and local exploitation and to improve the population position formula, modification in the weight factor (WF) has been suggested in [24] to eliminate such problems. Consequently, modifications based on weight factors have been considered in this work.

During the searching process, both exploration and exploitation are critical. However, they are conflicting with each other. To get superior performance on optimization, a counterbalance of these two abilities is required. It is well known that in the PSO algorithm, inertia weight has been suggested to nullify the evolutionary stagnation problem and to accelerate the convergence rate. However, from [24], it is understood that the particles have strong global exploration ability and strong local exploitation ability when the inertia weight is large and small, respectively. The algorithm may reach the local optimum when the inertia weight is small. Therefore, the WF has been introduced to the population position such that the population is proficient in better adjustment to the present search situation. It is clear that the followers update their position according to their own past position and the position of the previous individual. Equation (15) has been modified as (16) and (17) using the WF w in the followers' position update formula same as modified PSO methods

$$x_j^i = \frac{1}{2}w(I) \times \left(x_j^i + x_j^{i=1}\right), \tag{16}$$

$$w(I) = (w_{\max} \times rand) - (1/L) \times (w_{\max} - w_{\min}), \tag{17}$$

where $w_{\max}$ and $w_{\min}$ indicate the maximum and minimum limit of WF 'w', respectively. It is clear that if the value of 'w' is big in [0, 1], the algorithm search effectiveness is small and the local exploitation is restricted. Therefore, it is very difficult to search for an exact solution. Conversely, if the value of 'w' is small, the algorithm has higher convergence accuracy and for this reason, global search capability is weakened. As a result, ISSOT has more possibility of reaching the local extremum, which is not beneficial to the optimization.

The introduction of dynamic WF 'w' which changes according to the number of iterations (17) decreases when the iteration proceeds from 1 to maximum. However, during starting stage of iteration, the value of 'w' is large to focus on the large range of searches and to validate the global search ability. From [24], it has been proved that the fixed value of the weight factor throughout the evolution process has not yielded better performance. Therefore, equation (17) varies with some randomness. Simultaneously, to avoid the algorithm falling into local extremum and appearing evolution stagnation, a random number (*rand*) can add a variety of possibilities.

3.3. Application of ISSOT-WF for the chosen problem

The steps involved in the ISSOT-WF algorithm are discussed below:

Step 1. Initialize the search agents, number of iterations, and the dimension of the variables such as optimal nodes, the capacity of the capacitors / DGs. Generate the initial search agents of a size considering all the constraints from (6) to (12).

Step 2. For the generation of each search agent, calculate the system variables such as P_{Loss} and bus voltage profile using the LF discussed in [22]. Evaluate the appropriateness of the initial salps using (4) and (5) and the most excellent search agent position using (13) for the first iteration.

Step 3. The value of C_1 gets updated for every iteration using (14), (16), and (17), the updation of the follower salps are performed instead of (15).

Step 4. Considering the upper and the lower boundary conditions, modify the salps and determine the optimum value for (4) and (5).

Step 5. Once a maximum number of iterations is reached, terminate the process, and show the final value of the objective function value related to optimal structure of EDN, optimal CPS / DGAS values, or else, repeat steps 2 to 5.

Only the particles that satisfy all the constraints will be considered as the initial population. Table 1 indicates the details of SVs and their ranges for NR, capacitor, and DGs, respec-

Table 1

Typical value of variables (cases A to H)

Compensation technique	No. of variables	Solution vectors (SVs)	Solution vector range
NR	$5+5$	2–68 & 69–73	Closing of sectionalizing switches against the opening of tie-switches
Capacitor	$3+3$	Node No. 2 to 69	0.15–0.6 (50% load) 0.3–1.5 (100% load) 0.45–2.25 MVAr (160% load) (in discrete steps of 0.15 MVAR)
DG	$3+3$	Node No. 2 to 69	0 to 60% of (total $P_D + P_{\text{Loss}}$)

tively. The pseudocode for ISSOT–WF has been discussed in section 3.4. The min. & max. value of ‘w’ considered in this work is the same as considered in [24].

3.4. Pseudocode of ISSOT-WF based algorithm

```
Begin
  Initialize weight factor, mutation probability, population size, and iteration number
  Randomly initialize the position of salps $x_i (i = 1, 2, 3, 4 \ldots N)$
  Calculate the fitness of each salp
  F = the salp with the best fitness
  while (termination condition is not satisfied)
    Update $C_1$ according to equation (14)
    for each salp $(x_i)$
      if $(i == 1)$
        Update the position of the leading salp employing equation (13)
      else
        Update the position of the follower salp employing equation (16)
      end
    end
    Update the position of F
  end
  return F
```

4. CASE STUDY DETAILS AND SIMULATION RESULTS

To prove the effectiveness of the proposed methodology in suppressing the P_{Loss} with cost-saving and bus voltage enrichment, the standard PG&E 69-bus system has been considered as shown in Fig. 1. The details of the network have been taken from [16]. The total apparent power supply fed to this network under BC are $(1952.5822 + j1371.04)$, $(4026.95 + j2797.14)$ and $(6735.4165 + j4606.1142)$ KVA, respectively considering three load levels. The minimum bus voltage recorded under three load levels are 0.9567, 0.90918, and 0.8445 p.u., respectively. Except bus no. 1 all other nodes are considered as load nodes. The acceptable range of bus voltages after compensation has been fixed as 0.95 p.u. and 1.05 p.u., respectively. Eight cases have been considered to demonstrate the usefulness of ISSOT-WF in achieving P_{Loss} suppression, capacitor purchase cost (cases from A to E), and APLR with cost-saving (cases F, G and H). The standard available commercial capacitor sizes (KVAR) and its corresponding costs ($/KVAR) have been taken from [8]. The MS real power cost (K_{MS}) and DG power purchase price (K_{DGP}) are taken from [25] and [26], respectively. DISCO purchases power from the DG power producing company and hence cost related to DG purchase, installation, operation, and maintenance will not come under this scheme.

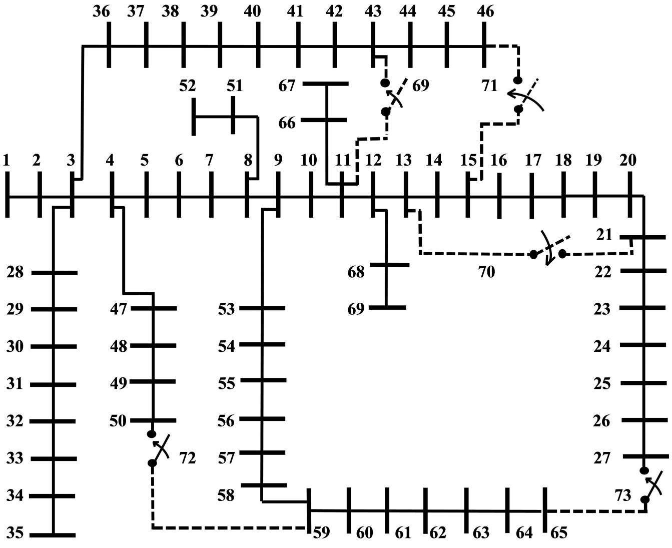

Fig. 1. IEEE 69-bus test system – BC

Case A. FR technique has been done by altering the topological structure of the BC EDN with all the five tie-switches opened initially (Fig. 1) to suppress the P_{Loss} and to achieve maximum cost saving.

Case B. To evaluate the P_{Loss} reduction and to achieve the maximum financial benefit, capacitors at three optimal nodes have been performed in the BC network (Fig. 1)

Case C. The condition is similar to case B, but FR has been done to investigate the effect of FR in achieving excess P_{Loss} reduction with cost benefit.

Case D. CPS at three optimal nodes after case A has been performed to examine the usefulness of reactive power compensation in further P_{Loss} minimization with capacitor purchase cost and net cost saving compared to cases C and D in achieving P_{Loss} minimization and cost-saving.

Case E. Optimal CPS simultaneous with FR at three optimal locations have been performed in BC EDN (Fig. 1) to identify the effectiveness of the simultaneous process compared to cases C and D in achieving P_{Loss} minimization and cost-saving.

Cases F, G & H. To assess the APLR with minimization of power purchase from GENCOs and to achieve maximum profit ($), optimal DGAS at three optimal locations have been performed after cases C, D & E, respectively.

4.1. IEEE 69-bus test system – results and discussion

The details of BC parameters are tabulated in Table 2. By conducting FR, the cost-saving has improved by 54.1563%, 56.1806%, and 59.01954%, respectively compared to BC cost considering three load levels. The bus voltages have improved by 0.0187 p.u., 0.0403 p.u., and 0.072 p.u., respectively. By comparing the results obtained under case A, it is found that the proposed methodology reduces the P_{Loss} and cost-saving improvement better than [3–6].

From Tables 2 and 3, it is apparent that after capacitor addition at three optimal locations, the P_{Loss} has been reduced by 33.884%, 35.4317%, and 37.81778%, respectively compared to BC P_{Loss} considering three load levels. However, the differences in P_{Loss} cost and net savings are 12.833%, 4.0993%, and 2.14977%, respectively. The bus voltages have been enhanced by 0.0101 p.u., 0.0222 p.u. and 0.0417 p.u. The bus voltage improvement under case A is better than that of case B and the Q_{Loss} reduction is more than case A. In Table 4, it is obvious

Table 2

Performance of ISSOT-WF (cases BC to E) – P_{Loss} & cost

Case	P_{Loss} (KW)	% P_{Loss} reduction	Q_{Loss} (KVAR)	ΔP_{Loss} cost ($)	Cost saving ($)	
					$	%
LIGHT LOAD LEVEL (50%)						
B C	51.5822	–	23.54	–	–	–
A	23.6472	54.1563	22.1685	1190.031	1190.031	54.1563
B	34.104	33.884	15.9762	744.57132	462.5713	21.051
C	16.6234	67.773	15.388	1489.245	1207.245	64.5188
D	16.0964	68.7947	15.4293	1511.6951	1247.845	65.75
E	16.0202	68.9424	15.359	1514.94	1251.09	65.898
MEDIUM LOAD LEVEL (100%)						
B C	224.95	–	102.14	–	–	–
A	98.5718	56.1806	92.0225	5383.7113	5383.7113	56.1806
B	145.2463	35.4317	67.7536	3395.3776	3002.5276	31.3324
C	68.1766	69.69255	64.0829	6678.547	6285.697	65.593
D	66.721	70.33963	63.134	6740.5554	6357	66.332
E	64.972	71.11714	61.7533	6815.063	6356.813	66.335
HEAVY LOAD LEVEL (160%)						
B C	652.2165	–	294.1142	–	–	–
A	267.2813	59.01954	249.0473	16398.24	16398.24	59.01954
B	405.5627	37.81778	187.7983	10507.452	9910.152	35.66801
C	183.3705	71.88503	167.286	19972.84	19375.54	71.34
D	177.065	72.8518	167.3587	20241.454	19702.954	72.3603
E	175.8293	73.04127	164.7754	20294.1	19729.8	72.5263

Table 3

Typical value of variables (cases A to E)

Case	A	B	C	D	E
LIGHT LOAD LEVEL (50%)					
Capacitor value & node	–	150 (18) 600 (61) 150 (66)	150 (18) 600 (61) 150 (66)	150 (11) 450 (61) 150 (64)	150 (11) 450 (61) 150 (64)
Switches open	69–70–12 –58–61	69–70–71 –72–73	69–70–12 –58–63	69–70–12 –58–61	69–70–14 –58– 61
V_{min} (p.u.)	0.9754	0.9668	0.9845	0.9826	0.98264
Capacitor cost ($)	–	282	282	263.85	263.85
MEDIUM LOAD LEVEL (100%)					
Capacitor value & node	–	450 (12) 150 (21) 1200 (61)	450 (12) 150 (21) 1200 (61)	450 (27) 900 (61) 300 (66)	450 (27) 1050 (61) 300 (66)
Switches open	69–70–14 –58–61	69–70–71 –72–73	69–70–14 –58–62	69–70–14 –58–61	69–70–14 –58–61
V_{min} (p.u.)	0.9495	0.9314	0.9683	0.967	0.9673
Capacitor cost ($)	–	392.85	392.85	383.55	458.25
HEAVY LOAD LEVEL (160%)					
Capacitor value & node	–	450 (19) 2100 (61) 450 (66)	450 (19) 2100 (61) 450 (66)	600 (27) 1500 (61) 300 (68)	600 (27) 1650 (61) 450 (68)
Switches open	69–70–13 –58–61	69–70–71 –72–73	69–70–14 –58–62	69–70–13 –58–61	69–70–14 –58–61
V_{min} (p.u.)	0.9165	0.8862	0.9509	0.9429	0.9454
Capacitor cost ($)	–	597.3	597.3	538.5	564.3

Table 4

Comparison of case B – all three load levels

Method	P_{Loss} (KW)	Capacitor details	V_{min} (p.u.)	Cap. Cost ($)	Cost saving	
					$	%
LIGHT LOAD LEVEL – 50%						
Fuzzy-GA [9]	40.48 / 51.6	0 (59) 0 (61) 300 (64)	0.9622 (65)	105	368.712	16.77367
DSA [9]	35.52 / 51.6	300 (15) 300 (60) 450 (61)	0.9618 (65)	315.75	369.258	16.7985
TLBO [9]	34.43 / 51.6	150 (22) 150 (59) 450 (60)	0.9662 (65)	255.75	475.692	21.6405
WCA [9]	34.45 / 51.6	150 (16) 150 (59) 450 (60)	0.9659 (65)	255.75	474.84	21.6017
GWO [9]	34.40 / 51.6	150 (16) 450 (60) 150 (61)	0.9663 (65)	255.75	458.226	21.0252
ISSOT-WF	34.104 / 51.5822	150 (18) 600 (61) 150 (66)	0.9666 (65)	282	462.57	21.051
MEDIUM LOAD LEVEL – 100%						
DSA [9]	147 / 225	450 (15) 450 (60) 900 (61)	0.9318 (65)	376.2	2946.6	30.742
TLBO [9]	146.8 / 225	300 (22) 1050 (61) 300 (62)	0.9321 (65)	449.4	2881.92	30.067
WCA [9]	146.73 / 225	300 (16) 450 (59) 900 (60)	0.9312 (65)	375.45	2958.852	30.8696
GWO [9]	146.74 / 225	300 (16) 900 (60) 450 (61)	0.9322 (65)	375.45	2958.426	30.8652
DVSA [7]	145.397 / 225	450 (11) 150 (22) 1350 (61)	0.9308 (65)	460.2	2930.888	30.5779
IIA [8]	145.38 / 225	450 (11) 150 (22) 1200 (61)	0.9308	384.75	3007.062	31.3726
GA-EMA [10]	145.55 / 225	150 (21) 1200 (61) 450 (66)	–	384.75	2999.82	31.297
ISSOT-WF	145.246 / 224.95	450 (12) 150 (21) 1200(61)	0.9314 (65)	384.75	3010.64	31.4169
HEAVY LOAD LEVEL – 160%						
Fuzzy-GA [9]	460.45 / 652.42	1100 (59) 800 (61) 1200 (64)	0.9001 (65)	–	–	–
DSA [9]	427.3 / 652.42	900 (15) 900 (60) 1800 (61)	0.8936 (65)	666	8924.112	32.1091
TLBO [9]	417.28 / 652.42	300 (22) 1050 (61) 750 (62)	0.8795 (65)	551.4	9038.712	32.5214
WCA [9]	416.7 / 652.42	600 (16) 900 (61) 900 (62)	0.8785 (65)	461.4	9580.272	34.47
GWO [9]	412.87 / 652.42	600 (16) 750 (60) 1050 (61)	0.8855 (65)	578.4	9626.43	34.636
ISSOT-WF	405.5627 / 652.2165	450 (19) 2100 (61) 450 (66)	0.8862 (65)	581.1	9926.352	35.7263

that the P_{Loss} reduction and the net profits under three load levels are better than [7–10].

Considering FR after case B, i.e. case C and from Tables 2 and 3, the cost-saving improvement beyond case B is found to be 33.8876%, 34.253%, and 34.06734% which is around 100% Extra P_{Loss} reduction compared to case B. The capacitor cost under all three load levels seems to be insignificant compared to the power loss reduction cost. It is obvious from Table 5 that, the cost-saving improvement is better compared with [11] except MBBO.

Table 5
Comparison of case C – medium load level

Particulars	MBBO [11]	CS [11]	MIC [11]	MBFBO [11]	ISSOT-WF
Capacitor details (kVAr)	300 (12) 900 (60) 150 (21)	450 (15) 600 (50) 900 (61)	1350 (59) 150 (69) 450 (15)	600 (59) 300 (68) 300 (20)	450 (12) 150 (21) 1200 (61)
Switch status	58–42–19 –60–45	49–10–59 –45–19	69–70–14 –58–49	10–19–14 –60–54	69–70–14 –58–63
P_{Loss} (KW) / (P_{Loss} – BC)	54.9369 / 224.9606	80.4276 / 224.9606	102.846 / 224.9606	80.6144 / 224.9606	68.1766 / 224.95
Vmin (p.u.)	0.97336	0.97189	0.97447	0.98651	0.9683
% P_{Loss} reduction	75.5793	64.2482	54.2827	64.1651	69.6993
ΔP_{Loss} cost ($)	7243.01	6157.1058	5202.082	6149.148	6678.547
Cost of capacitor ($)	344.7	410.55	468.3	342	392.85
% Cost saving	75.5793	59.9641	49.396	60.5964	65.593

Considering case D, i.e. CPS at three optimal nodes after case A, yields further P_{Loss} reduction of around 14% considering three load levels. The cost-saving under case D compared to case A amounts to $ 57.814, $ 973.2887, and $ 3304.714, respectively. The bus voltage improvements are 0.0072 p.u., 0.0175 p.u. and 0.0264 p.u., respectively. The cost difference between cases C and D is $ 40.6, $ 71.303, and $ 327.414, respectively. From Table 3, it is obvious that the capacitor costs are less than case C (light, medium and heavy load). From Table 6, it is clear that the P_{Loss} reduction and cost savings are better than [13, 15] except MBBO.

The performance of case E is presented in Tables 2 and 3. The net profit difference between cases C, D, and E is found to be minuscule. However, the bus voltage improvement under case E is better than cases C and D. By comparing the results obtained by ISSOT-WF under case E with [12, 14, 16, 17] mentioned in Table 7, the performance of ISSOT-WF is better considering all parameters.

The performance of the proposed method under cases from C to E considering all the three load levels yields cost saving between 65% and 72%. Hence, this test system has undergone a real power injection at three optimal nodes after cases C, D, and E to get APLR thereby gain in additional cost savings with an improvement in bus voltage.

Table 6
Comparison of case D – medium load level

Parameters	Analytical [15]	BTLBO [13]	DDE [13]	MBBO [13]	ISSOT-WF
Capacitor details	350 (50) 390 (64) 1050 (61)	300 (25) 300 (37) 900 (49)	600 (48) 600 (6) 300 (68)	300 (21) 300 (50) 300 (11)	450 (27) 900 (61) 300 (66)
Switch status	69–18–13 –56–61	12–60–15– 6–10	14–53–11 –9–60	14–60–48 –12–10	69–70–14 –58–61
P_{Loss} (KW)/ (P_{Loss} – BC)	66.74 / 225	116.6786 / 224.9606	105.554 / 224.9606	58.6166 / 224.9606	66.721 / 224.95
Vmin (p.u.)	0.97	0.99001	0.98744	0.9911	0.968
% P_{Loss} reduction	70.3377	48.13376	53.08	73.9436	70.33963
ΔP_{Loss} cost ($)	–	4612.813	5086.72	7086.254	6740.555
Cost of capacitor ($)	–	374.7	369	315	383.55
% Cost saving	–	44.22384	49.22844	70.65665	66.3372

Table 7
Comparison of case E – medium load level

Parameters	SOFBBA [14]	SASHA [12]	AGPSO [16]	A W O A [17]	ISSOT-WF
Capacitor details	1350 (27) 2250 (37) 1200 (62)	150 (57) 150 (58) 900 (61)	300 (64) 450 (11) 1050 (61)	150 (49) 125 (50) 138 (61)	450 (12) 1050 (61) 300 (66)
Switch status	69–70–11 –58–73	69–70–14 –55– 62	69–70–13 –58–61	69–13–71 72–73	69–70–14 –58–61
P_{Loss} (KW) / (P_{Loss} – BC)	88.4131 / 225	72.76 / 225	65.76 /224.95	83.357 / 223.36	64.972 / 224.95
V_{min} (p.u.)	0.9561	0.9655(62)	0.96704 (61)	—	0.9671
% P_{Loss} reduction	60.7053	67.66222	70.7670	62.68	71.11714
ΔP_{Loss} cost ($)	5818.602	6485.424	6781.494	—	6815.063
Cost of capacitor ($)	926.7	314.7	458.25	—	458.25
% Cost saving	51.03706	64.379	65.9849	—	66.3352

The performance of the proposed method in achieving APLR has been revealed in Tables 8 and 9. It is to be noted that the penetration of DGs (after reactive power compensation in the optimal EDN) lies between 42% and 51%. Similarly, the APLR gained under cases F, G, and H is around 26.5% (light LL), 24% (medium LL), and 22% (heavy LL). Thus, the total power loss reduction has risen to more than 94%. Significant improvement in bus voltages has been noticed after cases F, G, and H. The profit gained under cases F, G, and H is more than 14% considering three load levels. Finally, by screening Table 10, it is known that ISSOT-WF yields better performance than that of [19, 20]. However, due to the heavy penetration of DGs and capacitors in the bare EDN, the P_{Loss} reduction achieved by [21] is more than that of ISSOT-WA. Figures 2 to 7 show the bus voltages considering cases from BC to H.

Table 8
Performance of ISSOT-WF – cases F to H – all load levels

Case	P_{Loss} (kW)	Q_{Loss} (kVAr)	DG node & Size (kW)	$V_{\min}$ (p.u.)	APLR (kW)	% APLR	DG power cost ($)
LIGHT LOAD LEVEL (50%)							
F	3.0104	2.1493	154 (27) 209 (50) 605 (61)	0.99367	13.613	26.391	29040
G	2.3671	2.171	251 (27) 184 (60) 527 (61)	0.99569	13.7293	26.6163	28860
H	2.3429	2.1207	281 (27) 099 (60) 601 (61)	0.99575	13.6773	26.5155	29430
MEDIUM LOAD LEVEL (100%)							
F	14.245	12.101	390 (27) 407 (62) 908 (61)	0.98446	55.1441	24.5085	51150
G	13.112	11.727	252 (27) 343 (60) 1087 (61)	0.98472	53.5006	23.77804	50610
H	11.348	9.8931	381 (27) 278 (60) 1091 (61)	0.98854	54.7856	24.34915	52500
HEAVY LOAD LEVEL (160%)							
F	39.588	29.213	684 (20) 625 (60) 1543(61)	0.97288	143.7825	22.04517	85560
G	32.131	30.903	627 (25) 541 (60) 1485(61)	0.9763	144.9341	22.22177	79590
H	31.092	27.515	653 (24) 527 (60) 1602(61)	0.97733	144.7373	22.1916	83460

Table 9
Performance of ISSOT-WF – cases F to H – all load levels

Case	P_{MS} (KW)		Cost reduction in P_{MS}($)	Net profit	
	ACP	DGAS		Cost ($)	%
LIGHT LOAD LEVEL (50%)					
F	1917.6234	936.0104	41816.714	12776.714	15.6403
G	1917.0964	941.367	41566.072	12706.072	15.5581
H	1917.0202	922.3429	42373.253	12943.253	15.8492
MEDIUM LOAD LEVEL (100%)					
F	3870.1766	2111.245	74930.486	23780.486	14.4238
G	3868.7326	2133.112	73937.438	23477.44	14.2453
H	3866.9728	2063.348	76834.425	24334.425	14.772
HEAVY LOAD LEVEL (160%)					
F	6266.5705	3270.788	127620.3345	42060.3345	15.7555
G	6260.265	3462.331	119191.988	39601.988	14.8496
H	6259.029	3332.292	124679	41219	15.459

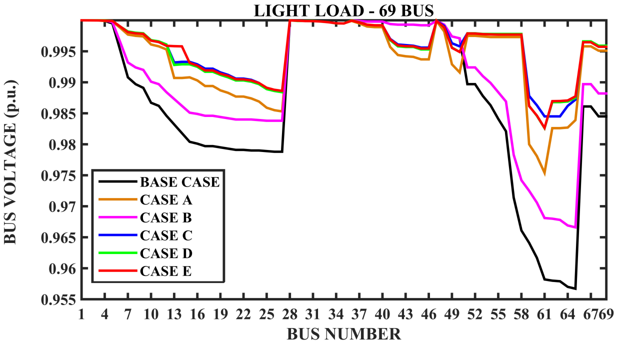

Fig. 2. Bus voltage profile – case BC to E – light load

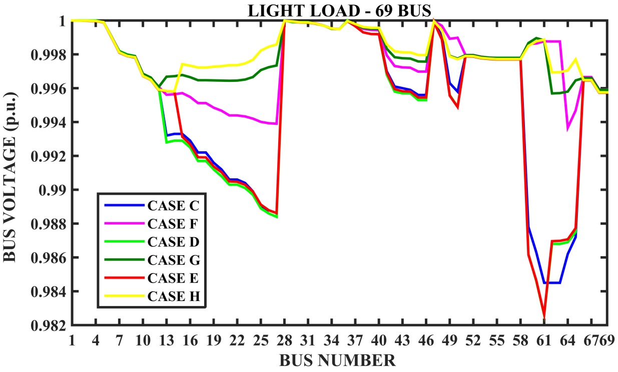

Fig. 3. Bus voltage profile – cases C to H – light load

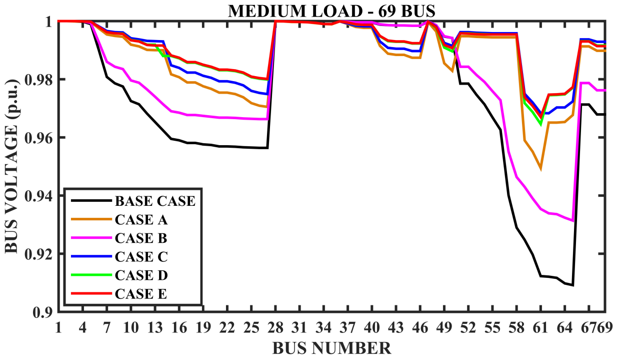

Fig. 4. Bus voltage profile – cases BC to E – medium load

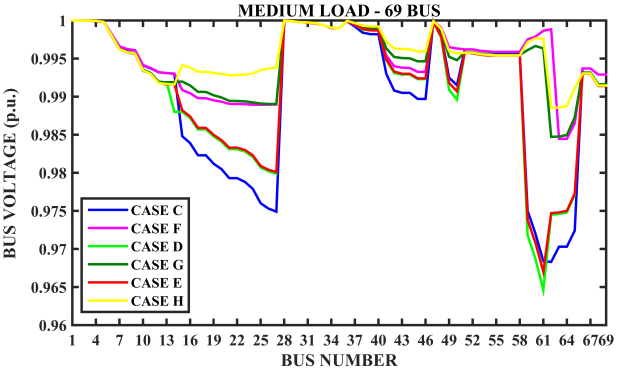

Fig. 5. Bus voltage profile – cases C to H – medium load

Table 10
Comparison of case H – medium load level

Ref.	DG details	Switch position	Capacitor details	P_{Loss} (kW)
[19]	500 / 0.8pf (58), 500 / 0.8pf (61), 500 / 0.8pf (65)	20–37–43–57–61	500 (7) 500 (12) 500 (50) 500 (61)	29.748 / 224.962
[20]	350 (11), 615 (18), 1164 (61)	13–17–47–50–69	150 (21) 300 (61) 450 (64)	28.87 / 226.92
[20]	450 (11), 734 (18), 1324 (61)	14–47–50–69–70	250 (11) 450 (61) 450 (64)	32.17 / 226.92
[20]	350 (18), 615 (61), 1164 (64)	18–43–56–61–69	450 (11) 300 (49) 450(61)	31.23 / 226.92
[21]	394 (12), 200 (21), 1656 (61)	14–17–69–72–73	528 (12) 934 (49) 1228 (61)	**4.82 / 225**
ISSOT–WF	1091 (61), 278 (60), 381 (27)	69–70–14–58–61	450(27) 300 (66) 1050 (61)	**11.348 / 224.95**

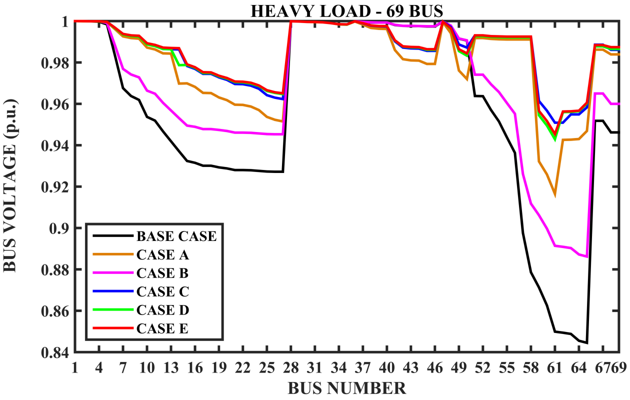

Fig. 6. Bus voltage profile – cases BC to E – heavy load

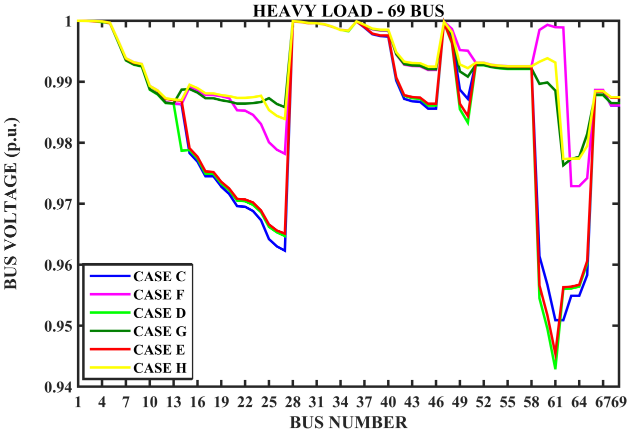

Fig. 7. Bus voltage profile – cases C to H – heavy load

5. CONCLUSIONS

In this work, ISSOT-WF has been utilized to solve the P_{Loss} based cost minimization problem using the combined optimization of FR and CPS / DGAS (type I DGs) under eight different cases considering three load levels. The PG&E-69 bus system is taken to appraise the P_{Loss} reduction as well as APLR with economic benefit. Key points which are worth noting are as follows:

1. In this work no SF is utilized to find the optimal nodes for capacitor/DG placement. ISSOT-WF must search for both CPS and DGAS.
2. The P_{Loss} reduction of EDN can be effectively and efficiently reduced by proper FR with CPS at three optimal nodes compared with other existing methods. Around 65% to 72% of profit has been achieved under cases from C to E.
3. DGAS in the reactive power compensated optimal network brings out around 22% to 26% of APLR with maximum DG penetration of 51%. Around 15% of profit has been noticed by conducting this study.
4. From the results, it is obvious that the difference in cost saving amongst cases C, D & E is minuscule and there is not much difference in achieving total power loss reduction considering cases from F to G compared with BC power loss.

The merits of adopting ISSOT-WF for this work is to overcome the evolutionary stagnation problem and lower plainly of stuck in local optima and to improve the convergence speed with higher feasibility and efficiency compared to SSOT. A promising and accepted performance over the other algorithms in terms of cost savings through effective P_{Loss} reduction with enrichment in bus voltage profiles has been exposed by the proposed method.

NOMENCLATURE

EDN	electrical distribution network
FR	feeder reconfiguration
CPS	capacitor placement & sizing
DG	dispersed generation
CBOF	cost based objective function
BC	base case
ACP	after capacitor placement
ADGI	after DG placement
NCN	number of capacitor nodes
NDG	number of DG
MS	main source
TNB	total number of buses
NTB	total number of branches
P_{Loss}	real power loss
Q_{Loss}	reactive power loss
TP_{Loss}	total real power loss
TQ_{Loss}	total reactive power loss
APLR	additional power loss reduction
DISCOs	distribution companies
DGAS	DG allocation & sizing
EDNLF	EDN load flow

ISSOT	improved salp swarm optimization technique
WF	weight factor
K_{MS}/K_{PL}	MS power/power loss cost
K_{DGP}	DG power purchase cost
SF	sensitivity factor

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