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The Optimal Location and Sizing of a Distribution Static Compensator in a New Stochastic Framework

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ABSTRACT

To account for the consequences of uncertainty in the Distribution Static Compensator (DSTATCOM) allocation and sizing issue, this study provides a novel stochastic framework based on the probabilistic load flow. To capture the uncertainty associated with the prediction inaccuracy of the loads, the suggested technique is based on the point estimate method (PEM). In addition, a novel optimization technique inspired by the bat algorithm (BA) is developed for conducting global searches. Minimizing overall active power losses and minimizing bus voltage variation are the objective functions to be studied. The concept of inter-active fuzzy satisfying approach is used in the multi-objective formulation to achieve an appropriate balance between the optimization of both the objective functions. The IEEE 69-bus distribution system is used to evaluate the practicability and satisfactory performance of the suggested technique.

Key words :

DSTATCOM Allocation; Uncertainty; Multi-Objective Optimization; the 2-m Point Estimate Method are all terms that should be familiar to you.

Introduction

Statistics show that outages in the distribution systems are the primary cause of customers being without power [1,2]. For this reason, it is crucial to accurately evaluate any strategy or method that might enhance the distribution systems as a whole in order to maximize efficiency and profit. Utilities companies, in this light, have been exploring novel approaches to enhancing the operation and planning of electrical services across the board. The optimal management of shunt capacitors, shunt reactors, automatic voltage regulators, series capacitors, and, more recently, distribution network flexible AC transmission system (DFACTS) technologies like distribution static compensator (DSTATCOM) [3] are some of the most well-known and popular approaches. DSTATCOM's low harmonic generation, low power losses, excellent regulatory abilities, and compact size set it apart as an effective reactive power compensate tion device [4]. In addition, unlike common reactive power compensation techniques like shunt capacitor placement strategy or series capacitors, the DSTATCOM does not experience any switching-related operating concerns like resonance or transient harmonics. Cleansing the voltage of any imbalance or harmonic distortion is another important function of the DSTATCOM [5]. In reality, the DSTATCOM may make local adjustments to the load demand so that fluctuations in the load are automatically managed. Over time, the electricity grid's aggregate load has increased. Again, the DSTATCOM may be the best tool for minimizing load on the power grid and increasing its stability and reactive power correction. Improved flicker suppression, voltage control, and voltage balancing are just a few ways that power quality is enhanced [6].

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The above explanation makes it clear that the DSTATCOM device may play an important part in the efficient administration and operation of the distribution networks of the future. From the utility's vantage point, the most pressing concern is minimizing resistive losses, which account for the majority of MW power losses [7-10]. Raising the bus voltage to enhance network power quality is another important objective. The electrical services may benefit from a higher bus voltage since it reduces the risk of destroying expensive electrical devices and the frequency with which the system must be restarted. Several texts [11–13] attest to the relevance of this criterion. However, there are still relatively few studies accessible in the field of DSTATCOM allocation to examine its influence on the distribution network from many perspectives. Taking into account active power losses and voltage profile goal functions simultaneously, [14] evaluates the DSTATCOM allocation issue. However, a major flaw in the study that might weaken the dependability of the final conclusions is that it ignores the uncertainty connected with the active and reactive loads. In [15], researchers look on the best way to allocate and size DSTAT COMs to reduce network voltage swings. The optimal DSTATCOM allocation is evaluated while also taking into account the simultaneous impact of the distribution generation (DG). However, once again, this ignores the uncertainty introduced by the random variables.

Definition of the Problem

This section provides a comprehensive description of the goal functions and associated equality and inequality constraints.

Goal-Related Activities

Active power loss minimization (f1): The cumulative resistive power losses of the network's nodes constitute the active power losses objective function. The following equation may be used to get the overall active power losses:

$$f_1(X) = P_{loss}(X) = \sum_{i=1}^{N_{br}} R_i \times |I_i|^2$$

where i is the resistance of i th branch, R i I is the current of i th branch, is the number of branches and X is the control vector. Nbr Minimization of the Voltage Deviation (f2): The voltage profile of the system is improved by reducing the maximum voltage deviation of the buses from the nominal voltage value. Therefore, this target can be evaluated as follows:

$$f_2(X) = d_{volt}(X) = \max\{|1 - V_{min}|, |1 - V_{max}|\}$$

where min and Vmax are the minimum and the maximum value of voltage magnitudes of i th bus. V

Limits and Constraints

Maximum Power Flow Constraint: This limit is associated with the maximum power transfer capacity of the distribution lines which should be observed during the optimization process

$$|P_{ij}^{Line}| < P_{ij,max}^{Line}$$

where is the active power flow over the distribution lines of buses i and j. Also, is the maximum active power flow which is allowed to flow between the buses i and j. Line Pij Line Pij,max Distribution Power Flow Equations: This limitation consists of two power flow equations which can be considered as an equality constraint

$$P_i = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$$
$$Q_i = \sum_{i=1}^{N_{bus}} V_i V_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$$

where i is the voltage magnitude of i th bus, V i δ is the voltage angle of i th bus, ij is the admittance magnitude between the buses i and j, Y θij is the admittance angle between the buses i and j, bus is the number of buses, is the net active power injection to the i th bus and N Pi Q

is the net reactive power injection to the i th bus. Bus Voltage Constraints: During the optimization process, the voltage level of the buses should be preserved in the pre-determined limited values follows :

$$V_{min} \le V_i \le V_{max}$$

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

$$|I_{f,i}| \le I_{f,i}^{max}; i = 1, 2, \cdots, N_f$$

where f ,i is the current of the i th I feeder, max f ,i I is the maximum current of the i th feeder and Nf is the number of feeders.

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Vol 12 Issue 2 April 2022

DSTATCOM Modelling

The Static Synchronous Compensator (STATCOM) as a member of the Flexible AC Transmission Systems (FACTS) devices is a regulating power utility which is connected to the power system in shunt mode. Once the STATCOM is used in the voltage level of distribution system is called Distribution STATCOM or shortly DSTATCOM. The DSTATCOM device works based on the power electronics voltage source converters and can either produce or consume the reactive power of the electrical network at the coupling point. Nevertheless, in the case of using a power source, it can also provide active power simultaneously. In the DSTATCOM, the voltage level is generated from a DC capacitor. Therefore, the direction and amount of reactive power is determined by the magnitude of the voltage source. In the case that the magnitude of the voltage source is higher than that of the connection point, the DSTATCOM will produce reactive power and so will work as a variable capacitor. However, if the magnitude of the voltage source is lower than the voltage of the connection point, the DSTATCOM will work as a reactor and so will absorb reactive power. In the steady state load flow analysis, the accurate DSTATCOM model should consist of the steady state power losses including the transformer and inverter power losses. Technically, the load flow model of the STATCOM is considered to be appropriate for the DSTATCOM device [14]. Therefore, considering the bus I with the active and reactive load values of P jQ Li Li + , the DSTATCOM can be supposed as a new PV bus (we name it bus j) with fixed voltage value which is connected to the bus i. Since we have supposed that there is no power source connected to the DSTATCOM, thus it can just supply reactive power in the network. In the other words, the amount of active power production is assumed zero. In order to model the active power losses of the transformer connection and the inverter, the series

reactance and resistance T T are utilized [4]. The schematic diagram of the model is shown in Figure 1. R jX + S Fz = ( ) , , ; l μ ξσ lk z ·

Uncertainty Modeling

In this section, a stochastic framework based on 2 m PEM is proposed to consider the uncertainty associated with the forecast error of the active and reactive loads. In comparison to the other well-known methods in the area, the 2 m PEM requires little statistical data of the probability density function of the random variables. Mathematically, the load flow equations can be described as follows [15] :

$$S = F(z)$$

w here z is the input uncertain vector and S is the output uncertain vector. The main idea behind the 2 m PEM is to replace the random variable zl (with probability of fzl) with two concentration points zl,1 & zl,2 as follows:

$$z_{l,k} = \mu_{z_l} + \xi_{l,k} \cdot \sigma_{z_l} ; k = 1,2$$

where l μ z is the mean value of the random variable zl and l σ z is its standard deviation. Here ζl,k is called the standard location and is evaluated is as follows:

$$\xi_{l,k} = \frac{\lambda_{l,3}}{2} + (-1)^{3-k} \sqrt{m - \left(\lambda_{l,3}^2/2\right)^2}, k = 1,2$$

The impact of the two locations zl,1 & zl,2 on the output variable is determined by the two weighting factors ωl,1 , ωl,2 respectively. This process is shown in Figure 2. According to Figure 2, the location moments ,1 & l,2 are transferred to the output data l,1 & via Equation (7). Finally, the skewness coefficient l z l,2 z S S (λl,3) as the third central moment is calculated as bellow:

$$\lambda_{l,3} = \frac{E\left[\left(z_l - \mu_{z_l}\right)^3\right]}{\left(\sigma_{z_l}\right)^3}$$

Here E is the expected value. In order evaluate the standard deviation of Si, the bellow equation should be evaluated:

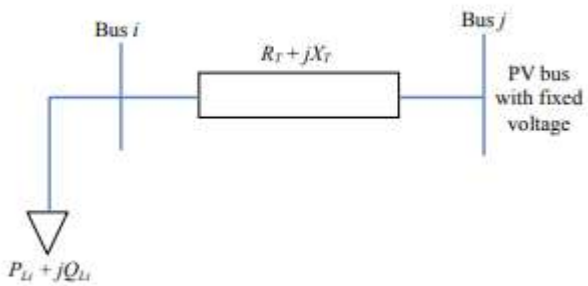

Figure 1. Schematic diagram of DSTATCOM model connected to bus i.

Optimization Technique

In this section, the proposed modified BA as well as the interactive fuzzy satisfying method based on membership function is described.

Original Bat Algorithm

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Vol 12 Issue 2 April 2022

The BA is a population-based optimization algorithm which was first introduced by Xin-She Yang in 2010 [16]. The BA simulates the searching ability of the bat animals for the food by using the echolocation phenomena. In definition, the echolocation is defined as the process of sending a signal to the environment and after that waiting to hear its echo. The BA is based on 3 main ideas [16]: 1) the distance is sensed by the echolocation phenomena; 2) each bat in the search space (Xi) flying with the veloceit of vi will produce a signal with frequency frei, the wavelength Γi and loudness Ai; and 3) it is supposed that the loudness Ai can vary from the initial large value A0 to its specific minimum value Amin . Initially, the BA population is generated randomly. After evaluating the objective function for each bat, the entire population is updated in each iteration k as follows:

$$fre_i = fre_{\min} + \left(fre_{\max} - fre_{\min} \right) \rho$$
$$v_i^{k+1} = v_i^k + \left(X_i^k - X_{gbest} \right) fre_i$$
$$X_i^{k+1} = X_i^k + v_i^{k+1}$$

where max min fre fre are the maximum/minimum values of the bat signal frequency, is the velocity of the i th bat in k th iteration and k i v ρ is a random number in the range [0,1]. Each bat is also updated in another way. In this regard, for each bat, a random value (rand)i is first produced. If is greater than the frequency rate of the relevant bat thus a new test solution is generated

$$X_{new} = X_{old} + \varepsilon A^k$$

where ε is a random number in the range [0,1]. The above formulation is much similar to the particle swarm optimization (PSO) algorithm updating process. On the other hand, if is less than i then a new test solution is generated randomly. The generated test solution is accepted if both the bellow criteria are satisfied:

$$\left[\text{rand} < A_i \right]$$
$$\left[f(X_i) < f\left(X_{gbest} \right) \right]$$

in the above equation, is a random number in the range [0,1]. Also rand gbest is the best bat found in the population. The process of updating X k Ai and in each iteration is as follows:

$$A_i^{k+1} = \alpha A_i^k$$
$$r_i^{k+1} = r_i^0 \left[1 - \exp(-\gamma k) \right]$$

where α and γ are constant values of BA.

Application

In order to apply the proposed stochastic method on the DSTATCOM optimal allocation and sizing, the following steps should be implemented: Step 1: Define the input data including the network data, the DSTATCOM data, the algorithm data, etc.

Step 2: Convert the constrained Multi-objective opti- mization problem to its equivalent unconstraint one using the idea of penalty factors as follows (see Equation (20) below): where h X j ( ) is the j th equality constraint and g j (X) is the j th inequality constraint. Also, Neq and Nueq show the number of equality and inequality constraints respectively. The penalty factors L1 and L2 are employed to meet the equality and inequality constraints. In this paper, the values of penalty factors are assumed 108 .

Step 3: Generate the initial bat population randomly. Each bat indicates a promising optimal location and size for the DSTATCOM devices in the network.

Step 4: Calculate the fitness function. In this step, the stochastic load flow based on 2 m PEM is run to calculate the expected value of the active power losses and the voltage deviation objective functions for each solution or bat.

Step 5: Apply the interactive fuzzy satisfying method to convert the multi-objective optimization problem to the equivalent single objective one. Here the membership function value of each objective function is calculated.

Step 6: Choose the best bat in the population as gbest Step 7: Update the bat population as described in Section 5.1. X . Step 8: Apply the proposed modification as described in Section 5.2. Here again the entire population is updated.

Step 9: Check the termination criterion. The termination criterion can be the maximum number of iterations to update the BA population or a specific value which the objective function should reach to. If it is satisfied then finish the algorithm otherwise return to step 6.

Simulation Results

In this section the simulation results of applying the proposed method on the test system is shown. The test system is the IEEE 69-bus radial distribution system which is chosen from a part of PG&E distribution system. The nominal voltage of the system is 12.66 kV. The amounts of total active and reactive loads which are supplied by the system are 3802.19 kW and 2694.59 kVar respectively. The single line diagram of the test system is shown in Figure 3. The complete data of the test system can be found in [17]

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Vol 12 Issue 2 April 2022

The initial size of the BA population is chosen 15 individuals

The termination criterion is supposed 100 it - erations. The reason for this decision is that there is no

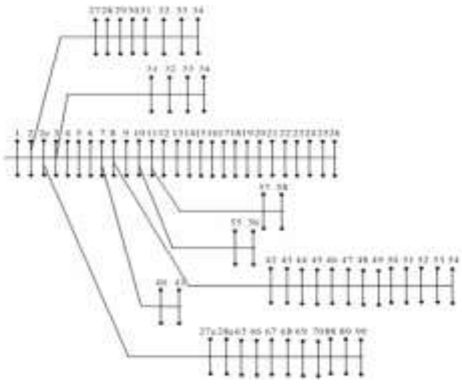

Figure 3. Single line diagram of the test system.

improvement in the objective function values after about 100 iterations. For better comparison, the analysis is implemented in both the deterministic and stochastic frameworks. Also, there are four different cases defined which are shown in the table:

improvement in the objective function values after about 100 iterations. For better comparison, the analysis is implemented in both the deterministic and stochastic frameworks.

Also, there are four different cases defined which are shown in the table:

Case 1: Initial system condition neglecting DSTATCOM

Case 2: DSTATCOM allocation and sizing for optimizing the total active power losses objective function

Case 3: DSTATCOM allocation and sizing for optimizing the maximum voltage deviation objective function Case 4: DSTATCOM allocation and sizing for optimizing both of the total active power losses and voltage deviation by the proposed interactive fuzzy satisfying technique In the first step, in order to see the satisfying performance of the proposed modified BA, a complete comparison is made with the other well-known methods in the area.

The simulation results are shown in Table 1. According to the Table 1, the superiority of the proposed method over the other well-known methods is evident. In order to see the positive effect of considering DSTATCOM in the system clearly, two different operating conditions (OCs) are defined. In the first OC, just 1 DSTATCOM is allocated in the system while in the second OC two DSTATCOMs are allocated. The maximum capacity of each DSTATCOM is 3 MW. The simulation results for the OC 1 and for all the four Cases in the deterministic framework (neglecting the uncertainty effects) are shown in Table 2. The word NG in the table means that negative power loss reduction (increase in the power loss) has happened. As it can be seen from Table 2, in the Case 2, the amount of active power losses is reduced effectively. This amount of power loss reduction equals about 33.245 percent of the initial power losses which means notable value.

Also as it is seen, in this case, the voltage profile of the buses is improved as an indirect result of reducing resistive losses in the network. In the Case 3, the main target is optimizing the voltage deviation of the buses which has resulted to increasing the minimum voltage of the network. Here the amount of active power loss reduction is reduced to about 19.6460 percent. Finally, in the third case, the proposed interactive fuzzy satisfying method could reach proper tradeoff between the active power losses and the voltage deviation. In fact, as it is seen from Table 2, the proposed multi-objective formulation has

Table 1. Simulation results of optimizing active power losses and voltage deviation objective function for 20 trails (OC 1).

Items	Optimizing power losses	Optimizing Voltage Deviation	Mean CPU Time
GA	151.67002	0.04555001	11.358
PSO	150.23882	0.04535289	10.102
Original BA	150.23882	0.04500756	10.093
Proposed MBA	150.19693	0.04485347	8.876

Table 2. Results obtained by optimal DSTATCOM allocation and sizing in the deterministic framework (OC 1).

Items	Case 1	Case2	Case 3	Case4
Active power losses (kW)	225.0	150.19696	269.28406	172.68408
Loss reduction (%)	———	33.245805	NG	23.251505
V_{min} (pu)	0.90944095	0.95092967	0.95514622	0.94171583
V_{max} (pu)	1	1	1	1
Voltage Deviation (pu)		0.06907032	0.04485347	0.0582841
DSTATCOM size (MW)	———	1.326	3	2.946
DSTATCOM location	———	61	65	62

optimized both of the objective functions suitably. Therefore, when the maximum bus voltage deviation of the system is improved to the appropriate value of 0.0582841 pu, the amount of power losses is reduced to the optimal value of

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Vol 12 Issue 2 April 2022

172.684 kW. By comparing the optimal size of the DSTATCOM in different cases, it is deduced that better voltage profile is achieved for higher values of reactive power compensation by the DSTATCOM but with the cost of incremental losses. This result shows the necessity of accurate sizing and allocating of the DSTATCOM in the system.

Conclusion

The aim of this article was to determine where and how big a DSTATCOM device should be installed in a distribution network. A novel stochastic optimization framework was proposed to address this issue; it is built on the 2 m PEM and the Modified BA. The concept of an interactive fuzzy satisfactory approach is used to deal with the two major goal functions of active power losses and the voltage variation. The simulation findings shown that the system condition may be significantly enhanced by integrating the DSTATCOM, a well-known Facts device. However, increasing the number of DSTATCOM in the system does not appear to have any direct effect on the objective functions. The simulation results showed that in the IEEE 69-bus test system, the amount of growth in the objective function values for just 1 DSTATCOM is more than that for using 2 DSTAT COM. The suggested stochastic framework has the potential to lessen the impact of uncertainty by lowering the standard deviation of the best solutions.

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