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# A new technique for optimal allocation and sizing of capacitors and setting of LTC

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ABSTRACT

An iterative based strategy is proposed for finding the optimal rating and location of fixed and switched capacitors in distribution networks. The substation Load Tap Changer tap is also set during this procedure. A Modified Discrete Particle Swarm Optimization is employed in the proposed strategy. The objective function is composed of the distribution line loss cost and the capacitors investment cost. The line loss is calculated using estimation of the load duration curve to multiple levels. The constraints are the bus voltage and the feeder current which should be maintained within their standard range.

For validation of the proposed method, two case studies are tested. The first case study is the semi-urban 37-bus distribution system which is connected at bus 2 of the Roy Billinton Test System which is located in the secondary side of a 33/11 kV distribution substation. The second case is a 33 kV distribution network based on the modification of the 18-bus IEEE distribution system. The results are compared with prior publications to illustrate the accuracy of the proposed strategy.



## 1. Introduction

Capacitors are used commonly in distribution systems to minimize the reactive component of line current. This compensation reduces the distribution line loss and improves the voltage profile. Particularly in the peak load, reduction of the line loss by capacitors can prevent additional investment for using high rating equipment. In order to minimize the capacitors cost and the line loss and to improve the voltage profile simultaneously, the Optimal Allocation and Sizing of Fixed and Switched Capacitors (OASFSCs) problem should be solved. During this procedure, Load Tap Changers (LTCs) tap is also set to minimize the line loss and improve the voltage profile.

Modeling loads in the capacitor planning problem is a main issue. Some papers allocate and size the capacitors based on the average load level [1–8]. Since the line loss is proportional to the square of the rms current, calculation of the average distribution line loss based on only the average load level is not correct. Also, it is not feasible to calculate the line loss for all levels of loads since this needs to do optimization for hundreds times. To avoid this problem, loads should be modeled using an approximation of the load duration curve in multi-level.

Selection of the optimization algorithm is another important aspect in OASFSC problem. Due to the discrete nature of the allocation problem and the discreteness of the capacitors' size, a number of local minima are present in the objective function. This creates a risk of being caught in local minima. Using the analytical based tools as optimization methods does not improve this problem. That is why only a few papers are based on this philosophy [9–12]. To deal appropriately with this difficulty, the heuristic based optimization methods are quite common in literatures [1–8,13–19]. The Particle Swarm Optimization (PSO) [20,21] is a well-known heuristic based method. In this paper, the discrete version of PSO called Discrete Particle Swarm Optimization (DPSO) [22] is modified and employed.

In [1–8], the capacitors are optimized using the heuristic methods for one specific load level. This assumption is improved in some papers by modeling the loads in multi-level. In [9,13,15,17,19], the capacitors are optimized for each load level sequentially. In [10–12], the OASFSC problem is solved separately for each load level and then, the minimum optimal capacitor size among all load levels at a bus is supposed as the fixed capacitor size and the rest as the switched capacitor size at the relative bus. Whereas the computation time is the main advantage of these two multi-level load-based methodologies, the capacitors calculated for the higher load levels are not included in the lower load levels computation while this likely reduces the total investment cost further. Another group of the available literatures [4,14,16,18] proposes an algorithm in which the capacitors in all load levels are optimized simultaneously. Dealing with a large number of optimizing variables is the main drawback in these methods which leads to a high computation time and low accuracy. These mentioned problems highlight the need for an algorithm with appropriate accuracy and reasonable computation time.

In this paper, a new strategy is proposed to determine the optimal placement and rating of fixed and switched capacitors in

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**Table 1**
Characteristics of the test system.

| No. of loads | Customer type | Load points | Average load level (MW) |
|---|---|---|---|
| 9 | Residential | 1–3,10–12,17–19 | 0.50 |
| 5 | Commercial | 6–7,15–16,22 | 0.45 |
| 6 | Government | 4–5,13–14,20–21 | 0.57 |
| 2 | Industrial | 8–9 | 1.10 |

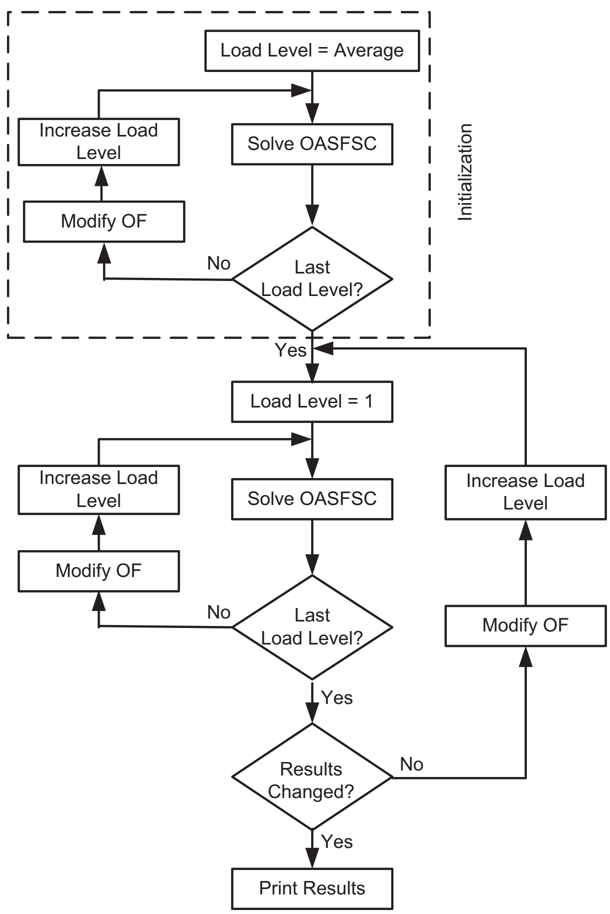


**Fig. 1.** Flowchart of the proposed algorithm.

distribution networks. In this iterative-based strategy, the capacitors calculated for higher load levels are re-used to modify the size and location of the capacitors obtained for the lower load levels in each iteration. During this procedure, the tap of LTC located at the substation is also set. The objective is to minimize the distribution line loss cost and the capacitors investment cost. The bus voltage and the feeder current as constraints are maintained within their standard range.

This paper is organized as follows. The problem formulation is presented in Section 2. Sections 3 and 4 explain the methodology as well as the optimization method and its implementation to the problem. The results and conclusions are expressed in Sections 5 and 6.

## 2. Problem formulation

The main objective of OASFSC problem is to minimize the total cost of capacitors as well as the distribution line loss. The bus voltage and the feeder current are also limited as the constraints and added to the objective function with a penalty factor. Since all of the objective function elements are simply converted into the composite equivalent cost, this problem can be solved using a single-objective optimization method. The objective function is defined as follows:

$$OF = C_{CAPITAL} + \sum_{t=1}^{T} \frac{C_{O\&M+C_{LOSS}}}{(1+r)^t} + \lambda \tag{1}$$

where $C_{CAPITAL}$ and $C_{O\&M}$ are the capital cost and the operation and maintenance cost of fixed and switched capacitors, $C_{Loss}$ is the line loss cost, $r$ is the discount rate, $T$ is the number of years in the study timeframe which is assumed 20 years here, and $\lambda$ is the constraint penalty factor.

The line loss cost is expressed in (2):

$$C_{LOSS} = k_L \sum_{l=1}^{LL} T_l \cdot PLoss_l + k_{PL} \cdot PLossLL \tag{2}$$

where $k_L$ is the cost per MWh, $T_l$ is the duration of load level $l$, $PLoss_l$ is the line loss in load level $l$, $LL$ is the number of load levels, $PLoss_{LL}$ is the line loss in the peak load level, and $k_{PL}$ is the saving per MW reduction in the peak load.

The constraints include the bus voltage and the feeder current. The bus voltage as the first constraint should be maintained within the standard level as defined in (3):

$$0.95\ \text{pu} \leqslant V_{bus} \leqslant 1.05 \tag{3}$$

where $V_{bus}$ is the actual bus voltage. The feeder current as the second constraint should be less than the feeder rated current as expressed in (4):

$$I_f \leqslant I_f^{rated} \tag{4}$$

where $I_f$ and $I_f^{rated}$ are the current and the rated current of a feeder, respectively.

## 3. Methodology

The algorithms presented for solving the OASFSC problem can be categorized into four main groups. Group1 [1–8] is related to the algorithms in which the capacitors are optimized for one specific load level. Consideration of one load level probably does not guarantee the accurate results. In group2 [9,13,15,17,19], the capacitors are allocated and sized from the lowest load level to the peak load level. The capacitors optimized in a load level are assumed as the fixed capacitors in optimization procedure of the next load level. Finally, the capacitors calculated in the lowest load level will be the fixed capacitors and those added to the fixed capacitors in other load levels are assumed as the switched capacitors. This strategy is called Building Strategy in this paper. In this strategy, the capacitors obtained for higher load levels are not used for lower load levels while some of them probably minimize the line loss much more without applying any extra cost. Group3 [10–12] is related to the methods in which the capacitors are obtained in all load levels separately and then, the minimum capacitor rating at a bus is assumed as the fixed capacitor, and the rest as the switched capacitors at the corresponding bus. This strategy is called Separating Strategy in this paper. This strategy causes using a large number of capacitors so high investment cost.