

A Review on Optimal Siting and Sizing of D-STATCOM



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ABSTRACT: The continuous demand for electrical energy by industries and domestic users have stressed the electricity consumption to a high level. Because most components of domestic and industrial systems are made of power electronics devices in their designs. In addition, modern electrical power distribution networks (DNs) are subjected to major disturbances. Consequently, today's power system is laden with power quality problems such as excessive energy losses, voltage deviations, poor power factor (PF), voltage instability and reliability issues to mentioned just a few. To forestall these disturbances, Distribution Engineers have introduced the use of Custom Power Devices (CPDs) in order to reduce power losses so as improve power quality. Amongst CPDs, Distribution Static Compensator (D-STATCOM) proves most promising in minimizing power quality issues because it generates minimal harmonics, waste less power, has small size, high regulatory capability and cost effective. Researchers in recent years have focused on methodologies required for identifying the most suitable location and rating of D-STATCOM device based on divergent views. However, to date, only one author has so far reviewed a paper on this aspect of study. This paper discusses the latest study on appropriate installation and rating of D-STATCOM techniques for balanced and unbalanced radial distribution networks (UBRDNs). The paper has also provided a comprehensive literature study on the location of D-STATCOM in RDNs for power loss reduction and power quality enhancement. Comparative analyses of various techniques for development of D-STATCOM Objective functions and constraints; Merits and Demerits are presented.

Key words: Distribution Static Compensator, Optimization, Power quality, D-STATCOM Control strategies, D-STATCOM sizing, functions and structure, Review

1. INTRODUCTION

Both domestic and industrial demand for electricity globally is shooting up geometrically. Electrical energy instability is associated with the ever-growing difference between Production end and the increasingly high demand from the consumers' domain. This is evident in industrial environments and residential consumption patterns. Several literatures such as [1-5] presented that as long as there is increase in demand for electrical energy and continuous strive for economic buoyancy, then, industries and domestic consumers would coerce utility companies to operate at their peak efficiency boundaries. These demands have exposed the power system to severe problems. Some of the related networks problems include: excessive power losses and voltage drops in network buses [6].

In 2016, Prakash & Khatod [7] reported that the problems are associated with active loads that dominate the present day power systems. Distribution lines have high

resistance to impedance ratio, and more inductive loads are often added on the lines relative to the growing population demand. The resultant effects are voltage drops in buses of one phase and three-phase unbalanced loads. Also, the introduction of DGs in today's DNs cause reversals of power flows in lines; this is unhealthy for the system [8]. Authors in [9] wrote that today's power electronics devices are most relevant for power quality improvement because of their fast-operating time and cost effectiveness compared to the traditional electromechanical devices that are slow in operation and expensive.

It has been shown that power electronics-based controllers in DS guarantee sufficient energy at desired level

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of quality for subscribers [10]. CPDs which perform related function like FACTS devices are relevant option to resolve today's problem of interruptions in DS. Although Flexible Alternating Current Transmission System (FACTS) and CPDs are of same technology, however, they perform different functions. FACTS devices are used in transmission system, CPs are used in DNs [11]. CPDs are normally applied when power quality, system stability and reliability is the demand in power systems. When properly implemented, D-STATCOM can protect the system against balanced and unbalanced voltage deviations & current harmonics [11]. It also protect against voltage flickers, sags, swells and low power factor. [14] stated that D-STATCOM is used to resolve power quality issues like: pf, voltage profile & voltage stability. If an energy source or flywheel is connected to it can exchange both active and reactive current with the network.

In another development authors in [15] explained that the device provides voltage support and circulate surplus power amongst the phases and also mitigates power reversals caused by PVS. D-STATCOM installation in DNs can improve the efficiency of PV systems [16].

Optimum installation and rating of D-STATCOM devices is based on its economic importance, standard, reliability and availability for use [17]. However, it is observed that most reviewed works were geared towards optimum placement and sizing of FACTS Devices in transmission networks, but few on the optimum allocation of CPDs in UBRDS.

Careful study of researched publications shows that only twenty-five (25) Papers have so far been published from 2012 - 2019 on different aspects of the problems under review. This necessitated for further study on optimum allocation of D-STATCOM devices based on the available techniques, objective functions, constraints, merits and demerits.

This paper highlights on several researched works on optimal allocation of D-STATCOM device in balanced and unbalanced DS. The document is organized thus: Section 2 is introduction to components and uses of D-STATCOM. Review of optimal siting and rating techniques of D-STATCOM presented in Section 3. Section 4 is discussion on D-STATCOM control strategies. Section 5 is recommendations for future studies, while section 6 concludes the reviewed work.

2. INTRODUCTION TO COMPONENTS AND USES OF D-STATCOM

This section describes the components of D-STATCOM and its implementation to mitigate power quality problems.

2.1 D-STATCOM structure and functions

The D-STATCOM is a shunt connected, voltage source converter (VSC) that when installed at PCC generates or absorbs active and reactive currents. It is a power electronic device that has the capacity to convert DC voltage to AC voltage (inverter). The components of the device include: a dc energy storage battery or a flywheel, ripple filter and coupling transformer for matching the

inverter output voltage with the bus voltage. The VSC is designed using IGBT and MOSFET for switching purposes; and it operates on the principles of PWM [18].

The topologies of D-STATCOM includes: three-phase three-wire (3P3 W) and three-phase four-wire (3P4 W) unbalanced distribution networks [19]. It can also work as a synchronous voltage input at different values and phase angle.

Figure 1a and b illustrates a single line diagram of a bus in a DNs installed with D-STATCOM. Based on the control technique used and the bus at the PCC, current could be injected, or drawn in switching modes. [20] stated that D-STATCOM can generate the required balancing current to the PCC. The voltage at the receiving bus, governed by the D-STATCOM will be raised near to the acceptable value under normal operating conditions with high loading or during faults. Primarily D-STATCOM possess the ability to trade both real and reactive power concurrently. Normally, the quantity of the of real power transported is a function of the amount of energy generated [16].

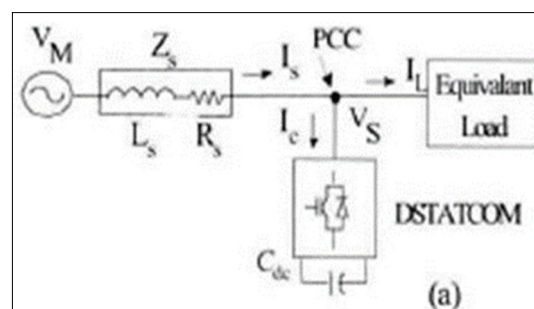


Fig. 1a. A line diagram of D-STATCOM [21].

From Figure 1a, V_m = Source voltage, Z_s = Source impedance, I_s = Source current, I_L = line current, L_s = series inductance, R_s = series resistance, I_c = capacitive current, V_s = inverter voltage and C_{dc} = dc link capacitor.

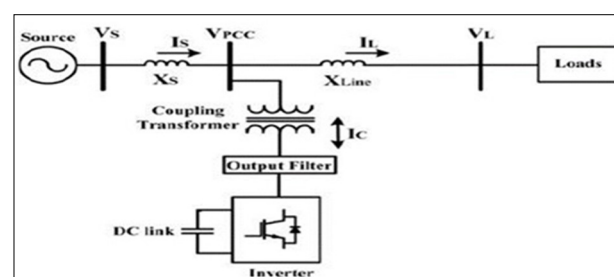


Fig. 1b. A typical D-STATCOM connected at PCC of a distribution network [21].

As shown in Figure 1b, V_s is source of the system voltage, I_s the source/system current, X_s the system reactance, V_{PCC} is the voltage at the point of common coupling or connection, I_L line current, V_L line voltage, I_c capacitive current and DC - link is a dc energy source or flywheel. The voltage level at the point of common connection of the bus will be enhanced. Similarly, voltages at other buses will also improve due to the reactive power absorbed, thereby reducing the power losses in the network.

2.2. Classification of D-STATCOM with respect to mitigation of power quality

The fundamental aim of D-STATCOM is to mitigate power quality problems. Common PQ issues include: voltage drop, sag & swell, harmonics distortion, Phase currents – unbalanced, neutral current overflow at PCC etc. In order to avert such PQ disturbances, D-STATCOM is one important CP device employed today by distribution engineers to forestall such ugly power quality scenarios. However, it must be properly analysed and installed appropriately to avert complications. The D-STATCOM usually operates in two modes: single and dual modes. The single mode operation compensates for either current or voltage only at a time. The device may also be installed to simultaneously compensation for both current and voltage in dual mode.

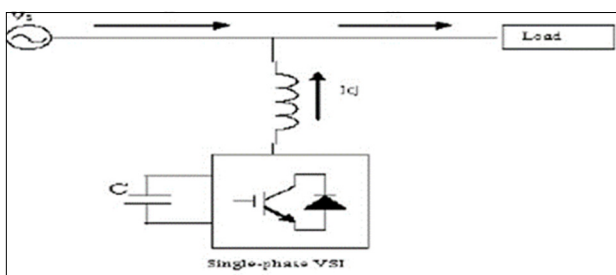


Fig. 2. single – phase control of D-STATCOM [22]

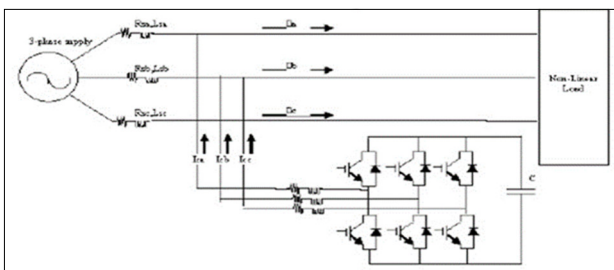


Fig. 3. Three – phase, three – wire D-STATCOM [23]

3. REVIEW OF RESEARCH WORKS ON D-STATCOM OPTIMAL LOCATION AND SIZING TECHNIQUES

Popular methods for optimum allocations of D-STATCOM in power distribution networks are: Artificial intelligence or metaheuristic techniques, Analytical techniques, Sensitivity analysis techniques, and hybridization of Sensitivity and metaheuristic techniques.

3.1 Artificial Intelligence (AI) techniques

Majority of day - to - day problems potent difficulties, some of which are distinct, uninterrupted or combined variables; others may have contradicting objectives that are often not straight or in disjoint etc. For instance, the problem boundary to be covered may be too wide that the overall best may not be found in short time. The analytical technique may not be relevant enough to tackle such issues. However, several trial and error methods, or the physics based techniques which emulates universal rules like immune intelligence, simulated annealing (SA), Gravitational Search Algorithm (GSA), Ray optimization

(RO) may be used in like conditions [24]. Engineers over the years have applied Artificial Neural Networks (ANN), SA, EAs, GAs and so on in real life situations.

AI or Metaheuristic techniques also called Computational Intelligence has another category of the nature inspired technique known as swarm method. It mimics the social behavior of animals in group. They include Grasshopper Optimization (GHO), cuckoo search (CS), Artificial fish swarm algorithm, Elephant Herding Optimization (EHO), PSO methods, Bat-inspired Algorithm (BA), Firefly Algorithm (FA) etc. These methods have been employed in power system studies during the past two decades to resolve problems.

The third AI is Evolution based inspired by natural law of genealogical development. The captivating aspect of evolution based technique is that optimal traits of parents is summed up to produce subsequent offspring. The techniques include: Genetic Algorithm (GA), Biogeography Based Optimiser (BBO) and Genetic Programming (GP) [25]. Metaheuristic is a widely used methods for best location and rating of D-STATCOM in DS.

Recently authors in [26] applied DE to optimally allocate D-STATCOM to reconfigure DNs for power loss reduction and voltage deviation enhancement. The technique was tested on standard IEEE- 69 and 83- bus DS. The method worked better than PSO. However, the authors did not account for the cost and rating of the D-STATCOM nor compared their work with relevant practical networks; besides, differential evolution algorithms involves complex computations and time consuming.

Artificial Neural Network (ANN) was used for optimum installation of DVR and D-STATCOM on DS to mitigate voltage sag during fault conditions in [27]. The authors utilized feed forward approach of ANN to optimally allocate DVR and D-STATCOM in RDN. The value of the voltages before each bus is used as the objective function for the study. The bus that exhibited the highest variation from the nominal value is considered the most appropriate for D-STATCOM placement. The demerit of the experiment is its inability to compare the results with existing standard methods.

In 2012, Salman et al [28] used binary gravitational search topology (BGSA) for optimum allocation of D-STATCOM to improve DS reliability. The purpose for allocation of DSTSCOM is to reduce voltage sag injected in DNs. However, the authors failed to consider the system power losses, rating of D-STATCOM, nor validated the work with existing practical networks. Taher and Afsari [1] proposed a novel technique, the IA algorithm, to appropriately rate and locate the bus for D-STATCOM installation to reduce energy waste in RDN. They employed BFS power flow technique for computation. Their objective functions are: total cost of energy waste, rate of D-STATCOM, voltage deviation level, and line current flows. D-STATCOM was modelled with an assumed voltage magnitude of 1p.u. at the candidate node. IA was employed to compute the rating of D-STATCOM. Three load categories: minimum, medium and maximum were chosen for yearly level modelling at separate time intervals. The results of the proposed approach run on standard IEEE 33

and 69-RDN test bus proved better than GA. However, the demerit of the work is its limitation to reactive power trading between D-STATCOM and the network only.

Optimum siting and rating of D-STATCOM in RDN for power loss mitigation and voltage deviation enhancement using was achieved using HAS in [29]. He applied BIBC matrix for DS power flow computation. The total annual cost saving, rate of D-STATCOM and price for yearly investment considered. The objective function comparing system power loss is construed for application in HSA. The efficacy of the proposed technique was tested on IEEE 33- test bus system, and the result compared with IA for validation. Although the results of the proposed approach outperform those of IA, the work failed to consider multiple D-STATCOM in reducing losses.

Enhanced PSO method showed a better siting and rating D-STATCOM on DS variable loads in [30]. They employed a new random sampling method to study the behaviour of variable loads in DN for optimum allocation of D-STATCOM. The method when deployed in IEEE 69 - bus test DS to ascertain the performance, produced a valid result of global optimum. However, authors did not make comparative analysis with other optimization methods to verify the validity of their work.

In an attempt to reduce losses, increment voltage magnitude authors in [31] used the Modified Shuffled Frog Leaping Algorithm (MSFLA) to achieve the optimal placement of D-STATCOM and DG in RDS,. The result of proposed technique is compared with that of GA, and tested on IEEE 33 - buses system as case study. Simulation results proved the method effective. The demerit of the research work is its failure to compare results with existing networks.

In 2017, Mustafa et al [32] allocated D-STATCOM in DS to minimize network losses, improve voltage level to stabilize the system. Authors used three indices to formulate the problem in order to achieve the set objectives. Power flow analysis is applied to model D-STATCOM to compensate for reactive power to enhance the network performance. BFS and PSO are the techniques employed for the optimal placement of D-STATCOM. IEEE 33-bus and 69- test bus systems are chosen to actualize the method. Simulation results shows that optimal location of D-STATCOM in DS reduces power losses, improve voltage profile and stabilize the system. The shortfall of the work is that it fails to compare the work with any practical network.

ANFIS based approach was used in [33] for optimal allocation of D-STATCOM to reduce voltage sag during fault conditions. The authors used MATLAB/SIMULINK software to determine the magnitude of sag under different short circuits scenarios. Feed forward neural network is applied to find the post-fault voltage magnitude for the three phases at individual buses. Case study is conducted on IEEE 30-bus system and the approach for siting D-STATCOM proved effective. The authors however, did not validate their study with existing evolutionary techniques.

3.2 Analytical optimization techniques

The analytical technique is a step - by - step approach to resolving practical problems manually without the use of computers. These methods include: direct, gradient, linear

programming techniques, Eigen Values and Eigen Vectors etc. The techniques are calculus based and are applicable to both individual or collective calculations. The reason for applying the classical technique for optimal allocation of D-STATCOM is to identify best result regardless of its difficulty. Some estimations are usually effected to the algorithms.

Also, an analytical technique for locating the best position for D-STATCOM in RDN has been demonstrated by some authors in [30]. They considered energy waste mitigation and voltage deviation as objective functions in the optimization process. The authors applied the developed technique on standard IEEE 33 - bus test system to verify its effectiveness. Comparative analysis was carried out for voltage deviations and regulation. D-STATCOM cost, merits and demerits were also examined. The result was verified using an established Genetic algorithm. Simulation outcome proves to be effective. However, analytical technique is usually prone to calculation errors.

3.3 Sensitivity analysis techniques

Sensitivity (responsiveness) describes the ability of an object to respond to stimuli, or background. It also compares between to outcomes: pass or fail; positive or negative; low or high, sick or healthy etc. The sensitivity of an examination gives the percentage/number of patience that are proved to be carrier of a disease on test. Responsiveness can be computed as = the chances of a student repeating a class is fail in examination. In power flow studies, we use sensitivity to identify nodes(junctions) that produce least voltage with reference to others. A sensitive junction is usually the weakest node whenever changes occur in load demands. The most often applied indices for D-STATCOM allocation based on accuracy and convergence rate are listed below:

- i. Voltage sensitivity index(VSI)
- ii. Power loss index (PLI)
- iii. Fast voltage stability index (FVSI).

Other sensitivity indices that are seldom used due their slow convergence time and computational errors are [31]:

- i. Line Stability Index (LSI)
- ii. Voltage Collapse Prediction Index (VCPI).
- iii. Modal Analysis.
- iv. Reactive Power Margin and
- v. New Voltage Stability Index (NVSI) etc.

3.3.1 Voltage sensitivity index(VSI)

To optimally allocate D-STATCOM using sensitivity-based methods, an index must first be defined and computed for different potential positions of D-STATCOM. The best site is then found depending on the calculated indices. Bus with the peak value of VSI is chosen for D-STATCOM placement [36].

Voltage sensitivity index(VSI) for finding the sensitive bus in DS by authors of [37]. Siting D-STATCOM in the weakest bus improved the voltage magnitude. Authors applied VSI on IEEE 33-bus RDN and the outcome of study proved effective. In the same way, authors in [38] used VSI-based technique to allocate D-STACOM in DS to reduce losses and improve voltage profile. They employed the method to compute the voltage magnitudes for each bus

in order to identify the most sensitive for installing the D-STATCOM. The result is tested on IEEE 33-bus test system of DS for validation.

Method that used bat algorithm to compute the optimal size of D-STATCOM in DS has been presented in [39] using VSI for allocation of D-STATCOM devices. However, authors failed to compare their work existing techniques. In 2016, Gupta & Kumar [6] employed VSI approach to optimally place D-STATCOM in mesh distribution system. Their aim is to appropriately rate D-STATCOM seasonally on load growth; compare D-STATCOM siting and sizing techniques using same approach and to equally determine the effect(s) of D-STATCOM allocation on voltage deviation, energy loss mitigation and cost of energy savings. Results obtained showed enhanced voltage, minimized losses, reduced cost of energy and low cost of installation. They examined their study on yearly savings of UK 38 bus practical mesh distribution system.

3.3.2 Power loss index

Power loss index (PLI) method is usually employed for optimum identification of D-STATCOMs placement. Power flow solution is the means for computing copper loss and energy losses at all nodes. To achieve a better result, reactive power must be injected at individual nodes except the source node. Any node that depicts the maximum value of PLI is selected for D-STATCOMs siting [40]. Authors in [41] applied hybridized LSF and bacterial foraging algorithm to optimally place D-STATCOMs and DGs to mitigate losses and enhance voltage profile in DS. They identified five sensitivity factors in decreasing order to randomly install the devices between the five buses. The buses with least losses are considered as candidates for DGs and D-STATCOMs placement. Result obtained from the technique is superior over IA. In another development, Gupta & Kumar [6] combined VSI and PLI to allocate D-STATCOM in RDN. Optimal location and sizing D-STATCOM based on the new methodology was realized and analysed both in winter and summer periods based on load increments. Authors then compared the validity of the methods to study the effects on energy loss reduction, voltage improvement and the cost of energy savings.

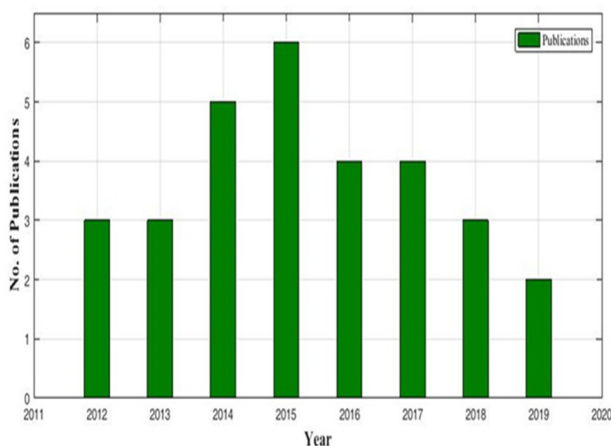


Fig. 4. Bar chart for the annual publications on D-STATCOM optimal siting and sizing [43].

Some researchers use hybridized method of sensitivity-based method and metaheuristic optimization topology for D-STATCOM siting and sizing problems solutions. Some of the existing works that proposed these methods including [29] were a new method of planning for allocation of D-STATCOM in RDS to mitigate losses has been developed. The researchers hybridized VSI and BA for optimum installation of the device. A step size of 1% used to regulate the feeder loads of test systems are: 0.5 for light and 1.6 for peak respectively. Curve fitting technique is applied for the optimal siting of D-STATCOM at individual load level and experiment conducted for single and multi-D-STATCOM installation on IEEE-33 and IEEE-69 test buses in RDS. Results shows an appreciable enhancement in both active and reactive power and total annual cost savings for the tests systems reduced. However, the work fails to ascertain application of two separate methods for siting the device in the test systems. Also, the choice of 1% step size in changing the loads in the feeder is devoid of scientific evidence. [42] applied a hybrid of scheme comprising DG and D-STATCOM to minimize power losses and improve bus voltages in active DS. Authors employed DLF technique to compute for load analysis. LSF and voltage deviation are considered as objective function for sizing DG. The experiment is tested on 33-bus RDN. The demerit of the proposed method is failure to compare results with other practical systems. Besides, LSF technique is prone to errors, has slow convergence and local minima.

3.3.3 Fast voltage stability index (FVSI).

This index is formulated from voltage quadratic equation of the system. It is based on the application/concept of the power flow through the line of the system and a FVS of less 1.0 indicates a stable system condition. There are several papers on the application of FVSI example is the congestion management in [44], in some papers artificial neural network was in to evaluate system FVSI [45]. Other application this system includes power system condition predictions as shown in [46].

3.3.4 Factors to be considered when Siting and Sizing D-STATCOM in RDN

Three fundamental factors must be considered when optimal location and sizing of D-STATCOM is required: precision, operating time and the complexity. The classical/analytical techniques are most versatile, easy and comparatively fast; however, they are limited to D-STATCOM placement only. Besides, they cannot be applied for appropriate sizing range of D-STATCOMs.

In addition, classical methods are prone to approximations that may alter the overall parametric analysis of D-STATCOM allocation computations, especially when varying loads are negligible. Although, Artificial neural network (ANN) techniques are robust, but difficult and slow [47]. ANN is restricted to ill-conditioned networks because of their requirements for input and output data. Despite the fact that metaheuristic optimization techniques proffer easy solution for optimal allocation of D-STATCOMs, however, they are not robust methods.

In similar manner, authors in [48] presented that majority of the optimization methods are very complex, full of errors and prone to early convergence. Based on this, more comparative study is required on various optimization techniques. Never the less, multi-objective functions and constraints using metaheuristic methods of optimization remains the best option for optimal solutions to these problems.

Sensitivity techniques are simple and better for optimal allocation problems, but confined to single objective functions. Sensitivity method is designed to critically install D-STATCOM in a desired node in a network, and hence cannot consider many - constraints at a time. Researchers today, hybridize sensitivity and metaheuristic optimization methods to resolve most multi-objective and multi-constraints problems in practical situations. They apply sensitivity approaches to optimally site critical nodes to reduce the problem range. D-STATCOM sizes are computed using optimization techniques. In so doing, it strikes a balance between speed and accuracy, making it suitable for multi-objective and multiple constraints problem solutions.

4. A REVIEW OF D-STATCOM CONTROL STRATEGIES

This section presents a brief review on D-STATCOM regulation techniques in DS. The fundamental factor to be considered in the control technique is the reference current generated by commutation device(s) required to trigger gate pulses to D-STATCOM in the system. Basically, D-STATCOM operate either in current or voltage control modes (CCMV or CM). When connected in CCM, the device can generate both reactive and harmonics signals of load current to balance the input current tuned in phase with voltages at PCC. When the device is operating in VCM, it has the ability to control voltage(s) at PCC to a specified value to protect critical loads from power quality problems. However, these control techniques cannot be applied concurrently because they are mutually independent [49].

4.1 Control Strategies

Normally, the active power needed by the system is produced by the source while D-STATCOM generates the reactive power desired by load to maintain the input current at 1pf. To get the loads steady, the input current must be balanced. The source contains actual basic frequency components of the load current that usually detects switching of VSC signals being extracted by control techniques [50]. Control strategies in use today include:

- Instantaneous reactive power (IRP) theory.
- Synchronous reference frame (SRF) theory.
- Adaline-based control algorithm (ABC) theory.
- Proportional integral (PI).

4.1.1 Instantaneous reactive power (IRP) theory

Authors in [51] proposed the IRP p-q theory. He used the method to change three-phase voltages and load currents into two-phase parameters in α - β frame using Clark's transformation technique. The method is used to compute for both real and reactive powers. Reverse Clark's

transformation reference currents are converted from α - β to abc frame. The IRP is a difficult strategy comprising complex mathematical transformations and theories and not the best option for resolving optimization problems.

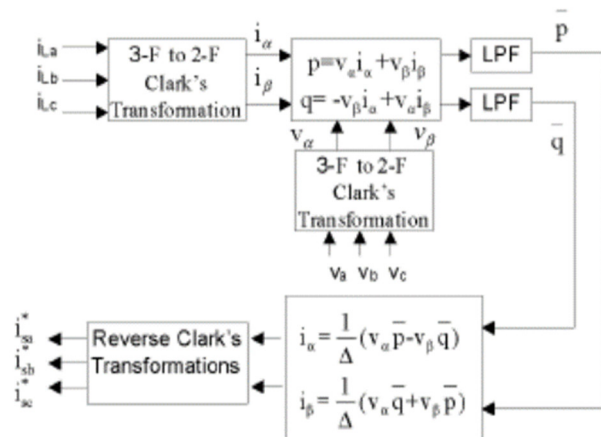


Fig. 5. Basic block diagram of the reference current extraction through p-q theory

4.1.2 Synchronous reference frame (SRF) theory.

Singh et al., [35] applied SRF indirect current control using switching signals for VSC of the D-STATCOM derived from the approximate reference input currents. The approach is deployed to balance loads on phases, reduce harmonics and to compensate for neutral current at 1pf and zero voltage operation modes. The result is run in MATLAB Simulink to validate the strategy. D-STATCOM proves to self-supportive on dc bus under different conditions. Authors could not validate their theory on any practical network. Besides, the strategy is time consuming involving complex mathematical transformations. In addition, the basic block diagram of this scheme is shown in fig below

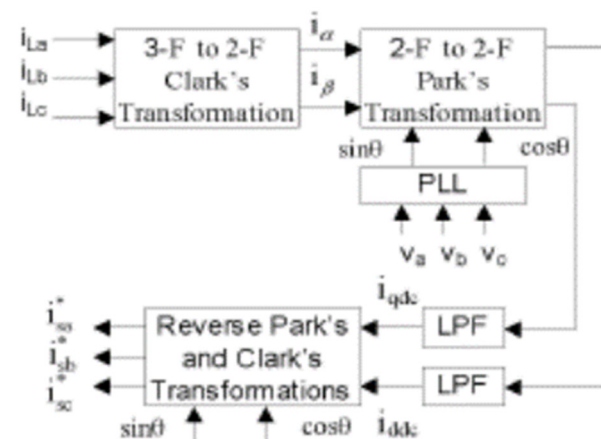


Fig. 6. Block diagram of the reference current extraction through SRF theory.

4.1.3 Adaline-based control algorithm (ABC) theory.

Usually, the basic concept of this method is better understood by the considering a single-phase system. This decomposer is based on Least Mean Square algorithm in which the adaline is used to track unit vector tamplet that enable it to maintain minimum error. Similarly, the block diagram is shown in figure 7

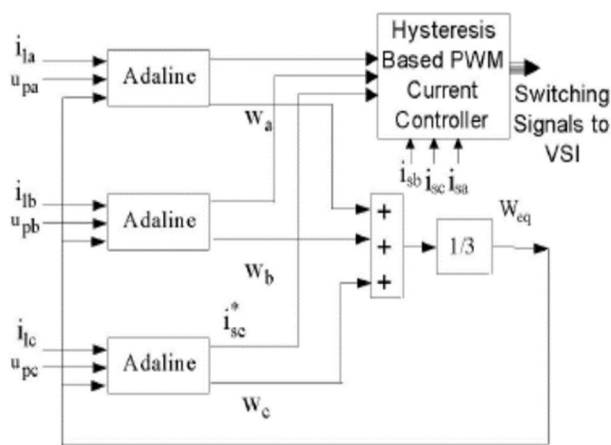


Fig. 7. block .diagram of the reference current extraction through Adaline based theory

4.1.4 Proportional integral (PI)

The output of this controller account for losses in D-STATCOM which eventually is considered as loss component of the current. In order to control the D-STATCOM by p-q theory, this current component is added with average real power.

4.2 Optimal Placement Objectives and Constraints for D-STATCOM

The following are summary of objective functions and constraints for D-STATCOMs optimal allocation problems in power distribution networks.

4.2.1 Objective functions

Objective function describes system parameter which may require reduction or increment in size, volume, height, number etc. The item that needs reduction or increment may have one or many objective functions. In most cases, some objectives may not agree with one another. One parameter that seems best for one, may be worst for another. Problems with many objectives could be redeveloped as one objective either by finding the average of the sum total or by restriction. Some of the objective functions normally encountered in power systems are [52]:

- Power loss mitigation
- Voltage profile improvement
- Voltage stability improvement
- Voltage reliability enhancement
- Improvement of load balancing
- Reduction of total harmonic distortion and
- Cost minimization

4.2.2 Equality and inequality constraints

Constraint describes situation(s) that permit the unknowns to assume values while excluding others. They are prerequisites that must be fulfilled to meet standard design requirements. Optimization issue is defined only when design parameters, objectives, limits, and the relationship that exist between the parameters are correctly selected [52]. Some constraints encountered during optimal placement of D-STATCOMs in power systems include:

- Reactive power compensation
- Limit of voltage deviation
- Power balance
- Current limit
- Costs limitations and
- D-STATCOM capacity limits

there are many literatures the on the development of objective functions, constraints and factors affecting optimal siting and sizing of D-STATCOMs. One of them is presented in [53] in which harmonic distortion (THD), voltage profile improvement and energy cost reduction were considered in the formulation of the system's objective function. Power balance, voltage deviation limit, real and reactive power compensation and D-STATCOM rating limits were the constraints for the study. THD for distribution network is computed and test result shows an appreciable improvement in voltage profile with reduced harmonic disturbance.

PSO was used to optimally locate and rate D-STATCOM and DGs units in DS [54]. Researchers considered power loss minimization as the objective function and bus voltage mitigation as constraint for the study. Test result in MATLAB simulation proved the method effective and reliable. In another development authors in [55] conducted a research on optimal siting and rating of D-STATCOM and DGs in DNs. They used power loss reduction and voltage deviation as objective functions; voltage deviation is taken as penalty function while power balance and branch current limits were the constraints for the problem solution. Load duration curve (LDC) analysis is employed for simulation and result obtained reveals the methodology effective.

Optimal allocation of D-STATCOM in RDN aimed at reducing the network losses to maintain both equality and non-equality constraints has been demonstrated in [29]. The developed constraints were power balance limits, voltage deviation and cost of reactive power compensation and yearly savings for the device. Loads models used are: constant power, constant current and fixed impedance types respectively. However, constant power model characteristics was adopted as objective function for the study in power grid system.

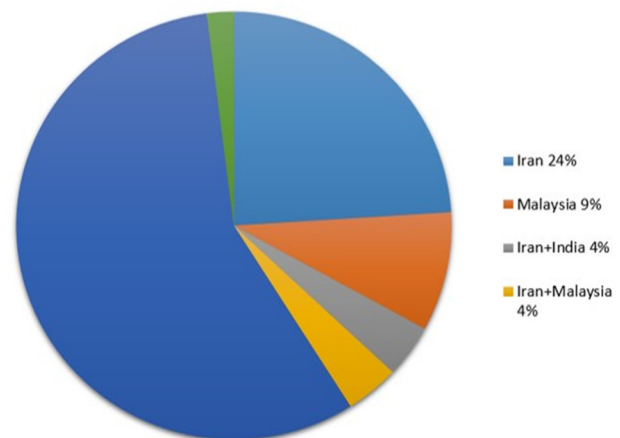


Fig. 8. Representation of researchers and their continent of origin in recognition for their publication on optimal allocation of D-STATCOM.

A study aimed at loss minimization, voltage deviation and operational cost as objectives of the study was presented in [35]. Some basic constraints that tend to affect DGs and D-STATCOMs optimal allocation in DS is real power compensation in siting DG, and reactive power compensation in rating D-STATCOMs. The researchers presented their study of the network in these perspectives: with only one D-STATCOM installed, one DG at 1pf, one DG at optimum power factor, with multi – DGs at 1pf, with multi-DGs installed at optimum power factor, D-STATCOM installed and with multi - DGs at 1pf installed. Variable loads and several DG types are validated on IEEE 69 and IEEE 119 – test bus systems feeders.

Authors in [17] used IEEE30-bus RDN test network to resolve D-STATCOM allocation problems for the following studies:

- Neither DG nor D-STATCOM installed in the network.
- Only D-STATCOM installed in the system, and
- DG and D-STACOM installed.

A factor is set as objective function to differentiate between voltage enhancement and cost reduction. The outcome of result indicates improved voltage level and minimised cost of installation. [43] conducted a study on D-STATCOM placement to drastically reduce voltage sag to its minimum value. Authors used load flow and short circuit analysis to study both the system condition and losses factor

to ensure unwanted complication in installing the device. Voltage deviation limits, current limits and power balance were the constraints used in the study. Reliability indices methods were applied to compute the for sags occurred at individual load points to generally evaluate the system's reliability.

[56] introduced sine and cosine algorithm (SCA) technique for optimal installation of D-STATCOM in RDS. The method is multi – objective comprising: mitigation of voltage magnitude and system reliability improvement at same time. Cosine approach is one of latest version in vogue for updating location of populations for optimum results. It uses the modified version of SCA that operates on the principles of levy flight sharing to optimise D-STATCOM rating and installation in RDS when the device is the reactive power source. The technique is applied on the standard 85-bus test system for validation. Results are compared to the established basic SCA and (PSO) techniques. The simulation proves that the algorithm is superior those reported literature. In addition, noticeable results are obtained with optimal allocation of D-STATCOM with reference to objective functions and constraints and case studies of [37,57]. Some research works on D-STATCOM allocation are shown in Table 1. In similar way, representatives' countries and their global outlook on D-STATCOM are shown in Figure 8.

Table 1 Summary Of Research Study On Optimal Allocation Of Dstatcom In Ds.

s/n	Authors	Objectives	Constraints	Remarks
1	Jazebi et al,2011 [24]	Reduction of losses & Voltage profile enhancement	Voltage variation and current limits	System resetting & D-STATCOM installation
2	Salman et al,2012 [28]	Enhancement of system stability & Reduction of Voltage sag	Equality, Voltage variation & Current limits	Short circuit study & reliability analysis has been conducted.
3	Tanti et al, 2012 [41]	Voltage sag mitigation	Power equality	Conductor bridging faults study for different of faults, allocation of CPDs
4	Hussain and Vitali, 2012 [37]	Energy waste loss mitigation, Voltage stability enhancement	Power balance	Only single load level results were presented.
5	Bagherinasab et al,2013 [58]	Power loss minimization, Voltage level improvement, Cost mitigation and network performance improvement	Energy balance	
6	Akbari et al,2014 [59]	Energy losses minimization, Voltage gradient enhancement	Energy balance, Voltage variation limit, Reactive energy supply	Examples of uncertainties of loads are in use.
7	Devi & Geethanji,2014 [54]	Energy waste reduction, Improvement of Voltage level	Energy balance, & change voltage limit, reactive energy make up & Current limits	Allocation of DG & DSTACOM
8	Jain et al,2014 [38]	Wasted power reduction, improvement & Voltage gradient	Energy balance	PFA is applied to correct figures for steady power, steady current and fixed impedance.

9	Taher and Afsari,2014 [5]	Wasted power reduction, Voltage profile enhancement, Cost minimization	Energy balance, boundary of voltage deviation, reactive energy make up & limits of Current	Installation of DG & D-STACOM is possible
10	Bajaj et al,2015 [62]	Energy loss mitigation		Load probabilities are modelled and accepted.
11	Parabu and Mathuveerapan, 2018 [60]	Wasted Power mitigation & improvement of voltage profile	Limitation of power balance, Voltage deviation & reactive energy make up	Penguins search Algorithm deployed for installation of DG and D-STATCOM.
12	Gupta and Kumar,2015 [41]	Reduction of losses, Voltage profile enhancement & reduced cost of energy		
13	Kanwar et al, 2015 [55]	Mitigation of energy loss & enhancement voltage gradient.	Equal power, bounds of voltage variation, real power & current division limits are constraints	Placement of DG & D-STATCOM on light, medium & peak load periods.
14	Yuvaraj et al,2015 [29]	Reduction energy waste	Equal power, limitation of Voltage gradient & correction of reactive power	
15	Chabok and Ashouri,2016 [17]	Steady Voltage enhancement & Cost reduction	Energy balance, boundary of Voltage variation, active & reactive power correction & limit of current division	
16	Devabalaji and Ravi,2016 [39]	Reduction of losses, Enhancement of voltage profile & Cost reduction	Power equality, Voltage deviation limit, real & reactive power correction	Placement of multi - DG & DSTACOM in different power Placement of multi - DG & D-STACOMs in different networks
17	Gupta and Kumar,2016 [6]	Reduction of energy loss, improvement of Voltage profile & minimised cost of energy		Meshed distribution Network is taken for study in place of RDN & results presented as seasonal load growth.
18	Mohammadi et al, 2017 [36]	Mitigation of active power loss & cost of operation are the objective functions	Voltage magnitudes and all types of loads are radial systems.	Fuzzy technique for loss sensitivity is used for optimal siting of DFACTS devices while GA method for tie selection applied to reset the network.
19	Musa et al, 2018 [61]	Reduction of energy loss & Voltage profile improvement		
20	Shahryari et al, 2018 [63]	Decrease power waste and augment voltage profile in DS.	Increment un equal constraint, boundary of voltage deviation & reactive power correction.	Used VSI to locate D-STATCOM & WOA to rate the device.
21	Ebeed et al, 2018 [54]	minimized active power wastes, enhance voltage level & stabilize the network at same time.	Maintain equal power, limit voltage deviation, correct reactive power & Current bounds	SCA technique employed for Optimal allocation of D-STATCOM.

5. RECOMMENDATIONS FOR FUTURE RESEARCH WORK

Sequel to fundamentals of the literature studies on optimum installation of D-STATCOM in DS, the following conclusions can be derived and suggestions proffered for future researches:

1. Several examples of optimization models are formulated for D-STATCOM allocation problems without cognisance to comparative analysis with existing standards. The consequences are the slow progress in the techniques used for optimal installation of D-STATCOM problem. There is an emergent need for comparative study on the administration of variant optimization methods on how fast and effective it will take to resolve these problems under varying conditions.
2. Most research study focused on optimal D-STATCOM location for balanced distribution networks. Future research should dwell on optimal allocation of DFACTS devices in UBRDNs because most networks are theoretically unbalanced systems.
3. It is also observed that authors emphasized on three load levels only i.e. light, medium and peak loads. Little or less attention is drawn towards variable loads in both radial and meshed DS. Practically, a slight variation in loading conditions affects the optimal position and rating of D-STATCOM. Moreover, authors overstressed on single D-STATCOM placement in DS for reducing power losses disregarding multi-D-STATCOM installation in radial or ring systems.
4. Authors need to also consider Multi- DG & D-STATCOM installations as well in other relevant cases to accommodate unforeseen loading conditions, otherwise such study could be incomprehensive with impossible outcomes in real life situations.
5. One crucial aspect of DS study is THD. Mitigation of harmonics in power systems is one most relevant issue and striking-edge in power quality improvement, but no researcher mentioned it in the reviewed papers.
6. Literature study shows that only few countries developed interest in the area of the study
7. D-STATCOM control strategy is another vital area that authors omitted in the literature. Since most DS are unbalanced systems, it is pertinent to note that each network will require specific topology to ensure the desired power quality requirement.

6. CONCLUSION

The need for power loss mitigation, voltage magnitude enhancement to stabilize power system are the major reasons that motivated researchers to employ D-STATCOM device in DS. To obtain the best position and size(s) of D-STATCOMs in DS, authors must conduct thorough study of the network. A comprehensive research on optimal siting and rating of D-STATCOM devices has been conducted. During the study, it is observed that there is slow progress in the optimization methods relevant to optimal location and sizing D-STATCOMs in DS. Therefore, an urgent need for comparative study on

alternative optimization methods with regards to speed and accuracy to resolve the problem from varying operating conditions. It has also been observed that authors relied mostly on installing one D-STATCOM in DN for reducing power losses, but failed to consider multiple installations of D-STATCOMs for such networks. In addition, authors also failed to conduct studies on optimal placement of D-STATCOMs in unbalanced distribution systems. Besides, they did not include D-STATCOM control strategies required for various optimal allocations. This work reviewed both balanced and unbalanced network for D-STATCOMs placement in DS.

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