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Optimal Location of DSTATCOM Considering Different Load Models Using Bat Algorithm

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***Abstract*—Distribution Static Compensator (DSTATCOM) is widely applied in mitigating common power quality problems. Optimal sizing and placement of this compensator is a critical aspect that ensures that power quality problems are mitigated with minimal losses. Bat Algorithm (BA) is chosen to optimize the size and location of DSTATCOM with the aim of minimizing power losses and improving voltage profile. Optimal allocation of DSTATCOM is obtained for both Constant Power (CP) and Constant Current (CI) load models. The success of the optimization algorithm is tested in IEEE-118 bus system. Under the proposed method, when optimally placed single DSTATCOM and optimally placed three DSTATCOMs are used, real power losses are reduced by 22% and 24% respectively for CP load model. For CI load model, when optimally placed single DSTATCOM and optimally placed three DSTATCOMs are used, real power losses are reduced by 18% and 21% respectively.**

Keywords—Bat Algorithm, Distribution System, DSTATCOM, Optimization.

I. INTRODUCTION

Nowadays, although the generation of power has been fairly reliable, power quality is not yet reliable. The increase in non-linear loads in modern distribution systems has given rise to quality related problems. When voltage or frequency deviates from the standard limits, power quality problems are encountered. Voltage sag and harmonic distortion are common power quality problems frequently encountered in modern distribution systems. Reactive loads, which are common in today's industrial processes draw lagging reactive power-factor currents creating reactive power burden on the power system [1].

Power quality problems increase power loss in the system, which lowers the overall efficiency of a power system. When a heavy load is suddenly connected, high load current is drawn and the voltage on consumer side reduces. This reduction of rms voltage to values lower than 1 p.u for a short time usually less than a minute is referred to as voltage sag [1]. Sag causes the torque of induction machines to reduce. Voltage sag can also cause data loss in communication equipment if it lasts for seconds. If a voltage dip lasts for more than a minute, voltage collapse can be experienced. Voltage collapse increases downtime duration, which causes consumers to incur losses and lose confidence on the power distribution company. When unbalanced loads are connected to the system, voltage imbalance occurs, which causes high currents to flow in neutral conductors. This has detrimental effect in the operation of transformers and generators.

The mentioned challenges can be addressed by the use of power loss reduction equipment because Automatic Voltage Regulation (AVR) and Load Frequency Control (LFC) are not sufficient. Some of these equipment include capacitor banks, Flexible AC Transmission (FACT) devices, series and shunt reactors. Capacitor banks and reactors are conventional compensators and one of their disadvantages is that they result in resonance frequency which reduces the stability of the system. As a result, FACT devices are preferrable over conventional compensators. FACT devices use power electronic switching converters to improve power transfer capability, stability, security, and reliability of AC systems. Distribution Static Compensator (DSTATCOM) is a FACT device that is widely applied in mitigating power quality issues [2].

DSTATCOM is simply a Voltage Source Converter (VSC) that is shunt connected to the system. The device can either inject or consume reactive power based on the grid condition. When the voltage magnitude is low, reactive power is injected to the system. At times of high voltage, the FACT device absorbs reactive power from the system. Features such as less harmonic production, fast response, and compact size makes DSTATCOM a preferrable candidate in mitigation of power quality issues [3].

However, the size and location of DSTATCOM is an important aspect that is critical in the design of DSTATCOM. Optimal allocation of DSTATCOM changes depending on the load connected to the system. Bat Algorithm (BA) is proposed for optimizing the size and location of the FACT device [4].

Contribution: This paper incorporates the cost of DSTATCOM as a constraint in the optimization problem of DSTATCOM. The use of multiple DSTATCOM devices is also considered. Two different load models have been considered. Besides, a higher Bus Test System (IEEE-118 bus) has been selected for optimization. Bat Algorithm is used for optimization.

Paper Organization: This paper is organized as follows: Section II covers the Literature Review, Section III covers Problem Formulation, Section IV covers the Proposed Methodology, Section V is the Results and Discussion part, Section VI is the Conclusion, and References makes the last part.

II. LITERATURE REVIEW

Voltage sag and voltage imbalance are common problems in modern distribution networks. Voltage imbalance occurs when there is a difference in the amplitudes of three-phase

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voltages [5]. Connecting unbalanced load is a major cause of voltage imbalance. Unbalanced systems indicate presence of negative sequence that is harmful to three-phase loads. For instance, in induction machines, voltage imbalance can cause reverse-rotating air gap, increasing losses and temperature.

DSTATCOM is simply a VSC that is shunt connected to the power system. This device can control voltage by either injecting or absorbing reactive power. Fig. 1 illustrates a DSTATCOM in a simple distribution system.

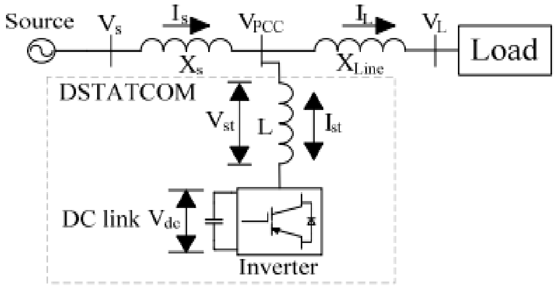

Fig. 1. DSTATCOM Connected to Power System [1].

In Figure 1, V_{st} is the DSTATCOM terminal voltage while V_L is the voltage at the load side. If $V_L = V_{st}$, no power exchange will occur. If $V_L < V_{st}$, reactive power will flow from DSTATCOM to the grid. If $V_L > V_{st}$, DSTATCOM will consume reactive power with respect to the grid.

Optimal allocation of DSTATCOM determines how a distribution system performs. Use of DSTATCOM is inevitable in today's power systems. Optimization techniques such as Modified Bat Algorithm [7] and Ant Colony Optimization [8] have been used in DSTATCOM allocation and sizing.

In [4], Bat Algorithm (BA) for DSTATCOM optimal location and sizing was suggested. The authors acknowledged that the size of DSTATCOM is proportional to the losses, and hence there is need to reduce DSTATCOM rating in each application. The study focused on minimizing DSTATCOM losses by optimizing its size. Reactive loads used in the study were varied from light to peak. For each load level, optimal DSTATCOM sizing was achieved. The results showed that Bat Algorithm was useful in ensuring that DSTATCOM mitigates voltage sag with minimal power losses. However, this study considered only constant power load model.

In [9], Particle Swarm Optimization (PSO) for optimizing the size and location of DSTATCOM was proposed. The authors focused on reducing power losses. Voltage limits, current limits, and angle difference were the constraints taken into consideration. The results showed that PSO was effective in minimizing system losses. However, the annual cost of saving index was not considered in the optimization problem.

III. PROBLEM FORMULATION

Objective function is formulated to optimize the size and location of DSTATCOM subject to system constraints.

Mathematical Model of DSTATCOM: DSTATCOM and grid exchange real and reactive power based on (1) to (2).

$$P = \frac{V_{pcc}V_{st}}{X_t}\sin\delta \qquad (1)$$

$$Q = \frac{V_{pcc}^2}{X_t} - \frac{V_{pcc}V_{st}}{X_t}\cos\delta \qquad (2)$$

The current injected by DSTATCOM can be expresses as:

$$I_{st} = \frac{V_{st}-V_{pcc}}{jX_t} \qquad (3)$$

Where: V_{pcc} is voltage at common coupling, V_{st} is the DSTATCOM voltage and X_t is the total line reactance.

Load Modelling: Real and Reactive powers for static loads are expressed as:

$$P = P_0\left(\frac{V}{V_0}\right)^{n_p} \qquad (4)$$

$$Q = Q_0\left(\frac{V}{V_0}\right)^{n_q} \qquad (5)$$

Where: P_0 is the active power at nominal voltage, Q_0 is the reactive power at nominal voltage, V is the bus voltage and V_0 is nominal voltage.

For Constant Power (CP) load model, n_p=0 and $n_q = 0$. Therefore, P and Q are independent of voltage. For Constant Current (CI) load model, n_p=1 and $n_q = 1$. Therefore, P and Q are dependent on voltage.

Power Flow Analysis: Fig. 2 is a simplified power system that is used to derive key equations.

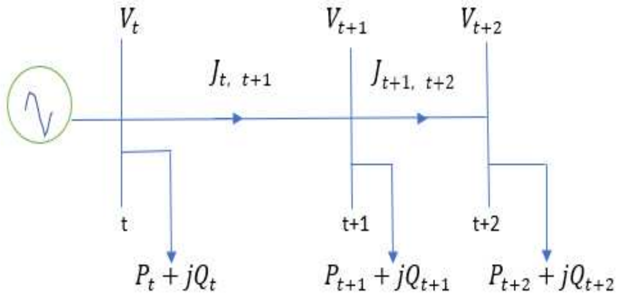

Fig. 2. Simple Distribution System [4].

The current injected at node t is can be expressed as:

$$I_t = \left(\frac{P_t + jQ_t}{V_t}\right)^* \qquad (6)$$

Current between t and t+1 can be obtained by applying Kirchoff's Current Law.

$$J_{t,t+1} = I_{t+1} + I_{t+2} \qquad (7)$$

Voltage at bus t+1 can be obtained by applying Kirchoff's voltage law.

$$V_{t+1} = V_t - J_{t,t+1}(R_{t,t+1} + JX_{t,t+1}) \qquad (8)$$

Power losses for the same section is thus expressed as:

$$P_{Loss(t,t+1)} = \left(\frac{P_{t,t+1}^2 + Q_{t,t+1}^2}{|V_{t,t+1}|^2}\right) * R_{t,t+1} \qquad (9)$$

$$Q_{Loss(t,t+1)} = \left(\frac{P_{t,t+1}^2 + Q_{t,t+1}^2}{|V_{t,t+1}|^2}\right) * X_{t,t+1} \qquad (10)$$

Total real and reactive power losses for the system can thus be expressed as:

$$P_{T,Loss} = \sum_{t=1}^{nb} P_{(Loss,t+1)} \qquad (11)$$

$$Q_{T,Loss} = \sum_{t=1}^{nb} Q_{(Loss,t+1)} \qquad (12)$$

Objective Function

The objective function to minimize system losses is formulated as:

Minimize (F_1)= Min ($P_{T,Loss}$) (13)

Where ($P_{T,Loss}$) is the total power losses in all the sections of the system.

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Power Balance Constraint

$$P_{T,Loss} + \sum P_{D(t)} = \sum P_{DSTATCOM(t)} \quad (14)$$

Where: $P_{D(t)}$ is the power demanded and $P_{DSTATCOM(t)}$ is the DSTATCOM power.

Cost Constraint

$$COST_{DSTATCOM,Year} = COST_{DSTATCOM} \times Q_{installed} \times \frac{(1+B)^n \times B}{(1+B)^n - 1} \quad (15)$$

Where: $COST_{DSTATCOM,Year}$ is the annual DSTATCOM cost, $COST_{DSTATCOM}$ is the investment cost in allocation year, B is the return rate, $Q_{installed}$is the installed DSTATCOM capacity, and n is the life span of the DSTATCOM.

Reactive Power Compensation Constraint

$$Q_{DSTAT(t)}^{min} \leq Q_{DSTAT(t)} \leq Q_{DSTAT(t)}^{max} \quad (16)$$

Where: $Q_{DSTAT(t)}^{min}$ and $Q_{DSTAT(t)}^{max}$ are the minimum and maximum compensation limits respectively.

Voltage Deviation Limit

$$V_t^{min} \leq |V_t| \leq V_t^{max} \quad (17)$$

Where: V_t^{min} and V_t^{max} are the minimum and maximum voltage values at bus t.

IV. METHODOLOGY

This section starts by discussing the previous methods that have been applied in optimizing the size and location of DSTATCOM. Later, the suggested optimization method is discussed and the proposed method is mapped to the problem.

A. *Previous Methods*

In 2014, [4] used Bat Algorithm (BA) to optimally allocate DSTATCOM in a distribution system. The authors aimed at minimizing system losses. However, the method was tested only in a CP load model and the other load models were neglected.

In 2016, [10] proposed Imperialist Competitive Algorithm (ICA) to position DSTATCOM at optimum position and to minimize its size. The objectives were to minimize losses, voltage deviation, and annual cost of saving index. However, this method has many tuning parameters. This can result in settling in DSTATCOM size that is not optimal.

In 2014, [11] used Immune Algorithm (IA) to position and size a DSTATCOM. The objective was to improve the voltage profile and minimize the system losses. However, the method takes long time before converging, which makes it unsuitable in distribution networks with many variables.

In 2019, [12] proposed Ant Lion Algorithm (ALA) for optimal sizing and placement of DSTATCOM. The authors wanted to have a DSTATCOM that can mitigate power quality issues with minimum losses. However, this method does not guarantee promising results in large network systems.

In 2017, [9] suggested Particle Swarm Optimization (PSO) algorithm for sizing and positioning DSTATCOM in a distribution network. The main focus was to minimize losses and improve the voltage profile. However, this method can result in premature convergence. This can lead to optimal solutions of DSTATCOM that are not accurate.

B. *Proposed Method: Bat Algorithm*

This paper proposes a Bat Algorithm (BA) to optimally place and size DSTATCOM. BA makes use of the echolocation behavior of bats [13]. Bats radiates sound signals called echolocation and this helps them to detect objects or prey within their surroundings.

Using parameters such as the position of bats, velocity, and frequency of their sounds, DSTATCOM can be placed on optimal position in a power distribution system while ensuring that the rating and losses are minimized. When compared to other metaheuristic algorithms, BA appears to be more powerful in solving non-linear problems more efficiently. Some pros and cons of BA are presented below:

Advantages: Optimal solution is guaranteed; fast convergence; easily implementable.

Disadvantages: BA has many control parameters that require to be tuned.

Bats are the only flying mammals and their characteristics can be idealized as follows[13]:

i) Bats use echolocation characteristic to sense distance to the prey or an obstacle.
ii) Bats fly randomly with frequency f_i, velocity v_i, and position x_i.
iii) The loudness of the bat varies from large positive A_0 to a minimum value.

The initial number of bats is taken randomly. The population is updated after getting the initial fitness based on loudness and pulse rate.

The frequency f_i, velocity v_i, and position x_i of virtual bats are updated based on the following equations:

$$f_i = f_{min} + (f_{max} - f_{min})\beta \quad (18)$$

$$v_i^t = v_i^{t-1} + (x_i^{t-1} - x^*) f_i \quad (19)$$

$$x_i^t = x_i^{t-1} + v_i^t \quad (20)$$

Where $\beta \in [0,1]$ is a randomly selected vector and x^* is the current best located bat from a population of n bats. As the bat is near the prey, pulse emission increases but the loudness reduces. Therefore, the convergence equation becomes:

$$A_i^{t-1} = \alpha A_i^t \quad (21)$$

$$R_i^{t+1} = r_i^o [1 - exp(-\gamma t)] \quad (22)$$

Where α and γ are constants: $0 < \alpha < 1$ and $\gamma > 0$. The initial values of loudness A_0 and pulse rate r_i are both in the range of $[0,1]$.

C. *Mapping Method to the Problem*

In Bat Algorithm, bat population, pulse frequency, pulse rate, and loudness are the important parameters. The population size will represent different sizes of DSTATCOM as each bat is similar to a specific size of DSTATCOM. The pulse rate of the bat increases as it moves near the prey. Similarly, the frequency of the bat increases as it moves near the prey. Conversely the loudness of the bat decreases as it approaches the prey. Depending on these Bat Algorithm

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parameters, the size of the DSTATCOM will be updated for each iteration until the optimal size and location of DSTATCOM is reached. Fig. 3 is a simplified flowchart of BA.

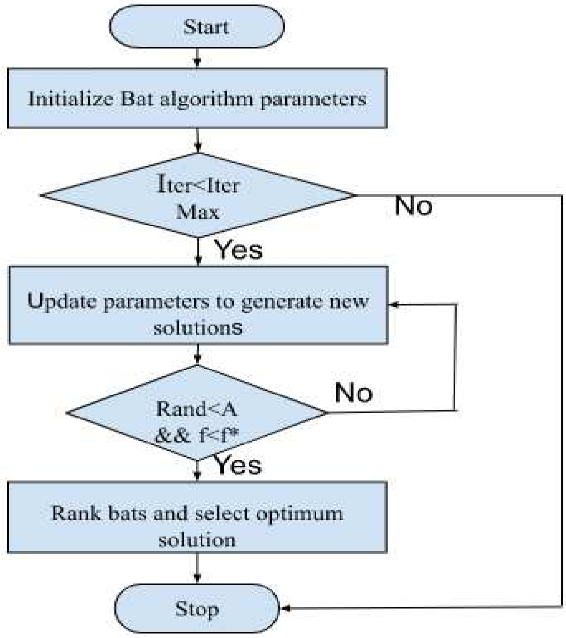

Fig. 3. Simplified BA Flowchart

V. RESULTS AND DISCUSSION

The proposed method is applied in IEEE-118 Bus Test System [14]. A computer program is written in MATLAB R2020a. The program locates optimal location and size of DSTATCOM based on the load model type.

A. System with Constant Power (CP) Load Model

Fig. 4 shows improved voltage profile after optimal DSTATCOM Placement. For the base case, bus 77 has the lowest voltage magnitude value of 0.9042 p.u. After incorporating DSTATCOM using BA, this has been upgraded to 0.9500 p.u. which translates to 5.1 % voltage profile improvement.

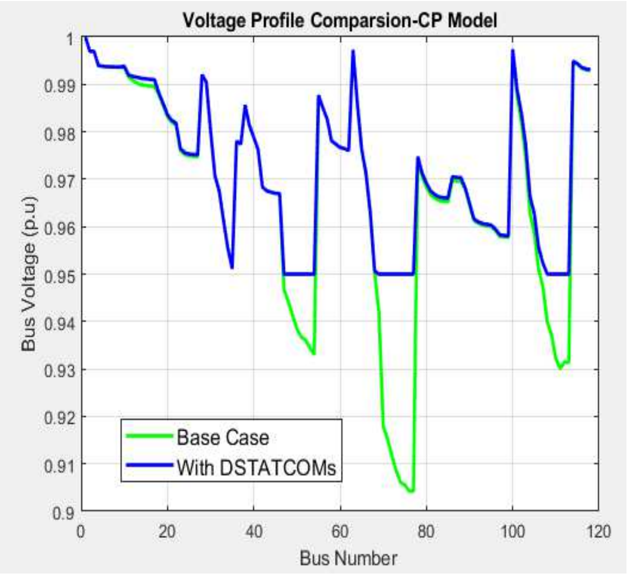

Fig. 4. Voltage Profiles for Constant Power (CP) Load Model

After optimization, when one DSTATCOM is used, 99th bus is selected as the optimal DSTATCOM location. When three DSTATCOMs are used, 21st, 32nd, and 72nd buses are selected as the optimal DSTATCOM locations. As shown in Table I, the system with one optimally placed DSTATCOM has total active power losses reduced by 22%.

Table I: Results Summary for Constant Power Load Model

CP Load Model	Base Case	Single DSTATCOM	Three DSTATCOMs
Total Active Power Loss (kW)	937	730	712
Optimal DSTATCOM Location	…….	99	21,32,72
Optimal DSTATCOM Size (kVAr)	------	860	289,177,748

B. System with Constant Current (CI) Load Model

Fig. 5 shows improved voltage profile after optimal DSTATCOM placement as compared to the base case. Minimum voltage magnitude for the base case occurs at bus 77 and its value is 0.9126 p.u. Incorporating DSTATCOM using BA upgrades this value to 0.950 p. u, which translates to 4.1% voltage profile improvement.

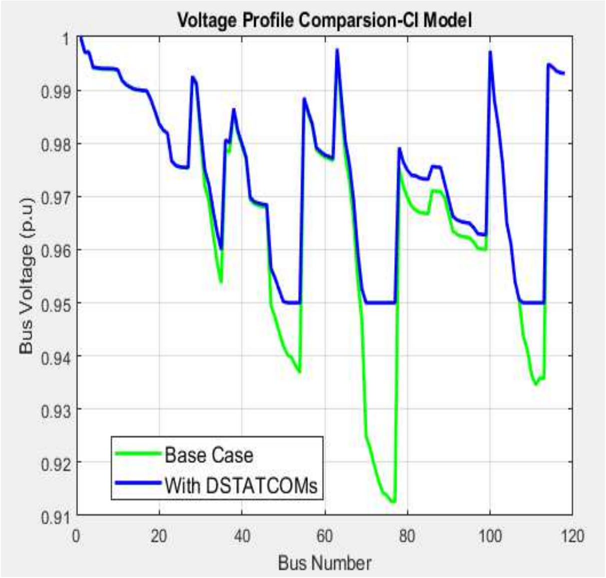

Fig. 5. Voltage Profiles for Constant Current (CI) Load Model

After optimization, 75th bus is selected as the optimal DSTATCOM location when a single DSTSTATCOM is used. When three DSTATCOMs are used, 59th, 87th, and 110th buses are selected as the optimal DSTATCOM locations. As tabulated in Table II, the system with optimally placed DSTATCOM device has total active power losses reduced by 18%.

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Table II: Results for Constant Current Load Model

CI Load Model	Base Case	Single DSTATCOM	Three DSTATCOMs
Total Active Power Loss (kW)	826	677	651
Optimal DSTATCOM Location	-----------	75	59, 87, 110
Optimal DSTATCOM Size (kVAr)	-----------	843	66,449,542

C. *Use of Multiple DSTATCOMs*

For CP load model, using single DSTATCOM reduces the total active power losses by 22% while using three DSTATCOMs reduced the total active power losses by 24%. For CI load model, use of optimally placed DSTATCOM achieves active power reduction of 18% while the use of three optimally placed DSTATCOMs reduces the system's active power losses by 21%. Hence, it can be concluded that using multiple optimally placed DSTATCOM devices in a distribution system is more advantageous than using a single DSTATCOM as illustrated in Fig. 6.

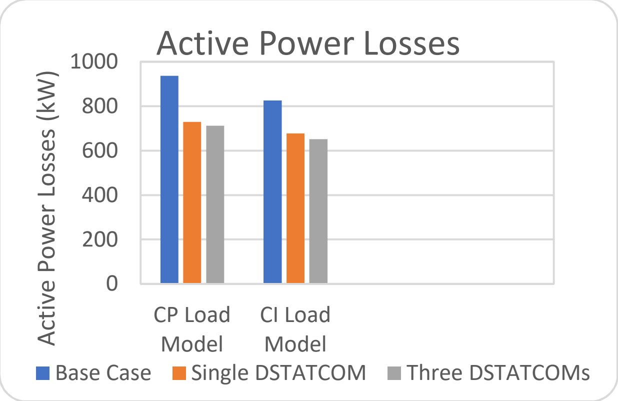

Fig. 6. Active Power Loss Reduction when Single DSTATCOM and Three DSTATCOMs are Used.

D. *Economic Analysis*

For CP load model, the optimal size of DSTATCOM is 860 kVAr. By taking the cost of installing and running DSTATCOM for one year to be $70/kVAr, the annual cost of DSTATCOM becomes $60,200. Introducing a single DSTATCOM reduces active power losses by 207 kW. This translates to annual energy savings of 1,813,320 kWh by assuming 8760 hours in a year. Taking the average global cost of electricity as $0.136 per kWh, the incorporation of DSTATCOM results in annual cost saving of $246, 611.52 which is much higher than the annual cost of installing and running the DSTATCOM. BA has significant economic benefits to the distribution companies.

VI. CONCLUSION

This work proposed Bat Algorithm for optimal sizing and location of DSTATCOM. IEEE-118 bus system is used to test the feasibility of the proposed approach. Constant Power and Constant Current load models have been considered. With the inclusion of cost constraint and use of multiple DSTATCOM devices, power losses in the test system have been significantly reduced upon optimization. Furthermore, voltage profiles for the two selected load models have been improved after optimization, which shows the effectiveness of the proposed technique.

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