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Optimal Allocation of Multiple D-STATCOM in Distribution System Using PSO.

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Optimal Allocation of Multiple D-STATCOM in Distribution System Using PSO

التوزيع الامثل للمعوضات المتزامنة الساكنة الموزعة في نظم التوزيع الكهربية باستخدام خوارزمية الأسراب

Mohammed N. Abdrabo, Ahmed Y. Hatata, Sahar S. Kaddah, Mohammed I. Elsaid

KEYWORDS:
D-STATCOM, LSF, PSO, DG penetration level, Power loss, Voltage profile.

***الملخص العربي:*- في هذا البحث تم تطبيق خوارزمية الأسراب للحصول علي العدد، الأماكن، والحجم الأمثل للمعوضات المتزامنة الساكنة الموزعة من أجل تقليل مفاقيد الإستطاعة الكلية وإنحراف جهود قضبان التجميع و التحميل الزائد للمغذيات وذلك في نظم التوزيع الكهربية ذات التوليد الموزع. وقد تم تطبيق تعويض القدرة غير الفعالة بإستخدام اسلوب فعّال مرتكز علي عامل حساسية المفاقيد فضلًا عن اسلوب خوارزمية الأسراب المقترح واختبرت صلاحية الأسلوب المقترح علي نظام توزيع الكهربي ذو 33 قضيب تجميع والمعدل بتوصيل توليد موزع عند مختلف قضبان التجميع مكونًا بذلك حالات تشغيل مختلفة للدراسة. نُفذت جميع المحاكات بإستخدام برنامج حاسوبي ضمن بيئة (MATLAB) حيث اُختبرت واثبتت صحة نمذجة اجهزة المعوضات المتزامنة الساكنة الموزعة. وتمت مقارنة مستوي تغلغل التوليد الموزع ومستوي الجهد و المفاقيد الكلية للإستطاعة لنظام التوزيع الكهربي قبل وبعد تعويض اجهزة المعوضات المتزامنة الساكنة الموزعة.**

***Abstract*— In this paper, the Particle Swarm Optimization (PSO) is proposed to obtain the optimal number of Distribution Static Compensator (D-STATCOM) devices, sizes and locations in order to minimize total power losses, bus voltage deviations, and overloaded lines in the radial distribution system with Distributed Generations (DGs). The reactive power compensation is implemented using an effective technique based on the Loss Sensitivity Factor (LSF) as well as the proposed PSO technique. The validity of the proposed technique is examined on IEEE-33 bus radial distribution systems and modified with DG connection at different buses representing various cases studies. All simulations are done using a coded program using MATLAB where the modeling of D-STATCOM is tested and verified. The DG penetration levels, the voltage profile and total power losses of the distribution system are compared before and after D-STATCOM compensation.**

I. INTRODUCTION

In recent years, there is a massive electric power demand which has been grown rapidly. So, many untraditional power generation resources in the distribution system are constructed to meet this increase where it is impractical to construct a central power generation plant. The improper location and capacity of DGs have an adverse effect on the feeders' total power losses, power flow, loading and the voltage profile of distribution systems.

Distribution networks have mainly been designed and operated to passively distribute power from the upstream generation and transmission system toward the final customers. In active distribution networks, the power can be also transferred reversely. Such bi-directional power flows due to DGs pose some issues on the quality of the electric power in the distribution networks. The contribution to the reduction or

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increase of the power losses is mainly depending on the DG location, type, the network structure, and configuration. Moreover, they affect the voltage profile of the system.

D-STATCOM is a shunt connected device of Distribution Flexible AC Transmission System (D-FACTS) devices among other reactive power compensation devices. In recent years, D-STATCOM has been implemented with operation flexibility and control of power systems for providing reactive power flow control, power loss reduction, and voltage and current control. D-STATCOM devices do not have any operational troubles such as resonance nor transient harmonics unlike shunt or series capacitors. D-STATCOM devices have many advantages including less harmonics, low power losses, high regulatory capability, low cost, and compact size [1].

Many types of research were developed for power loss minimization in the distribution networks by various means. A modified Tabu Search (TS) algorithm was used to reconfigure the distribution systems so that the active power losses are globally minimized with turning on/off sectionalizing switches [2]. On the other hand, multiple DGs were allocated with the objective of minimizing the power losses and generation costs, both for the distributed and conventional generators [3]. A method based on an analytical approach for optimal allocation (sizing and setting) of DG and capacitor combination in order to minimize the total real power loss in the distribution network was presented in [4]. Flower Pollination Algorithm (FPA) was applied for optimal allocations and sizing of only capacitors to reduce the total cost and consequently to increase the net saving per year [5].

Many types of research used the D-STATCOM in distribution networks for many benefits. The distribution system tie switches, along with D-STATCOM location and size have been optimally determined to obtain an appropriate operational condition. Differential evolution algorithm (DEA) was used to solve and overcome the complicity of this combinatorial nonlinear optimization problem [6]. The dynamic behavior of the network with seasonal variation of loads was taken into account in the presence of D-STATCOM for improving the voltage profile and power factor [7].

Other researchers used the DG besides the D-STATCOM simultaneously in the distribution networks for power loss minimization and power quality improvement. The Optimal placement of multiple DGs and D-STATCOM in a radial distribution system was carried out in [8] and resulting in a reduction of line losses as well as power quality represented by Total Harmonic Distortion (THD). The load models were considered in the enhancement of voltage profile and minimization of system power loss using DG incorporated with D-STATCOM by means of Genetic Algorithm (GA) [9]. Furthermore, the allocation of both D-STATCOM and DGs were implemented using LSF [10]. The LSF was used to pre-determine the optimal location of the DGs and D-STATCOM. The Bacterial Foraging Optimization Algorithm (BFOA) was presented to determine the optimal size of the DG and D-STATCOM with different load models for improving the voltage profile, loss reduction, Voltage Stability Index (VSI) and system security level [11]. Finding the optimal location and sizing of the DG and D-STATCOM with the main objective of reducing the total power loss along with voltage profile improvement was applied using PSO and Multi-Objective Modified Particle Swarm Optimization (MOMPSO) [12, 13]. Simultaneous placement of DG and D-STATCOM in the radial distribution networks for minimizing power loss, and Total Voltage Deviation (TVD), as well as maximizing the VSI was done using novel lightning search algorithm [14].

D-STATCOM allocations were performed using various techniques, computational methods have been used for allocation and sizing of D-STATCOM [15, 16]. Comparison of D-STATCOM allocation using the voltage stability index and power loss index approach was discussed in [17]. Allocation and sizing of two D-STATCOMs were implemented using optimization algorithm based on Bat Algorithm (BA) [18]. D-STATCOM optimal allocation for minimizing the total network power losses using Harmony Search Algorithm and Immune Algorithm were presented in [19, 20]. D-STATCOM placed on the nodes with the highest D-STATCOM Suitability Index (DSSI) using a set of fuzzy rules was advised in [21]. The allocation of three D-STATCOMs in presence of the DGs was presented in [22] using new evolutionary computation combination of Discrete Imperialistic Competition and Nelder-Mead Algorithms (DCIA-NM) at different load levels. The impact of various load models on the optimal allocation of D-STATCOM was obtained for power loss reduction, voltage improvement and energy saving [23].

However, these papers failed to obtain or highlight the optimal number of multiple D-STATCOM devices allocation in order to overcome this issue. A proposed PSO algorithm is implemented in this paper to determine the optimal number, locations, and sizes of the D-STATCOM devices corresponding to minimum power loss and voltage deviation in the presence of DGs.

In this paper, the DGs are already allocated in the distribution system. Then the optimal number, sizes and locations of D-STATCOM are determined with the help of LSF and the proposed PSO. The performance of the distribution system is enhanced by reducing the total power losses, improving the voltage profile, maximizing the DGs penetration and relieving the feeder loading. The D-STATCOM devices are implemented in IEEE-33 bus radial distribution system using a software code build with MATLAB program. The novelty of the proposed technique declares the ability to obtain the D-STATCOM optimal number, which is beneficial to the distribution network operators. It takes into account the presence of DG already allocated which was not implemented in the similar researches.

Rest of this paper is organized as follows; in section 2, the modeling of D-STATCOM is reviewed as an efficient solution in a radial distribution network. In section 3, the problem formulation and the objective function are declared. Also, the LSF as an indicator of candidate buses for D-STATCOM allocation is defined. As well as, the proposed PSO algorithm is presented. The simulation studies and numerical analysis using the proposed PSO optimization technique is performed in section 4 and the conclusion remarks appear in the last section of the paper.

II. MODELING OF D-STATCOM DEVICES

The D-STATCOM is similar to the transmission STATCOM in that it uses a Voltage Source Converter (VSC) with a required rating. The VSC used in the D-STATCOM is a type 1 converter with PWM control over the magnitude of the injected AC voltage while maintaining the constant DC voltage across the capacitor. Faster power semiconductor devices such as IGBT or IGCT are used instead of GTO in the D-STATCOM. The rapid switching capability provided by IGBT or IGCT switches enable the use of more sophisticated control schemes to provide functions of balancing (by injecting negative sequence current), active filtering (by injecting harmonic currents) and flicker mitigation.

The D-STATCOM can be considered as a variable current source controlled by the control functions. To increase the dynamic rating in the capacitive range, a fixed capacitor/filter can be used in parallel with the D-STATCOM. By connecting an energy storage device such as a Superconducting Magnetic Energy Storage (SMES) on the DC side through a DC/DC power conditioner, it is possible to exchange real power with the network for a limited time (during momentary interruptions or large voltage sags). The D-STATCOM is a shunt device that injects or absorbs both active and reactive current. Its connected diagrams are shown in Fig.1. In Fig.1a, it can be seen that the D-STATCOM consists of energy storage and voltage source converter. In this model, the D-STATCOM is capable of injecting active power in addition to reactive power. Since the energy storage has a capacity limit, it cannot inject active power for a long-term for voltage regulation purpose. Therefore, for the steady-state application D-STATCOM consists of a small DC capacitor and a voltage source converter, and the steady-state power exchange between D-STATCOM and the AC system is reactive power as illustrated in Fig.1b [24].

For a distribution system consisting of two buses i and j as shown in Fig. 2, the D-STATCOM is installed at bus j for voltage regulation. The bus j voltage changes from V_j to $V_{j\,new}$ when D-STATCOM is implemented. For the sake of simplicity, the angle of voltage V_i , i.e., δ is assumed to be zero.

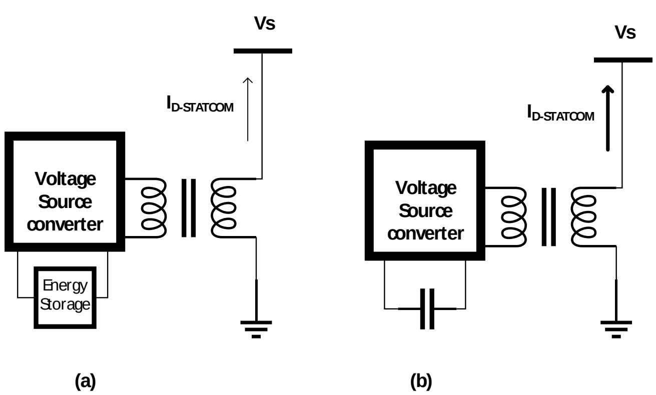

Fig. 1 A typical model of D-STATCOM, (a) Active and reactive power exchange, (b) Only reactive power exchange.

The injected reactive power by D-STATCOM can be written as:

$$Q_{D-STATCOM} = Imaginary\ (V_{j\,new}.I_{D-STATCOM}{}^{*}) \quad (1)$$

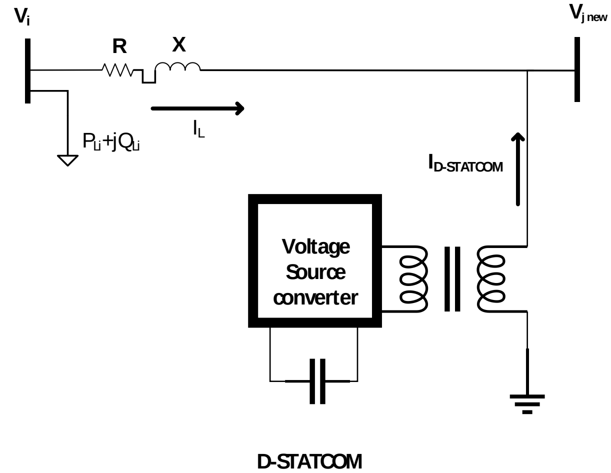

Fig. 2 single line diagram of two bus system with D-STATCOM.

$$V_{j\,new} = V_{j\,new}\angle\, \alpha_{new} \quad (2)$$

$$I_{D-STATCOM} = I_{D-STATCOM}\angle(\,\alpha_{new} + \pi/2) \quad (3)$$

Where, $Q_{D-STATCOM}$ and $I_{D-STATCOM}$ are the injected reactive power and current by D-STATCOM respectively. α_{new} is bus j voltage angle after installing D-STATCOM.

III. OPTIMAL ALLOCATION AND SIZING OF D-STATCOM

The objective of placement of the D-STATCOM in the distribution system with DG is the minimization of the total power losses of the system, subjected to working constraints for ensuring the system voltage profile and feeder currents within the acceptable limits.

The candidate locations of D-STATCOM is determined by LSF, using a designed MATLAB code. Then the optimal number, locations, and sizes of the D-STATCOM devices are calculated using a modified PSO optimization technique based on the MATLAB program. The optimal solution is the best among candidate buses which power loss is the minimum. The following stages declare the major elements of the proposed method for the optimal allocation of D-STATCOM devices.

Stage 1. Obtaining the candidate buses for D-STATCOM devices installation using LSF.

Stage 2. Obtaining the optimal sizes of the D-STATCOM devices using PSO optimization.

Stage 3. Obtaining the optimal number of D-STATCOM devices by comparing P_{Loss} values of various combinations.

A. *Stage (1) determination of the candidate buses for D-STATCOM allocation using LSF*

To identify the preferred locations for D-STATCOM placement in the distribution system, the LSF has been used. The LSF is able to predict which bus will have the biggest loss reduction when the D-STATCOM is placed. Therefore, these sensitive buses can serve as candidate buses for the D-STATCOM placement. The estimation of these candidate buses basically helps in reduction of the search space for the optimization problem. A few numbers of buses can be candidate buses for compensation. Consider a distribution line with an impedance $R + jX$ connected between 'i' and 'j' buses and a load of $P_{eff} + jQ_{eff}$ as given below in Fig.3 [17].

The real power loss is given by $[I_k^2\ ] * [R_k]$, which can also be expressed by:

$$P_{lineloss}(j) = \frac{\left[P_{eff}^2(j)+Q_{eff}^2(j)\right]*R(k)}{[V(j)]^2} \tag{4}$$

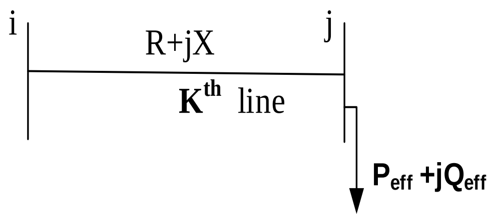

Fig. 3 Two bus system.

Similarly, the reactive power loss of the k^th line can be given by:

$$Q_{lineloss}(j) = \frac{\left[P_{eff}^2(j)+Q_{eff}^2(j)\right]*X(k)}{[V(j)]^2} \tag{5}$$

Where $P_{eff}\,[j]$ and $Q_{eff}\,[j]$ is the total effective active and reactive power supplied beyond the bus 'j'. Now, the LSF can be calculated by:

$$\frac{\partial\, P_{lineloss}(j)}{\partial\, Q_{eff}(j)} = \frac{[2*Q_{eff}(j)]*R(k)}{[V(j)]^2} \tag{6}$$

$$\frac{\partial\, Q_{lineloss}(j)}{\partial\, Q_{eff}(j)} = \frac{[2*Q_{eff}(j)]*X(k)}{[V(j)]^2} \tag{7}$$

The LSF, $\partial p_{loss}/\,\partial Q_{eff}$ has been calculated from the load flows studies of the base case. The values of LSFs have been arranged in descending order and correspondingly the bus numbers are stored in bus position P_{pos}[i] vector. The descending order of $\partial p_{loss}/\,\partial Q_{eff}$ elements of P_{pos}[i] vector will decide the sequence in which the buses are to be considered for compensation. The normalized voltage magnitudes at P_{pos}[i] buses are calculated by considering the base case voltage magnitudes given by [25]:

$$Norm(i) = |V(i)|/0.95 \tag{8}$$

Where the $Norm(i)$ function decides whether the buses need reactive compensation or not. The buses which $Norm(i)$ value is less than 1.01 can be selected as the candidate buses for D-STATCOM placement, the steps for finding out the potential buses for D-STATCOM placement are illustrated as:

Step 1: Calculate the Load flow of the distribution system in the base case.

Step 2: Calculate the LSF for all buses of the distribution system.

Step 3: Arrange the value of LSF in descending order and store the respective buses into bus position vector P_{pos}[i].

Step 4: Calculate the normalized voltage magnitude, Norm(i), of the buses of P_{pos}[i] vector.

Step 5: The buses which $Norm(i)$ is less than 1.01 are selected as candidate buses for D-STATCOM placement. Buses whose $Norm(i)$ is more than 1.01 i.e. their voltage profile are within limits thus, no need for reactive power compensation.

B. Stage (2) determination of the optimal sizes of the D-STATCOM

The problem of D-STATCOM sizing can be expressed mathematically as an optimization problem with objective function subject to some equality and non-equality constraints. The following sections illustrate the objective function and the constraints applied in this paper.

1) Objective function

The objective function is a nonlinear one. It is minimizing the amount of the power loss in the distribution system. The objective function can be written as follows:

$$F = \min(f) \tag{9}$$

$$f = P_{LOSS} + Voltage\ \text{Penalty} + Line\ \text{Penalty} + Slack\ \text{Penalty} + \text{Gen}\ Reactive\ \text{Penalty} \tag{10}$$

$$f = P_{LOSS} + \sum_{i=1}^{n} r_{gi}\left(V_i - V_i^{lim}\right)^2 + \sum_{i=1}^{n} r_{Ai}\left(A_i - A_i^{lim}\right)^2 + \sum_{i=1}^{n} r_{Pi}\left(P_i - P_i^{lim}\right)^2 + \sum_{i=1}^{n} r_{Qi}\left(Q_i - Q_i^{lim}\right)^2 \tag{11}$$

Where, P_{LOSS} is the total power loss of the radial distribution system, n is the number of system buses.

r_{gi} : The penalty multiplier for the voltage inequality constraint.

r_{Ai} : The penalty multiplier for the line ampacity inequality constraint.

r_{Pi} : The penalty multiplier for the slack bus active power inequality constraint.

r_{Qi} : The penalty multiplier for the generator reactive power inequality constraint.

$$V_i^{lim} = \begin{cases} V_i^{max};\ V_i > V_i^{max} \\ V_i^{min};\ V_i < V_i^{min} \end{cases} \tag{12}$$

$$A_i^{lim} = \begin{cases} A_i^{max};\ A_i > A_i^{max} \\ A_i^{min};\ A_i < A_i^{min} \end{cases} \tag{13}$$

$$P_i^{lim} = \begin{cases} P_i^{max};\ P_i > P_i^{max} \\ P_i^{min};\ P_i < P_i^{min} \end{cases} \tag{14}$$

$$Q_i^{lim} = \begin{cases} Q_i^{max};\ Q_i > Q_i^{max} \\ Q_i^{min};\ Q_i < Q_i^{min} \end{cases} \tag{15}$$

2) Constraints

The problem constraints include voltage constraints, feeder current limitation, generators reactive power limitation, slack bus active power limitation, power balance constraints and active and D-STATCOM size limits. They can be expressed as following:

Bus voltage constraints

$$V_{j\,min} \le V_j \le V_{j\,max} \qquad ,j = 1,2,\ldots\ldots,n \tag{16}$$

Where, $V_{j\,min}$ and $V_{j\,max}$ are the minimum and maximum voltages of the j^th bus respectively. N is the total number of buses.

Feeder Current Limitation

The main feeders of the network can supply a maximum current magnitude as follows:

$$|I_{fi}| \leq I_{fi}^{max} ; \;\; i = 1,2, \dots \dots , N_f \qquad (17)$$

Where, I_{fi} is the current of the i[th] feeder, I_{fi}^{max} is the maximum current of the i[th] feeder and N_f is the number of feeders.

Generator reactive power limitation

$$Q_G \leq Q_G^{max} \qquad (18)$$

Where, Q_G is the generator reactive power and Q_G^{max} is the maximum permissible generator reactive power limit.

Slack bus active power limitation

$$P_{slack} \leq P_{slack}^{max} \qquad (19)$$

Where, P_{slack} is the active power generated at the slack bus and P_{slack}^{max} is the maximum permissible slack bus active power limit.

D-STATCOM Size constraints

$$Q_{DSTmin} \leq Q_{DST} \leq Q_{DSTMax} \qquad (20)$$

Where, Q_{DSTmax} and Q_{DSTmin} are the max and min permissible D-STATCOM size to be installed in the network.

Power balance constraints

$$Total\ Active\ power\ losses = \sum_{j=1}^{n} P_{Gj} - \sum_{j=1}^{n} P_{Dj} \qquad (21)$$

The total active power generation must be equal to the sum of the total active power loss and the active power demand.

$$Total\ reactive\ power\ losses = \sum_{j=1}^{n} Q_{Gj} - \sum_{j=1}^{n} Q_{Dj} \qquad (22)$$

The total reactive power generation must be equal to the sum of the total reactive power loss and the reactive power demand. The following section demonstrates the methodology of proposed PSO optimization technique used in obtaining the optimal size of D-STATCOM.

3) The Procedure of the proposed PSO

In the PSO algorithm, the population is randomly generated which contains individual particles. Each particle in the swarm denotes a probable explanation of the optimization problem. With a random velocity, each particle moves through a D-dimensional search space. Each particle's velocity and position are updated. Figure 4 demonstrates flowchart of the proposed PSO algorithm.

The proposed PSO algorithm for solving the optimal sizing of the D-STATCOM in order to minimize the total power loss is performed by:

Step 1: Read distribution system data (bus data, line data, voltage min & max limits, lines ampacities limit, active & reactive power limits), minimum and maximum limits of D-STATCOM size and the PSO parameters.

Step 2: Determine the candidate buses according to LSF and the number of candidates according to the specified acceptable LSF margin.

Step 3: Randomly generate the population of particles, their velocities and for each particle run load flow to find out the power losses.

Step 4: Evaluate the fitness of the objective function of each particle using equation (9) and find personal best (P_{best}) of all particles and global best (G_{best}) particle from their fitness values.

Step 5: Update the velocity, position of the particles and run the load flow to find out the power losses searching for the best solution.

Step 6: Obtain for the D-STATCOM combination; the optimal D-STATCOM size with minimum objective function and corresponding total power loss, voltage profile, lines loadings, and penalties values.

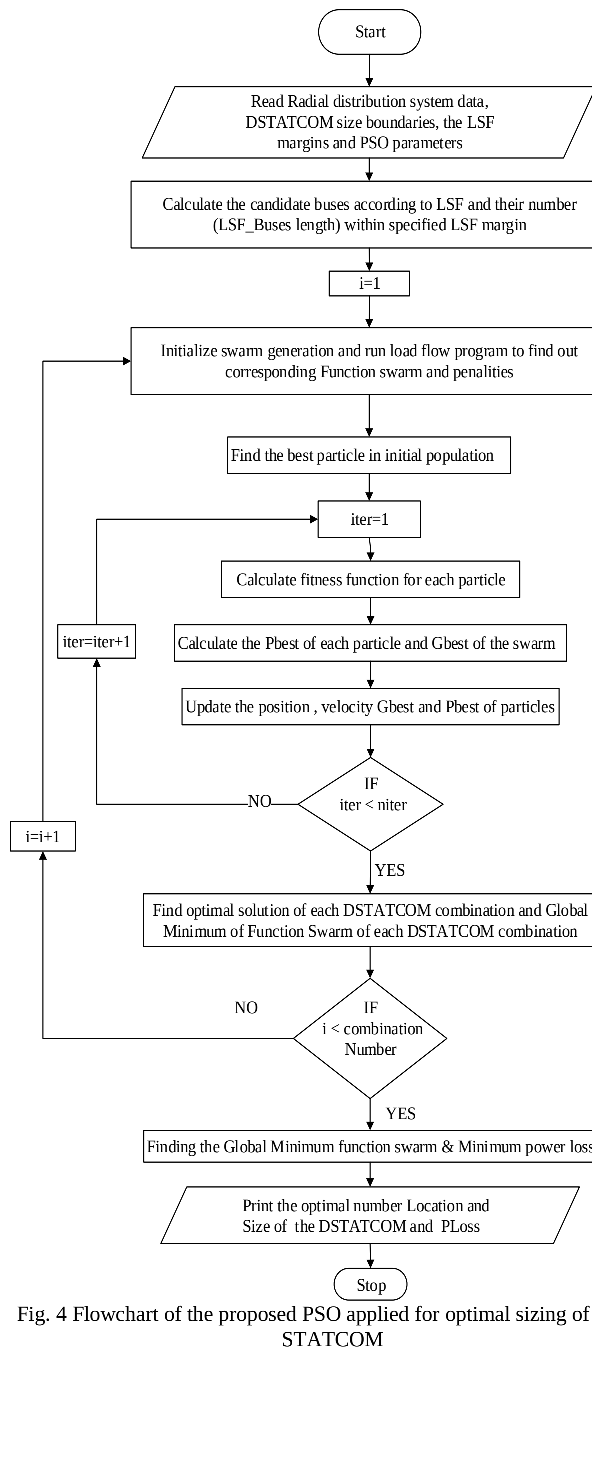

Fig. 4 Flowchart of the proposed PSO applied for optimal sizing of the D-STATCOM

Step 7: Repeat steps 3-6 for each D-STATCOM combination candidates and store the swarm objective function values for each combination to find the optimal number of the D-STATCOM.

Step 8: Print the optimal solution corresponding to the optimal D-STATCOM combination including (optimal number of D-STATCOM devices and their sizes and locations).

C. Stage (3) determination of the optimal number of the D-STATCOM

After obtaining all candidate buses, a combination consists of a number of candidate buses. At each combination optimal sizing of DSTATCOM device is performed for minimizing the objective function. The optimal number of the D-STATCOM devices could be found by comparing the objective function values of optimal sizing of DSTATCOM devices at various possible combinations of all candidate buses. The proposed code finds the minimum power loss of the system and its corresponding optimal sizes of DSTATCOM at all candidate DSTATCOM locations. And stores all these values to be compared to find the minimum power loss among different combinations that corresponds to the optimal number, locations and sizes of DSTATCOM devices.

IV. SIMULATION RESULTS AND DISCUSSION

In this section, the simulation results of the implementation of the LSF and the proposed PSO technique on IEEE-33 bus radial distribution system demonstrated the effectiveness of the proposed method. This application gives more importance to power loss minimization and voltage profile enhancement with fulfilling the constraints. Three different operating scenarios will be studied on the two test systems. These scenarios as follows:

Scenario # 1 System without DG and D-STATCOM.

Scenario # 2 System with only D-STATCOM

Scenario # 3 System with D-STATCOM and DG.

Scenario # 4 System with D-STATCOM & DG at different load factors.

An analytical program has been designed using the MATLAB software to run load flow, calculate power loss and determine optimal number, location, and size of D-STATCOM.

A. IEEE-33 bus system

The IEEE-33 bus radial distribution system consists of 33 buses and 32 branches. The base values are 100 MVA and 12.66 kV and the total real and reactive power loads of this system are 3715 kW and 2300 kVAR. The total active and reactive power loss for the base case are 202.51 kW and 135.03 kVAR. The bus number #1 in this system is considered as the electric power feeder from a generation/transmission network. The rest of the buses are considered as candidate location of D-STATCOM. The single line diagram of the system is shown in Fig. 5 [26].

The PSO population size is chosen as 50 particles. The termination criterion is supposed to be 200 iterations. The D-STATOM sizes vary between 0.1 and 10 MVAR. The bus voltage maximum voltage mismatch is considered as 10%, The current carrying capacity of branches from 1 to 5 is 400 A,

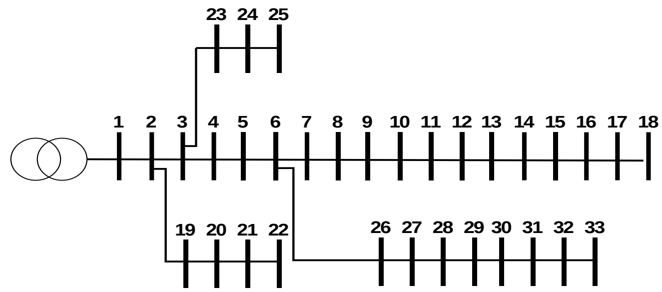

Fig. 5 The single line diagram of IEEE-33 bus radial distribution system bus system

branches from 6 to 7 and branches from 25 to 27 is 300 A and for all other branches including ties line is 200 A.

1) Scenario # 1 System without DG and D-STATCOM

The total active and reactive power loss of this case is 202.51 kW and 135.03 kVAR. The minimum voltage of the system is 0.913 p.u.at bus 18 (maximum voltage deviation is 0.037). There is no overflow lines.

TABLE I
COMPARISON BETWEEN THE THREE SCENARIOS FOR IEEE-33 BUS SYSTEM

Case	Scenario #1	Scenario #2	Scenario #3
Candidate Buses	-	Five (6, 28, 29, 30 and 9)	Four (28, 29, 30 and 31)
Optimal Number of D-STATCOM	-	**Two**	**Two**
Locations	-	28 & 9	28 & 30
Sizes [MVAR]	-	1.5082 & 1.1909	0.2799 & 1.2049
P_{Loss} [kW]	202.51	160.27	66.9
% Loss Reduction.	-	21%	56%
Minimum corresponding voltage [p.u]	0.913 at bus 18	0.94895 at bus 18	0.96709 at bus 33
Overloaded Lines	**No**	**No**	**No**

2) Scenario # 2 System with only D-STATCOM

In this case, in order to improve the distribution system performance, it is intended to allocate D-STATCOM in the system, first, the LSF is calculated to the system buses. Then the proposed algorithm is applied to determine the number and size of the D-STATCOM devices. According to LSF values, the five candidate buses are 6, 28, 29, 30 and 9. The optimal number is two devices at buses 28 and 9 with sizes of 1.5082 and 1.1909 MVAR respectively. The minimum power loss is 160.27 kW with 21% power loss reduction referred to the base case with improvement in maximum voltage deviation from 0.037 to 0.001 and no congested lines. The improvement in voltage profile is depicted in Fig. 6.

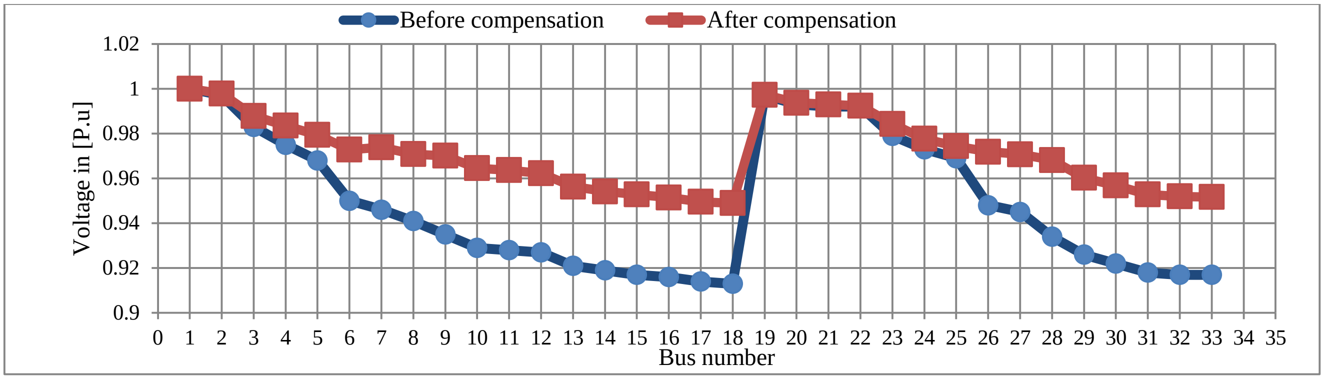

Fig. 6 Scenario #2Voltage profile before and after connecting two D-STATCOMs at buses 28, 9

3) Scenario # 3 System with D-STATCOM and DG

In this case, It is assumed that the IEEE-33 bus system has DG at bus 10 connected with 1.2398 MW. The relation between the power loss and the DG size installed at bus 10 is declared in Fig.7. The power loss after connection of 1.2398 MW DG at bus 10 is 122.55 kW with no overloaded lines. It is observed that the power loss decreases due to the connection of the DG at Bus 10 of the IEEE-33 bus radial distribution system. So at this load level, D-STATCOM is required to be allocated optimally seeking for further improvement in the distribution system. The DG penetration level in the distribution system could be defined as [27]:

$$\%\ DG\ Penetration\ level = \frac{P_{DG}}{P_{DG}+P_{Utility}} \quad (23)$$

DG penetration level = 24.4%

In this case, when calculating the LSF, it is found that the four candidate buses are 28, 29, 30 and 31. The optimal number of D-STATCOM devices is two with sizes 0.27992 and 1.2049 MVAR at buses 28 and 30 respectively.

The total power loss after placement of 0.27992 and 1.2049 MVAR D-STATCOM at buses 28 and 30 respectively is 66.9 kW with a minimum voltage of 0.96709 p.u. at bus 33 with 56% power loss reduction referred to the case with DG. Also, the DG penetration in the system increased from 0 to 24.4 % while the system power loss and performance was enhanced. It is observed the great impact of the application of D-STATCOM device on the performance of the distribution system. The improvement in voltage profile is depicted in Fig. 8. Moreover, Table I summarizes the improvement in performance of IEEE-33 bus system

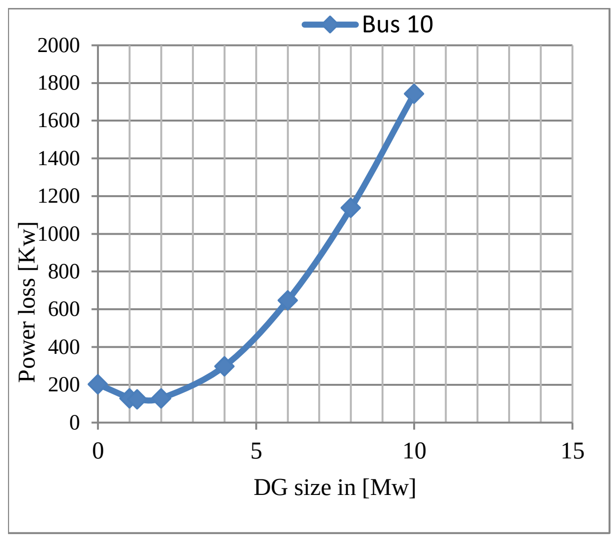

Fig. 7 The relation between P_{Loss} [kW] and DG size [MW] at Bus 10 system

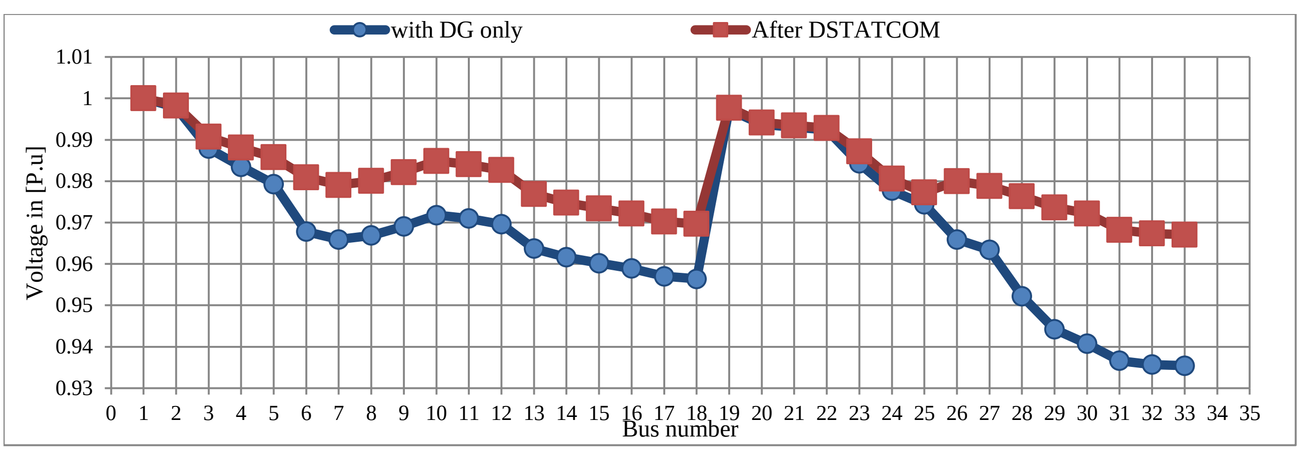

Fig. 8 Scenario #3 voltage profile before and after D-STATCOM at bus 30 with 1.2398 MW DG at bus 10

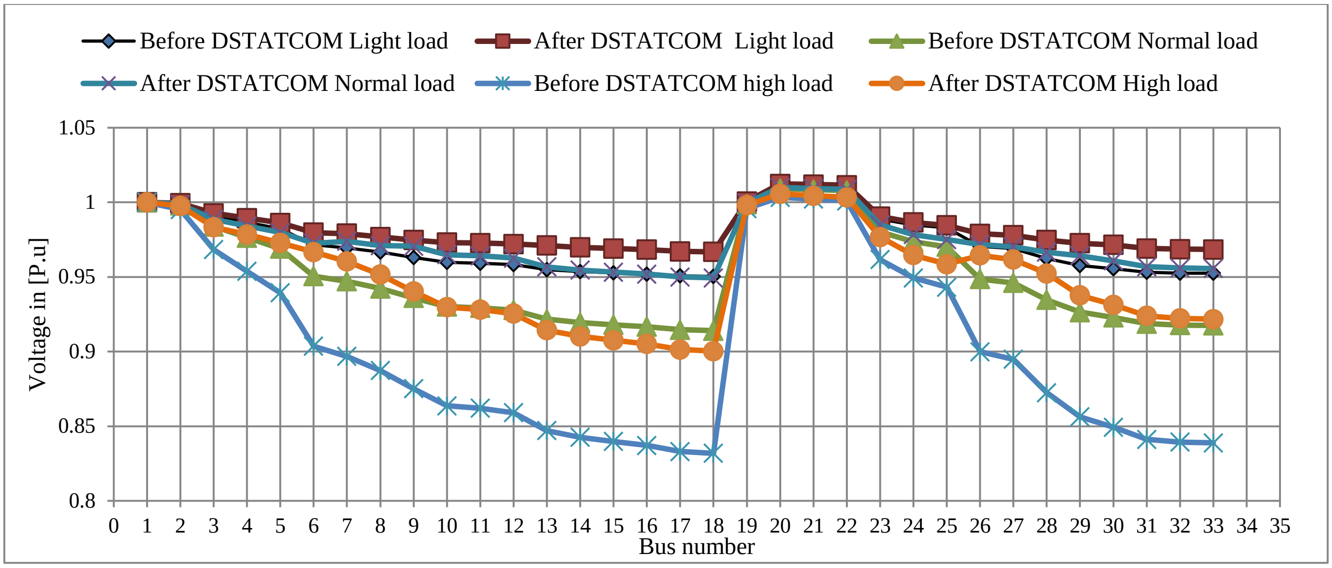

Fig. 9 Scenario # 4 Voltage profile before and after D-STATCOM at a various load factor

TABLE II
COMPARISON BETWEEN DIFFERENT LOAD LEVELS FOR IEEE-33 BUS SYSTEM WITH 1.5 MW DG AT BUS 20

Case	Item	Light load	Normal	High load
Before D-STATCOM	Load factor	0.6	1	1.8
	Ploss [kW]	84	211	752
	Corresponding Minimum voltage [p.u]	0.95 at bus 18	0.914 at bus 18	0.832 at bus 18
	Overloaded Lines	**No**	**No**	**No**
	Penetration level	39.37% =1.5/(2.31+1.5)	27.62% =1.5/(3.93+1.5)	16.78% =1.5/(7.44+1.5)
After D-STATCOM	Candidate Buses	Five (29, 30, 13, 31 and 14)	Five (6, 28, 29, 30 and 9)	Five (6, 28, 29, 5 and 4)
	Optimal Number of D-STATCOM	**Two**	**Two**	**Four**
	Locations	30 & 13	29 & 9	6 & 28 & 5 & 4
	Sizes [MVAR]	0.58343 & 0.35826	1.3141 & 1.2534	4.4731 & 2.0227 & 0.50059 & 1.2959
	Ploss [kW]	62.56	162.08	680.39
	Corresponding Minimum voltage [p.u]	0.96678 at bus18	0.94938 at bus 18	0.9003 at bus 33
	Overloaded Lines	**No**	**No**	**No**
	% Loss Reduction.	39.57 %	27.88 %	9.5 %

Scenario # 4 System with D-STATCOM & DG at different load factors

When the load variation is considered during the daily load curve. It is assumed that IEEE-33 bus radial distribution system with 1.5 MW DG at bus 20, the D-STATCOM shows a great effect on improving distribution system performance. Three load levels were considered during a day with load factor 0.6, 1, and 1.8. Table II summarizes the results obtained with the three load levels.

It is observed that D-STATCOM response all over the day is beneficial where it reduced the total system power loss by 25.5, 23.18 and 9.5 % referred to the base case with only DG at load factor 0.6, 1 and 1.8 with great enhancement of the distribution system voltage profile besides increasing the DG penetration level. The improvement in voltage profile at different load factors is depicted in Fig. 9.

V. Conclusion

With increasing the percentage of DG in distribution system, the D-STATCOM becomes one of the solutions for the side effect of this practice. The optimal number, size, and location of D-STATCOM are of a great concern in distribution systems.

A new algorithm to optimally allocate multiple D-STATCOM was proposed using PSO. This optimization problem has multi-objective mainly to improve the distribution system performance by improving the voltage profile, decreasing the total power losses and maximizing the DG penetration contributed to the fulfillment of the consumers' loads. The proposed algorithm is implemented using MATLAB program. Optimal allocation of D-STATCOM devices in IEEE-33 bus radial distribution systems with DG was done according to LSF and PSO optimization technique. Total system losses and voltage profile of the distribution network were compared with and without D-STATCOM. The results showed that the proposed technique is very beneficial for distribution system operators for allocating the D-STATCOM devices in the distribution system. The best possible parameters of the system could be determined and various operating scenarios of distribution networks could be managed.

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