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Optimal placement and sizing of distribution static compensator (D-STATCOM) in electric distribution networks: A review

Reza Sirjani[a], Ahmad Rezaee Jordehi[b,*]

[a] Department of Electrical and Electronic Engineering, Eastern Mediterranean University, Gazimagusa, Mersin 10, Turkey
[b] Department of Electrical Engineering, Lashtenesha-Zibakenar Branch, Islamic Azad University, Lashtenesha, Iran

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ABSTRACT

With the growth and development of power grids, optimal utilization of electric networks is very important. Because of the high cost of construction and development of power networks, mitigation of existing issues, such as excessive power losses, voltage profile problems, voltage instabilities, reliability problems and etc. is inevitable. To obviate these problems, Distribution Synchronous Static Compensator (D-STACTOM) as a shunt compensator device can be used in electric distribution networks. Optimal location and size of D-STACOM, should be determined on the basis of economic viability, required quality, reliability and availability. In recent years, several papers have concentrated on the techniques used for finding optimal location and size of the D-STATCOM units considering different aspects. However, to date, no review paper has been published in this field. This paper presents an up to date survey of the literature on the optimal allocation of D-STATCOM in distribution networks. The existing research works have been classified into five categories including analytical methods, artificial neural network-based approaches, metaheuristic methods, sensitivity approaches, and a combination of sensitivity approaches and metaheuristic methods. Moreover, it was found that in D-STATCOM allocation problem, the objectives may be alleviation of power loss, mitigation of voltage deviations, improvement of reliability metrics and enhancement of voltage stability. All methods, objectives and constrains have been compared and discussed in details. Eventually, an overall review on the reviewed works has been provided and some directions for future research were suggested.

1. Introduction

Increased loading and the need for economic efficiency of electric power networks have prompted companies to use transmission and distribution networks at the highest possible efficiency and loading [1]. Some challenges associated with these networks include stability issues, high losses and excessive voltage drops in buses [2–4]. These challenges usually occur when there is an indiscriminate increase in non-linear loads [5]. A voltage drop in the distribution network may be caused by distribution lines with high impedance or growing loads in three-phase or unbalanced loads. Today's advanced distribution networks take on a more sophisticated form due to the incorporation of distributed generation units which redirect the flow of current through the lines [6]. Nowadays, there is a general consensus on this idea that power electronics devices and methods are more suitable than traditional methods that were working based on electromechanical technologies and have low speed and high cost [7]. Using flexible alternating current transmission system (FACTS) devices is inevitable for optimal utilization of current electric networks [8,9].

Power electronics-based controllers in power distribution systems help to provide energy with an appropriate quality for subscribers [10–13]. In general, custom power (CP) devices, which are similar to FACTS devices, are a useful solution to address the problem of interruptions and poor power quality in power networks [14]. Although FACTS and CP devices share a common technical base, they have different performance goals. FACTS devices are used in the transmission, while CP devices are used in distribution [15]. CP devices are especially effective in the system reliability and power quality. Distribution Static compensator (D-STATCOM), is a shunt CP device, used in distribution networks. It is used to improve power quality (i.e., power factor, voltage profile, voltage stability) [16]. The ability to inject and absorb reactive power with very fast, dynamical responses made its application very wide within the field. D-STATCOM injects current into the system at the point of common coupling, which helps in power factor correction, harmonic filtering, etc. [17]. A review of the literature indicates that potential applications of D-STATCOM include reactive power compensation [18], voltage support [19], circulating excess power among the phases [20], reduction of fluctuations caused by photovoltaic systems

* Corresponding author.
E-mail addresses: reza.sirjani@emu.edu.tr (R. Sirjani), ahmadrezaeejordehi@gmail.com (A. Rezaee Jordehi).

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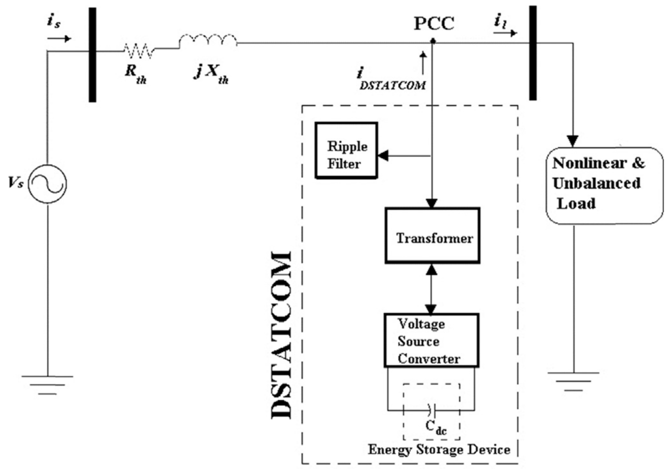

Fig. 1. D-STATCOM configuration in distribution network.

[21], Enhancing the PV installation capacity of a distribution networks [22], and the attenuation of the voltage sags/swells/flickers [23].

D-STATCOM is a static synchronous compensator (STATCOM) configured with a coupling transformer, an energy storage device and an inverter. Please see Fig. 1.

For a detailed description of D-STATCOM, the interested reader can consult [17].

In order to optimally use D-STATCOM devices, their location and size should be determined on the basis of economic viability, according to the quality, reliability and availability required [24,25]. Compared to the extensive research on the optimal location and size of FACTS devices in power transmission systems, there exists less research works in the literature on optimal allocation of CP devices. Although there are a few studies of the placement and sizing of CP devices in distribution networks, most of the existing reviews focus on the application of optimization techniques to solve that problem. Furthermore, there is no published review in the field of optimal placement and sizing of D-STATCOM. As shown in Fig. 2, since 2015, at least 10 papers have been published about the different aspects of this problem [26–35]. Thus, there is an urgent need for a comprehensive review in optimal placement and sizing of D-STATCOM considering all used methods, objective functions and constraints.

In the present paper, a comprehensive review is presented on different research works for optimal placement and sizing of D-STACOM devices in distribution systems. First of all, D-STATCOM is introduced in brief, then different research works on D-STATCOM allocation will be reviewed in details. Finally, an overall review will be presented and some directions for future research will be suggested.

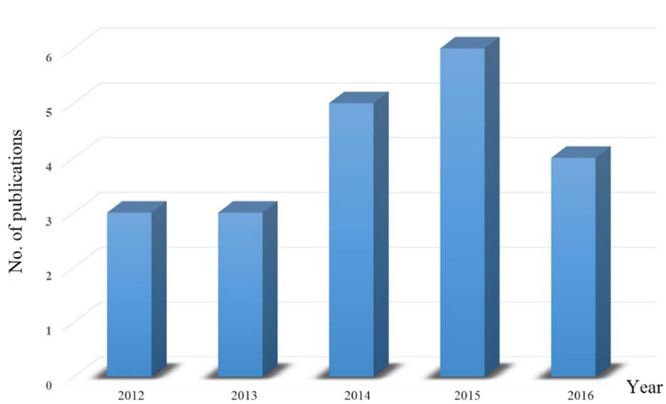

Fig. 2. Number of publications on D-STATCOM placement in different years.

2. Review of research addressing D-STATCOM allocation

All existing methods for optimal allocation of D-STATCOM's in distribution systems can be divided into five categories: analytical methods, artificial neural network based methods, metaheuristic methods, sensitivity approaches, and a combination of sensitivity approaches and metaheuristics.

2.1. Analytical methods

The analytical methods consisting simple algorithms that have been proposed in privation of powerful computing resources. The aim of proposing analytical methods in optimal allocation of D-STATCOM, is to identify the optimum solutions without considering nonlinearity and complexity in the problem. For reducing the computational procedure, some approximations should also be applied to these algorithms.

In [36], an analytical method has been developed for determining the optimum position of DSATATCOM in a distribution network. power losses and the voltage profile of the system are considered as the objectives in optimization process. The proposed method was tested in a 33 bus radial distribution system. In the results, voltage regulation and the number of buses that have an under/over voltage problem were examined and compared. D-STATCOM cost and other related advantages were also considered. This method was compared to the well-established genetic algorithm (GA).

2.2. Artificial Neural Network based methods

The Artificial Neural Networks (ANN) are used for modeling online nonlinear systems with multiple inputs and outputs. Some applications of ANN-based approaches, such as fault detection, voltage control, reactive power control and detection of voltage disturbances, can be found in the literature [37]. These approaches are able to find the optimal place of D-STATCOM in the distribution network under faults. However, they are not applicable for optimal D-STATCOM sizing.

In [37], artificial neural network (ANN) has been utilised for optimal allocation of DVR and D-STATCOM in distribution networks in order to alleviate the voltage sag under faults. Optimum positions of DVR and D-STATCOM have been found using a feed forward ANN. The pre-fault voltage of each bus has been considered as the output target data. The bus having greatest deviation of voltage from the target value is the best for D-STATCOM placement. This study did not include comparisons with other methods.

2.3. Metaheuristic methods

Metaheuristics are the most commonly used methodologies for solving D-STATCOM allocation problems. They are stochastic, population-based optimization algorithms which are generally efficient in handling multimodal, multi-objective, discrete and constrained environments [38,39].

In [40], Taher & Afsari used immune algorithm (IA) to find optimal location and setting of D-STATCOM in distribution networks, in order to reduce energy loss, cost, power congestion and improve the voltage profile. A newly defined objective function is introduced, which includes installation cost of D-STATCOM and the cost of energy loss. Compared to GA, IA provides lower objective function value, in light, medium and peak load levels, in both IEEE 33 and 69-bus distribution systems. Despite its outperformance over GA, IA suffers from premature convergence issue which is a common drawback of metaheuristics.

In 2014, Devi & Geethanjali [41] used particle swarm optimization (PSO) to find the location and the size of distributed generation (DG) and D-STATCOM in order to reduce copper losses and improve the voltage profile. The simulations were performed on the some radial distribution systems, for five different test cases. However, this analysis did not include a comparison of this method with other techniques. PSO is a metaheuristic that is likely to converge into local optima instead of the global optimum [7].

In 2014, Jazebi et al. [42] used differential evolution algorithm (DE) for reconfiguration and D-STATCOM allocation to alleviate losses and improve the voltage profile in distribution networks. The proposed method was tested on 69 and 83 bus distribution networks where DE outperformed PSO.

In [43], binary gravitational search algorithm (BGSA) has been used for D-STATCOM allocation in order to improve the reliability of the distribution system. D-STATCOM placement is done to reduce the number of sags propagated through distribution systems. The proposed algorithm has not been validated by comparing with other optimization algorithms.

In 2015, Kanwar et al. [26] introduced an improved cat swarm optimization (CSO) for simultaneous allocation of DGs and D-STATCOM in electric distribution networks to minimize copper losses and improve voltage profile. Cat swarm optimization is an optimization technique based on the intelligence of a newly developed powerful swarm that mimics the natural behavior of cats, but generally suffers from poor convergence and accuracy. Therefore, the improved CSO (ICSO) technique is proposed to effectively solve the problem by amending the search behavior of CSOs. The simulation results testify the outperformance of the proposed modified CSO with respect to conventional CSO and PSO.

Tolabi et al. [27] applied fuzzy-based ant colony optimization (ACO) for optimal allocation of photovoltaic arrays and D-STATCOM. This research aimed to minimize losses, improve voltage profiles and enhance the feeder load balancing. Fuzzy concepts were assisted for dealing with multiple objectives. The findings show the outperformance of the proposed fuzzy-ACO with respect to conventional ACO, fuzzy-based PSO and fuzzy-based GA.

In [44], firefly algorithm is used to identify D-STATCOM optimum placement for power quality enhancement. The objectives of study are to alleviate harmonics and improve voltage profile. In solving the problem of optimal allocation of D-STATCOM, four D-STATCOM's were used. The results indicated the outperformance of firefly algorithm over GA and PSO.

In another research work, harmony search (HS) algorithm, inspired from improvisation process in music, was used to find optimal location and size of D-STATCOM with an objective function to minimize copper losses [28]. The proposed methodology was validated on IEEE 33-bus distribution network. The results of the proposed HS in loss minimization show its outperformance over IA.

Chabok and Ashouri [35] proposed a hybrid of imperialistic competition and Nelder-Mead algorithms for solving D-STATCOM allocation problem. Active power losses of the network and a voltage stability index have been included in objective function.

In [45], a hybrid of genetic algorithm and ant colony optimization algorithm were designed for optimal allocation of D-STATCOM's. This method minimized the losses of the feeding system containing power losses in the transmission lines. Three D-STATCOMs was applied to IEEE 30-bus system. The optimal values of reactive power generated or absorbed by three D-STATCOM is calculated by GA to reduce overall system losses. ACO is used by smart search to determine the best point for installing three D-STATCOMs in the network. Two random points near the nest and away from the nest were selected for the cost function.

In [46], bat swarm optimization algorithm is presented For D-STATCOM allocation in distribution systems considering the uncertainty of loads. A new stochastic structure modeled the effects of the uncertainty of loads in the distribution system for D-STATCOM placement and sizing problem. The described methodology has been tested on IEEE 69 bus distribution network to validate its efficiency.

In [30], a penguin optimization search algorithm (PSOA) was used to find the optimal location and design of D-STATCOM in order to reduce power losses and improve voltage profile in the distribution system. The efficient performance of the proposed optimization algorithm was approved by application to 14, 30 and 57 bus distribution systems.

2.4. Sensitivity approaches and their combinations with metaheuristic methods

In sensitivity-based D-STATCOM allocation methods, first an index is defined and computed for different potential locations of D-STATCOM and then the optimal location is determined based on the computed indices. The two common indices used for D-STATCOM allocation problem are as follows.

3. Voltage sensitivity index

The suitable location for installing D-STATCOM can be determined by finding the voltage stability index (VSI) for different buses. The bus with highest VSI value is chosen for D-STATCOM placement [47].

Jain et al. [48] proposed a voltage sensitivity-based method to enhance the voltage profile and reduce ohmic losses by D-STATCOM. Initially, the voltage stability of all buses was determined by calculating the voltage stability index values, and the most unstable bus was selected for D-STATCOM placement. Finally, the results have been presented for IEEE 33-bus distribution system.

Hussain and Visali [49] used voltage sensitivity index for determining the weakest bus of distribution network. The voltage profile is enhanced by the placement of a D-STATCOM on the weakest bus. The efficiency of the proposed VSI have been approved by application to a radial distribution system with 33 buses.

4. Power loss index

The power loss index (PLI) approach is a process for selecting the suitable location for D-STATCOM's. Power losses are calculated based on load flow studies. At all nodes, except for source node, reactive power is injected, and the total ohmic losses and loss reduction at each node are calculated. The node with the highest PLI value will be the best place for installation of D-STATCOM [50].

In [32], the following sensitivity indices were used for optimal placement of D-STATCOM's: fast voltage stability index, the combined power loss sensitivity index, voltage stability index, voltage sensitivity index and proposed stability index. Optimal location of the D-STATCOM based on the new voltage sensitivity index voltage was determined. The optimal size of D-STATCOM was found in summer and winter seasons, considering load growth. The efficiency of different sensitivity-based approaches in optimal allocation of D-STATCOM's were compared, and the impact of the optimal placement of D-STATCOM's to improve the margin of voltage stability, reduce energy losses and increase energy cost savings were investigated.

In [3], a voltage stability index has been used for optimal allocation of D-STATCOM devices in unbalanced radial distribution systems. For DSTATCOM sizing, the objective is to reduce the power loss and to improve voltage profile in all phases providing maximum net saving. Load model, Load growth, Cost of energy loss and Cost of D-STATCOM have been considered and analyzed in the different load levels including light load (50% the rated load), medium load (at rated load), high load (160% of the rated load). The results showed that With D-STATCOM, there is a considerable decrease in the real and reactive power loss and a significant improvement in voltage profile as well as a significant enhancement in voltage stability margin has been achieved.

In some research works, sensitivity-based approaches and metaheuristic optimization algorithms have been hybridised and applied to D-STATCOM allocation problem.

In [33], loss sensitivity factor (LSF) and bacterial foraging optimization algorithm have been hybridised and used for optimal allocation of

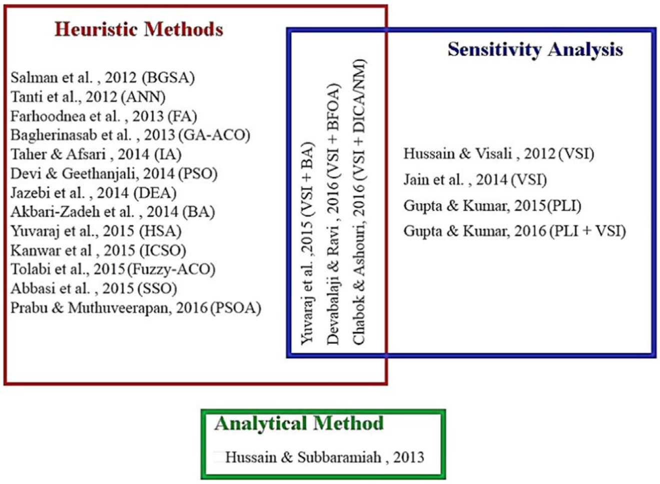

Fig. 3. Classification of different methods on D-STATCOM allocation.

D-STATCOM's and DG's in order to minimize power loss and improve the voltage profile of distribution systems. The five loss sensitivity factor values were sorted in descending order, and trial and error was used to find the optimum location between the five buses. The bus that provides the least amount of power loss was selected as a candidate for placement of DG or D-STATCOM. The obtained results testified the outperformance of the proposed methodology over IA. In [34], VSI was used for placement of D-STATCOM devices, while bat swarm algorithm was used to determine the optimal D-STATCOM size.

Classification of different methods on D-STATCOM allocation has been shown in Fig. 3. Three important factors should be considered when determining D-STATCOM placement and sizing: complexity, accuracy and speed. Analytical methods are simple and relatively fast and robust, but they are not successful in determining the accurate D-STATCOM size, especially when the D-STATCOM range is wide. Furthermore, in analytical methods, in order to reduce the computation procedure, some approximations have been used that cannot cover all required assumptions of D-STATCOM placement problem (e.g. load variation neglected). The ANN based methods are robust but they are quite complex and relatively slow [51,52]. Since ANN approaches need input and output target data, the application of them in solving D-STATCOM allocation problem has been limited for abnormal conditions of operation when the data from short circuit analyses are available. These approaches are able to find only optimal location of D-STATCOM not their size.

Although the application of metaheuristic optimization techniques makes it easier to find the solution, they are not robust methods [53–57]. Most optimization techniques are quite sophisticated and suffer from premature convergence and lack of accuracy [57–65]. In addition, for this specific problem, there is no comparative study on the application of different optimization techniques. However, in compared with the other methods, it is easier to define and use a multi-objective function and consider many constraints in metaheuristic optimization techniques.

Sensitivity approaches are relatively simple and very suitable for the placement problem, but it is possible to consider only one objective [66–69]. Any sensitivity approach is designed to find the critical location of the D-STATCOM from a specific point of view, and it is difficult to consider many constraints for the problem. The combination of sensitivity approaches and optimization methods to solve this problem, is becoming very popular in the recent researches, which can be divided into two sub-problems. The most critical nodes can be found by using sensitivity approaches to make the problem smaller. Determining the best D-STATCOM size is among the few nodes for which the optimization techniques can be applied. Using this procedure, there is a balance between the accuracy and speed, and it is possible to use multi-objective functions and consider many constraints.

5. D-STATCOM allocation objectives and constraints

According to the literature, the following objectives have been considered in the examination of solutions for the problem of D-STATCOM allocation:

- power loss mitigation,
- voltage profile improvement,
- reliability improvement
- voltage stability improvement,
- cost reduction
- load balance improvement
- THD reduction,

Moreover, the following factors have been considered as equality or inequality constraints of the problem:

- power balance,
- voltage deviation limit,
- current limit,
- reactive power compensation,
- D-STATCOM capacity limits
- cost limitations.

Here, we present a review of the literature concerning the objectives, constraints and considerations of optimal D-STATCOM placement.

In [41], during the optimal allocation of DSTATCOM and DG units by PSO, power loss was minimized as objective function and limitations on voltage buses were considered as constraints of the optimization problem. In [42], optimal size and location of DSTATCOM's along with optimal configuration of distribution system has been determined in order to minimize power losses and enhance voltage profile. The results on IEEE 69 bus distribution network and a real-life distribution network show significant reduction in loss and significant improvement in voltage profiles.

In [26], optimal allocation of DG and DSTATCOM's have been done in order to minimize power losses, while voltage violations have been considered as penalty functions. Current limits of branches and power balance equation are the constraints of the problem. During the simulations, load duration curve (LDC) have been used. Akbari-Zadeh et al. [46] also used power losses and voltage violations as the objectives of optimization problem. They also took the uncertainties of distribution system into account. Moreover, in [48], power losses and voltage violations have been included in the objectives of optimization problem.

Gupta and Kumar [33] found the optimum place and rate of the D-STATCOM in radial distribution systems to reduce losses and voltage deviation while minimizing the total energy savings. The percentage of loss reduction, loss saving and annual energy saving after installing D-STATCOM on the suitable nodes have been obtained and a comparison with the results of other references has been presented.

In [34], the proposed work provided an objective function to minimize total power dissipation, voltage fluctuation and the operation cost, simultaneously. The optimal distribution of the DG and D-STATCOM in the distribution system is subject to the following restrictions: voltage deviation limit, real power compensation in DG allocation and reactive power compensation in D-STATACOM sizing. The authors analyzed the distribution system with eight different cases: 1) system without DG and D-STATCOM, 2) system including only DG at power factor equal to one (UPF), 3) system including only DG at optimum power factor, 4) system with multiple DGs at UPF, 5) system with multiple DGs at optimum power factor, 6) system with only D-STATCOM, 7) system with DG (UPF) and D-STATCOM and 8) system with several DGs (UPF) and D-STATCOM. Variation of load as well as different types of DG have been considered and tested on 33-bus and 119-bus feeders.

Table 1
Review of different research works on D-STATCOM allocation.

Ref.	Objectives	Constraints	Remarks
[26]	Power loss reduction, Voltage profile improvement	Power balance, Voltage deviation limit, Real power compensation, Reactive power compensation, Branch Current Limit, Radiality Constraint, System Compensation Limit	Allocation of both D-STACOM and DG has been done. Three different load levels (light, medium and peak) with three corresponding load durations have been considered.
[23]	Power loss reduction, Voltage profile improvement, Load balance improvement	Power balance, Voltage deviation limit, Branch Current Limit, Radiality Constraint	Network reconfiguration and DG (PV)/D-STATCOM allocation has been done in three different load levels (light, medium and peak)
[28]	Power loss reduction	Power balance, Voltage deviation limit, Reactive power compensation	
[29]	Power loss reduction	Power balance, Voltage deviation limit, Reactive power compensation	Uncertainties of loads have been modeled and considered.
[30]	Power loss reduction, Voltage profile improvement	Power balance, Voltage deviation limit, Reactive power compensation, Current limits	Placement of both DG and DSTACOM
[31]	Power loss reduction, Voltage stability enhancement	Power balance, Voltage deviation limit, Reactive power compensation, Cost of D-STATCOM	Allocation D-STACOM has been done for three different load levels (light, medium and peak)
[32]	loss mitigation, Voltage profile improvement, cost reduction and energy saving increment	Power balance	Instead of radial distribution system, meshed distribution system has been used as case study and the results reported for seasonal load growth.
[33]	loss mitigation, Voltage profile improvement, Cost reduction and energy saving increment	Power balance	
[34]	loss mitigation, Voltage profile improvement, Cost reduction	Power balance, Voltage deviation limit, Real power compensation, Reactive power compensation	Placement of multiple DG and DSTACOM in different power factors
[35]	Voltage stability enhancement, Cost reduction	Power balance, Voltage deviation limit, Real power compensation, Reactive power compensation, Branch Current Limit	Placement of DTATCOM when DGs are already existed
[36]	loss mitigation, Voltage profile improvement	Power balance	
[40]	loss mitigation, Voltage profile improvement, Cost reduction	Voltage deviation limit, Reactive power compensation	Three different load levels (light, medium and peak)
[41]	loss mitigation, Voltage profile improvement	Power balance, Voltage deviation limit, Reactive power compensation, Current limits	Placement of both DG and DSTACOM
[42]	loss mitigation, Voltage profile improvement	Voltage deviation limit, Current limits	Network reconfiguration and D-STATCOM allocation
[43]	Reliability improvement, Voltage sag reduction	Power balance, Voltage deviation limit, Current limits	Short circuit analysis and reliability evaluation have been done
[44]	Reducing the THD of voltage, Voltage profile improvement, Cost reduction	Power balance, Voltage deviation limit, Real power compensation, Reactive power compensation, D-STATCOM capacity limits, Cost limitations	A distribution system with some source of harmonics has been used as case study.
[37]	Voltage sag reduction	Power balance	Short circuit analyses for different types of faults, Placement of DVR / D-STATCOM
[45]	Power loss reduction, Voltage profile improvement, Cost reduction and system efficiency increment	Power balance	
[46]	Power loss reduction, Voltage profile improvement	Power balance, Voltage deviation limit, Reactive power compensation	Uncertainties of loads have been modeled and considered
[48]	Power loss reduction, Voltage profile improvement	Power balance	The load flow is carried out by implementing the compensating values for constant power, constant current and constant impedance.
[49]	Power loss reduction, Voltage stability enhancement	Power balance	The results have been presented for one load level.

Bagherinasab et al. [45] developed a new approach for optimal arrangement of D-STATCOM in distribution networks for reduction of losses, improvement of voltage profile, cost reduction and system efficiency increment. The ACO is used to determine the placement of the three D-STATCOM in 30-bus network, and GA is used to determine the amount of reactive power or power that is absorbed for use by each D-STATCOM.

In [40], a newly defined objective function for D-STATCOM optimization was introduced including the installation cost of D-STATCOM and the cost of energy losses. The number of overvoltage buses and number of overcurrent lines have been compared for two cases of before and after D-STATCOM installation in load variations. In [27], loss reduction, load balancing and voltage deviation were the objectives of optimization process. The results on various load levels approve that all these objectives have been improved in optimization process.

In [32], instead of radial distribution system, meshed distribution system was considered and the results reported for seasonal loads considering load growth. The following cases were considered: Case A) best D-STATCOM placement in summer load without load growth, Case B) best D-STATCOM placement in winter load without load growth, Case C) best D-STATCOM placement in summer load with load growth and Case D) best D-STATCOM placement in winter load with load growth. With the D-STATCOM, there is significant improvement of the voltage profile, voltage stability limit and reduction of the power losses and costs of energy losses. The annual energy savings attributable to energy loss reduction achieved higher growth with load after installation of the D-STATCOM. The proposed method and power loss sensitivity give a better location compared to the other sensitivity indices.

In [31] the aim of D-STATCOM placement in radial distribution system was to minimize the overall power losses while maintaining the equal and unequal constraints such as: voltage deviation limit, power balance fulfilled restrictions, reactive power compensation, costs of D-STATCOM, annual cost savings. The load models can be divided into three types: 1) the constant power model, 2) the constant current model and 3) the constant impedance model. In this study, the authors

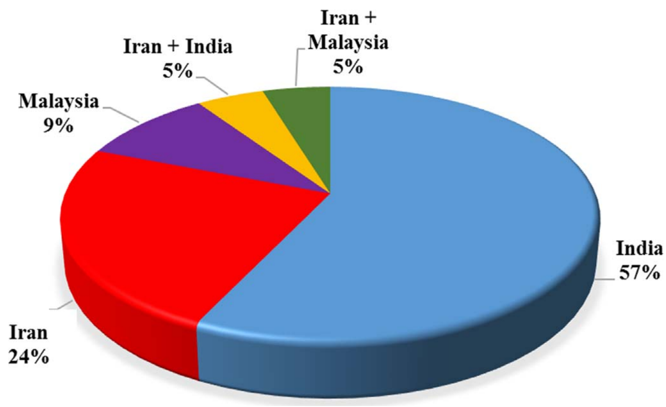

Fig. 4. Distribution of countries according to authors' affiliations in the published papers on the field of D-STATCOM placement.

used a constant power load model for modeling the behavior of loads in power grids.

In [35], D-STATCOM placement has been solved for IEEE 30-bus radial test system in the following cases: 1) no DG or D-STATCOM present; 2) without DG and with the D-STATCOM present and 3) both DG and the D-STATCOM present. The coefficient factors in the objective function are selected to keep a balance between voltage stability enhancement and cost minimization.

In [43], the objective function of D-STATCOM placement was to minimize the total number of voltage sags as much as possible. Using both load flow and short circuit analyses grid losses as well as number of healthy buses should be calculated for any change in the place of D-STATCOM. The problem constraints were power balance, voltage deviation limits, and current limits. Finally, a method of calculating the number of sags that experienced at each load point of distribution network was used considering reliability indexes; this is done to assess the system's reliability.

In [37], voltage sag mitigation under faults was considered as the objective function. For load buses, post-fault voltages have been shown for three cases: 1) no DVR or D-STATCOM installed, 2) D-STATCOM installed at the optimum node and 3) DVR installed at the optimum line. The relative performance of DVR and D-STATCOM in voltage sag mitigation was also examined. The simulation results show the placement of D-STATCOM seems to be more effective than the placement of DVR in voltage sag mitigation in meshed interconnected network.

In [44], the objective function is reducing the total harmonic distortion of voltage (THDv), voltage profile improvement and cost reduction. Power loss reduction is not considered as objective. The constraints were considered as power balance, voltage deviation limit, real power compensation, reactive power compensation, D-STATCOM capacity limits and cost limitations. A distribution system with some sources of harmonics has been considered for THDv calculation. After the optimization, systems' voltage profile considerably improved.

The objective functions, constraints and case studies of [49] and [30] are exactly the same as what have been considered in [31] and [41], respectively. Review of different research works of D-STATCOM allocation has been summarized in Table 1.

6. Overall review of D-STATCOM allocation studies

Based on the literature, we can make the following conclusions and provide suggestions for future research:

- Many optimization models have been proposed for D-STATCOM allocation problem, but their performances have not been compared, and there has been very little improvement in optimization techniques used for D-STATCOM placement and sizing. There is a need for a comparative study on the application of different optimization techniques in terms of accuracy and speed to solve this problem in different conditions.
- Most of the authors focused only on three load levels (light, medium and peak), and the load variation has not been considered in a radial distribution system. Each change in loads may affect the optimal location and size of D-STATCOM. In addition, most studies only used a single D-STATCOM in the distribution networks for minimization of power loss and failed to consider multiple D-STATCOMs in the radial distribution networks.
- Multiple DGs and multiple D-STATCOMs should be considered, as well as many different cases to cover all load conditions and all combinations of DG/D-STATCOM allocation. Otherwise, the research is incomplete and the results are not practical in real networks.
- THD reduction is one of the most important aspects of distribution networks and, perhaps, the most important issue in power quality enhancement. It is very strange how this important objective has been neglected by many studies.
- Almost all the reviewed research works have done optimal D-STATCOM allocation for balanced distribution systems. Optimal allocation of D-STATCOM's for unbalanced distribution networks is recommended for future research.
- Distribution of countries according to researchers' affiliations on various D-STATCOM placement papers, has been shown in Fig. 4. Although there is a growing interest of working on this topic, only a few Asian countries could focus properly and propose novel methods that worth to publish in literature.

7. Conclusion

Power loss mitigation, voltage profile improvement and system reliability improvement are the most important objectives that motivated researchers to use D-STATCOM devices in power systems. However, an extensive investigation has to be undertaken in order identify the best location and size of D-STACOMs in electric distribution networks. In this review, research works on optimal allocation of DSTATCOM units have been reviewed. Based on the conducted review, it can be concluded that there has been very little improvement in optimization techniques used for D-STATCOM placement and sizing. There is a need for a comparative study on the application of different optimization techniques in terms of accuracy and speed to solve this problem in different conditions. It can also be concluded that most studies only used a single D-STATCOM in the distribution networks for minimization of power loss and failed to consider multiple D-STATCOMs in the radial distribution networks. Moreover, it is concluded that optimal allocation of D-STATCOM's for unbalanced distribution networks has not been done and is recommended for future research. It must be pointed out here that this is the first comprehensive review on D-STATCOM allocation in power distribution networks.

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