Optimum shunt capacitor placement in distribution system—A review and comparative study

M.M. Aman, G.B. Jasmon, A.H.A. Bakar, H. Mokhlis, M. Karimi

Abstract

Shunt capacitors are commonly used in distribution system for reactive power compensation. Different analytical, numerical programming, heuristic and artificial intelligent based techniques have been proposed in the literature for optimum shunt capacitor bank (SCB) placement. This paper will present a very detailed overview of optimum SCB placement techniques. Six different approaches of optimum SCB placement based on minimization of power losses, weakest voltage bus approach and maximization of system loadability will be applied on four different radial distribution test systems. The results will be compared on the basis of power loss reduction, voltage profile improvement, system loadability maximization and the line limit constraint.

1. Introduction

Prior to 1950s the shunt capacitor banks (SCB) were placed nearer to the main substation for capacitive reactive power compensation, it helps in improving the power factor, reduces I^2R power losses and improving the voltage profile. SCB changes the power losses up to the point of coupling, however to get the maximum benefit it must be placed as nearer to the load as possible. With the availability of pole mounted equipment including SCB, the trend has changed. The capacitor banks are now placed on primary distribution lines as well [1–5]. The capacitor unit is considered as the basic building block of SCB. Capacitor units are connected in paralleled-series combinations and

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Voltage stability
form a single-phase capacitor bank, within a steel enclosure. The series combination reduces the cost of dielectric while parallel combination increase the total capacitance of SCB. As a general rule, the minimum number of units connected in parallel is such that isolation of one capacitor unit in a group should not cause a voltage unbalance more than 110% of rated voltage on the remaining capacitors of the group. Equally, the minimum number of series connected groups is that in which the complete bypass of the group does not subject the others remaining in service to a permanent overvoltage of more than 110% [2]. The amount of reactive power (QC) from capacitor depends on applied voltage (V) and capacitive reactance (XC), given by Eq. (1) [6].

\[ QC = \frac{V^2}{XC} \]  

The recent power system blackouts [7,8] due to insufficient reactive power have also resulted in focused towards meeting reactive power demand of the system locally using static capacitor banks. The combined US Canada task force on August 2004 blackout also concluded that the reactive power supplies in Northeast Ohio were exhausted which resulted in loss of several critical bulk power supply systems and helped cascaded generator interruptions [9]. During low voltage emergencies e.g. generator rescheduling, line restoration or operated directed load tripping, the author in [10,6] proposed shunt capacitor bank series group shorting (CAPS) method. CAPS shorted section increases the reactive power supplied during periods of low voltages by shorting several series groups of capacitor units \( QC = \frac{V^2}{XC} \). The shorted section in CAPS comprises of 20% to 33% of total bank. The detailed study and feasibility of CAPS on EHV and HV network are also presented in [11]. In case of highly loaded systems, it is believed that the optimum capacitor placement solve the mini- 

mization of losses more adequately and optimum setting of voltage regulators solve the voltage drop problems in a better manner [3].

The need for reactive power support in distribution system may be arises due to the following reasons.

1.1. Maximizing the distribution system efficiency

Distribution system usually suffers from two major problems, high power losses and poor voltage profile. Losses are defined as the difference between the energy into the system and the energy that is utilized by the end users. Generally electric system losses can be categorized as technical or non-technical losses [12,13]. Technical losses in distribution system occurs at different stages from the main substation till the consumer end, including substation transformer, primary lines, line equipment voltage regulators and surge arrestor, distribution transformer, secondary lines and consumer services. The loss calculation methods at different stages are discussed in detail in [14]. Electric Power Research Institute (EPRI) and Energy Information Administration (EIA) of U.S. concluded that [14,15]:

1. The distribution losses range from 33.7% to 64.9% of the total system losses.
2. About 7% of the total electricity production is transmitted in the United States as transmission and distribution losses [15].
3. EPRI research on 42 distribution circuits estimated that 54% of total losses are occurring in distribution transformer (although the efficiency of distribution transformer lies above 99%) and 38% of total distribution losses are occurring in primary lines, as shown in Fig. 1. One of the major reason for such a high losses in distribution transformer is total number of distribution transformer placed in distribution system [14]. In 2003, it is estimated that there are 50 million distribution transformers in use in United States [16].

With such a higher power losses in distribution system, it is highly necessary to reduce the line losses occurring in primary line as much as possible. The higher losses results in limiting the line capacity (thermal limits) as well as higher voltage drop (voltage limits) in the power system. In literature it has also been concluded that the maximum loading of the distribution system is limited by the voltage limit rather than the thermal limit [17]. Large power consumers also installed shunt capacitor to improve the overall power factor and thus save the cost of poor power factor penalty. Three different compensation techniques are available in literature including individual compensation: group compensation and centralized compensation to improve the power factor. Any one of the method or all of the method can be utilized to take the maximum advantage of improved power factor [18]. For power factor improvement, an unloaded synchronous motor can also be used instead of shunt capacitor. The amount of reactive power is controlled from its excitation system and thus it behaves like a variable capacitor [19]. Now-a-days, manufacturers are bound to design electrical equipment with higher efficiency and high power factor [20].

1.2. Reactive power management in deregulated power market

With the restructuring of power system, the complexity of power system has been increased. The vertically integrated power system has been separated into GenCos, TransCos, and DisCos. A central regulating company Independent System Operator (ISO) and Regional Transmission Organizations (RTO) has been formed for maintaining the quality, reliability and security of electric service [21,22]. It is also a fact that the existing transmission systems in most of the countries are quite old. For example in United States, the 345 kV bulk transmission system and associated substation, cables and wires are 40 years old and above [23]. Such a system is not able to meet the growing demand and transfer the generated power from the centralized generation to the distribution system. Transmission investment has been falling for a quarter century at an average rate of almost US$50 million a year (in constant 2003 U.S. dollars), however there has been a small upturn in the last few years [23]. Other than constructing new transmission lines there are other options to release the transmission system congestion including distributed generator placement, static capacitor bank, FACTS (Flexible AC Transmission Systems) devices, voltage regulators and energy conservation [24,25]. It is also a fact that the generation the addition of extra kVAR on a generator operating at 0.9 power factor decreases the amount of real power output by about half a kilowatt [26]. Thus in restructured power market, the generator companies prefer to generate maximum active power (kW) and get maximum profit ($).

The reactive power (kVAR) market is not as simple as real power (kW) market. The fundamental difficulty with reactive power markets is that reactive power does not “travel” far, thus it is expected there would be extreme local geographical market
power in the provision of reactive power [27]. This philosophy of reactive power market suggests the following things [26]:

1. The generator should maintain close to unity power factor under normal conditions using capacitor bank. However generator dynamic response is used to provide reactive reserves in case of contingency.
2. The distribution system must have enough reactive power support so that distribution feeders have a net unity power factor or even slightly leading power factor at low loads and so that transmission system steady state reactive power is essentially all provided by transmission system capacitors.

1.3. Reactive power management in presence of distributed generation

Electric power generation that is integrated within the distribution systems are known as "distributed" or "dispersed" generation (DG). The DG source or technology can be a traditional combustion generator (such as diesel reciprocating generator and natural gas-turbine) and non-traditional generator including fuel cell, storage device and renewable energy source (such as wind turbine and photovoltaic). Non-utility companies are investing in distribution system to meet the active power demand (MW) and get the maximum profit. For example in United States the percentage of nonutility generators (NUGs) has increased from 40GW to more than 150 GW in 10 years from 1990 to 2000 [28–32].

DGs are mainly considered as active source of energy [33], however at higher system loading with maximum DG penetration, the poor voltage profile can be a big challenge for the system operator thus the reactive power compensation approach must be utilized to maintain the voltages in allowable limits [34]. In restructured power system, the system operator is responsible to maintain the allowable voltages by call upon the GENCOs to produce more or less reactive power, by adjusting the field current, by adding or removing reactive power devices (capacitor and reactors) or changing the tap changer position on the transformer. The author in [35] has analyzed the importance of reactive power in presence of DG and conclude that the presence of DG may results in voltage rise problem at light load, thus the voltage regulating device must be also presented. The energy curtailment from DG is not a good solution as this will result in revenue lost. DG presence in the system also affects the reactive power management plan. For example in case of wind generation, asynchronous induction generators are used. Such generators need reactive power from the system to which they are connected. Different methods of reactive compensations are stated in literature [36] including synchronous generator, shunt capacitor banks and end-user reactive power compensation within the reactive power consumption equipment. Here it is also need to be mentioned that the growing trend of using non-conventional power generation (using wind and solar energy) has led to the bounding that the renewable energy generation must also play their role in improving the voltage profile and providing necessary reactive power support. Now-a-days state of the art technology has come out, the wind generation is now using double fed induction generator and PV inverters are using special self-commutated line inverter, capable of absorbing and supplying reactive power at different system loading. The reactive power capability of solar and wind power plants can be further enhanced by the addition of SVC, STATCOMS and other reactive support equipment at the plant level. Currently, inverter-based reactive capability is more costly compared to the same capability supplied by synchronous machines [37–39].

Thus the importance of reactive power compensation has been significantly increased due to restructuring of power market and conversion of passive network to active network. Utilities are also focussing towards reduction in power losses and utilizing the distribution lines efficiently. SCB being the low initial cost, no maintenance and no personnel cost is the most cost effective solution for reactive power compensation. Section 2 will present a detailed overview of capacitor bank placement techniques stated in the literature. The non-optimum placement or sizing of SCB may result in increased power losses as losses versus capacitive MVAR follows the deep bath curve relationship [40]. Thus it is necessary to optimally place VAR equipment in the distribution system.

2. Optimum shunt capacitor placement techniques—A review

In literature, different authors have proposed different methods considering different fitness function including minimization of power losses, reduction in installation cost, improvement in voltage profile, lessen the burden on existing lines, maximization of system stability and others. Shunt capacitors are placed in a combination of fixed and switched (variable) capacitor banks. The size of fixed capacitor bank depends on average reactive power demand of the system while switched capacitor banks supply difference of current reactive power demand and fixed capacitive power available. Special control mechanism is used to control the switched capacitor bank power. Shunt capacitors (Qc) are available in market in discrete sizes which are multiple (k) of smallest capacitor size (Qmin), given by Eq. (2) [41,42]. However authors have proposed such methods which results in both continuous and discrete capacitor size. In case of continuous capacitor size, it will be assumed that the capacitor size will be a combination of fixed and switched capacitor.

$$Q_c = k \times Q_{\text{min}}$$

The capacitor placement problems from the literature can be categorized into analytical methods, numerical programming methods, heuristic methods and artificial intelligent methods. Authors have also combined the capacitor problem with other power system problems including distributed generation, network reconfiguration and voltage regulator.

2.1. Analytical methods

In earlier time, when powerful computing resources were unavailable or expensive, the author proposed calculus based analytical algorithm. The authors have also made some approximation in order to reduce the computation procedure. Analytical methods have also been proposed in optimum capacitor placement and sizing. The initial work was carried out by Neagle [1] in 1956 for optimum single and multiple capacitor bank in case of uniform and non-uniform distribution of load. He suggested that in uniformly distributed load the capacitor bank must be placed at 1 – (1/2) (capacitive kvar/system kvar) distance from the main substation. Cook worked on the same guideline of [1] and proposed a more practical algorithm for fixed capacitor bank for uniformly distributed considering average reactive load in the system [43]. Cook [43] suggested that the optimum location of SCB must be 2/3 (Reactive load factor). Cook extended his work in [44] to include switched capacitors. Later on several other analytical based methods have been proposed for the capacitor placement [45,46]. Schmill [47] extended the work of Cook [43]. Equations are
given for sizing and placement of n capacitors on a uniform feeder with a uniformly distributed load. The necessary conditions for optimal sizing and placement of one or two capacitors on a feeder with discrete loads and non-uniform resistance are presented. An iterative approach is suggested to solve the problem. Chang et al. [48,49] assumes a feeder with a uniform load and a concentrated end load. Accounting for both peak power losses and energy losses, he determines the optimal location of a fixed capacitor and the resulting savings, given the capacitor size. The optimal solution is determined by considering each of the available capacitor sizes.

Analytical methods are considered as simple methods, however implication of such methods to solve the capacitor placement problem required all assumptions (e.g. load variation neglected) and scenarios (e.g. distributed non-distributed) as considered by the author in developing that algorithm. The author in [50] has indicated that the famous “2/3 rule” may result in negative saving if considered in different scenario. Here it is also noted that most of the analytical methods discussed earlier considered modelling of the capacitor placement locations and sizes as continuous variables. Therefore, the results would need to be rounded up or down to the nearest practical value, which may result in an overvoltage problem or loss savings ($) less than the calculated one. The more recent analytical methods [46,51–54] are much more accurate and practical for distribution systems.

2.2. Numerical programming methods

Numerical Programming is a technique by which mathematical problems are formulated so that they can be solved with arithmetic operations. Numerical programming methods are iterative techniques used to maximize (or minimize) an objective function of decision variables. The values of the decision variables must also satisfy a set of constraints. With the availability of fast computing skills and large memory availability, the utilization of numerical methods in power systems has increased [55,56]. In optimum capacitor location problem, authors have formulated different mathematical models and have utilized numerical methods to solve the problem. Duran in [57], have used the dynamic programming approach and implemented the Schmil work [47] of uniformly and randomly distributed load to find the optimum capacitor placement. The formulation in [57] is simple and only considers the energy loss reduction and accounts for discrete capacitor sizes. Fawzi et al. [58] extended the work of [57] and included the released kVA into the savings function. Ponnavisikko and Rao [59] used a numerical method called the method of local variations and further expanded the problem to include the effects of load growth, and switched capacitors for varying load. Lee [50] has proposed iterative based optimization technique considering net monetary saving as convergence criteria in optimum placement of fixed and switched capacitor banks. Later on Baran and Wu [60,61] used the mixed integer programming approach to solve the capacitor problem. Sharaf used the full load flow model to find the optimum shunt capacitor placement in distribution system. He mentioned that the equivalent model proposed in [62] is not useful in finding optimum SCB location as the receiving-end voltage on a distribution system decreases quadratically as system load increases [63]. Khodr [64] solved the SCB problem using mixed-integer linear problem and considered overall energy saving as fitness function.

2.3. Heuristics methods

Heuristics methods are “hints”, “suggestions”, or “rules of thumb” based methods that are developed through intuition, experience, and judgment. Heuristic methods produce fast and practical strategies which reduce the exhaustive search space and can lead to a solution that is nearer to the optimal solution with confidence [65,66]. Heuristic based techniques are also commonly used to solve shunt capacitor placement problem. [3,67–71]. Abdel-Salam et al. [67] proposed a heuristic technique based on identifying the sensitive node and placing such capacitor bank (size) giving the greatest loss reduction due to capacitor placement. Chis et al. in [68] extended the work of [67] and considered cost of capacitor bank (size) from both energy and peak power loss reductions. In [69], the author has evaluated bus-bar sensitivity index to decide the capacitor position(s), sigmoid function is utilized to find the discrete value of capacitor size. In latest research [70], the author has used node voltage stability index to find the candidate bus for capacitor position and maximization of net savings from power loss reduction and the capacitors investment as optimum capacitor size. In [40], the author has considered the end of the weakest line as the potential candidate for optimum shunt capacitor placement and capacitor size is selected corresponding to the minimum power losses using PSO algorithm. In [71], the author has used direct search algorithm to determine the optimal sizes of fixed and switched capacitors together with their optimal locations in a radial distribution system so that net savings are maximized and improvement in the voltage profile is achieved.

2.4. Artificial intelligent methods

The simplest of search algorithms in optimization is exhaustive search that tries all possible solutions from a predetermined set and subsequently picks the best one. However such methods are considered as non-efficient in terms of computation time and space requirement. Intelligent, greedy and nature observed heuristic techniques have also been proposed in literature [72], commonly known as artificial intelligent (AI) methods. AI methods are a special class of heuristic search methods [72]. Intelligent based optimization methods have also been utilized in finding optimum shunt capacitor location and sizing. Authors have used genetic algorithms (GA) [3,73–77], fuzzy, immune algorithm [80,81], Tabu search [82], fuzzy-GA [83], particle swarm optimization [84], plant growth simulation algorithm [41,85], memetic-algorithm approach [86], teaching learning based optimization algorithm [87], ant colony [88], graph search algorithm [89] and hybrid algorithm [90–92].

In [93], the author has used non-dominated sorting genetic algorithm (NSGA) to solve multi-criteria problem in capacitor placement. A multi-criteria optimization problem requires simultaneous optimization of a number of objectives with different individual optima [11,14]. Objectives are such that none of them can be improved without degradation of another. Hence, instead of a unique optimal solution, there exists a set of optimal trade-offs between the objectives, the so-called pareto-optimal solutions. The author in [94,95] has presented an algorithm for optimizing shunt capacitor sizes on radial distribution lines with non-sinusoidal substation voltages, such that the rms voltages and their corresponding total harmonic distortion lie within prescribed values. The result shows that the optimal capacitor sizes found by neglecting the harmonic components may result in unacceptable voltage distortion levels. In [96], the author has considered the presence of non-linear load in distribution system in solving the optimal capacitor placement problem. The authors has used PSO to search for optimal locations, types, and sizes of capacitors to be placed and optimal numbers of switched capacitor banks at different load levels. In [97], the author has solved the problem of capacitor placement using genetic algorithm (GA) in the presence of voltage and current harmonics. The author has claimed that the proposed method results in lower THDV and greater annual benefits as compared to [98–100]. Presently AI methods are
considered as the most powerful methods in solving many power system problems including single-objective-multi-constraints, multi-objective-multi-constraints or multi-criteria-pareto-optimal problems. However in large system, AI methods suffers from high computation time and large memory space requirement, in such cases hybrid methods are considered more powerful.

2.5. Multi-dimensional problems

In multi-dimensional problems, the authors have combined the capacitor placement problems with other power system problems including network reconconfiguration [101–107], DG placement [108–111], voltage regulators [112–118] and load tap changer [119]. The author in [112–114] considered the capacitor placement problem a multi-dimensional problem and incorporated the voltage regulator placement in addition to control the volt/var. The author in [120] has combined different type of DGs, shunt capacitor and network reconfiguration in a single problem and stated that power losses are significantly reduced when all three objectives are solved simultaneously.

In next section (Section 3), six different methods based on minimization of power losses, weakest voltage bus and maximization of system loadability for optimum shunt capacitor placement will be presented and discussed in detail.

3. Comparative study

In this section, six different methods for optimum shunt capacitor placement and sizing are compared on the basis of power losses reduction, voltage profile improvement, maximization of system loadability and line limit constraint, summarized in Table 1. Following constraint, given by Eqs. (3) and (4) is used throughout the analysis:

Position of SCB: $2 \leq Q_{SCB}$ Position $\leq nbus$ (3)

Size of SCB: $Q_{SCB} \leq \sum_{i=1}^{nbus} Q_i$ (4)

where $nbus$ is total number of buses and $Q_i$ is the reactive power load at bus $i$.

The brief overview of methods is discussed below:

Method 1: Analytical method [121]

In analytical approach, a loss sensitivity factor $(\partial P_{loss}/\partial P_i)$ is formulated for the determination of the optimum size and location of capacitor bank to minimize total power losses. Like other methods, analytical method does not use admittance matrix, inverse of admittance matrix or Jacobian matrix. This method is based on the equivalent current injection that uses the bus-injection to branch-current (BIBC) and branch-current to bus-voltage (BCBV) matrices.

Method 2: Grid search algorithm [122]

In grid search algorithm, shunt capacitor is added to each bus and the size of capacitor is changed from 0% to 100% of total connected load in small steps. Minimization of losses is considered as the objective function. For this purpose, successive load flow methods are used for each step of capacitor size. The main constraints are to restrain the maximum capacitor size selected as total load size.

Method 3: Golden section search algorithm [122]

In golden section search algorithm, the searching space is decreased by checking some discrete values of capacitor size only, in every iteration. Minimization of losses is considered as an objective function. The main constraints are to restrain the maximum capacitor size selected as total load size.

Methods 1–3 is implemented using the MATLAB based voltage stability and optimization programming (VS&OP) tool [122].

Method 4: Optimum shunt capacitor placement and sizing based on min of losses using PSO

In this method, the optimum location and optimum size is determined simultaneously using particle swarm optimization (PSO) algorithm. PSO has advantage over other methods in terms of simplicity, fast convergence as compared to other algorithms (e.g. genetic algorithm) [123,124]. The brief overview of PSO method is presented in the appendix. Minimization of active $P_R$ power losses $(P_i)$, given by Eq. (5) is considered as fitness function.

$$f = \text{Min} \left\{ P_i = \sum_{i=1}^{nbus} |i| i^2 R_i \right\}$$

where $l$ is the line current, $R$ is the resistance of branch $i$, $nbus$ is total number of branches.

Method 5: Hybrid method based on weakest line and minimization of power system losses using particle swarm optimization

In this method, the SI index proposed in [125] is utilized to find the weakest voltage bus in power system which could lead to voltage instability, when the load will cross the critical limit. The value of index is given by Eq. (6) and termed as stability index (SI).

$$\text{SI}(r) = |V_i|^2 - 4 \times |P_i x_{ij} - Q_r^2| - 4 \times |P_i r_i + Q_r x_{ij}|^2 \times |V_i|^2 \geq 0$$

where $V_i$ is sending end voltage, $P_i$ is active load at receiving end, $Q_i$ is reactive load at receiving end, $r_i$ is resistance of the line $i-j$, $(ij)$ is reactance of the line $i-j$.

Under stable operation, the value of SI should be greater than zero for all buses. When the value of SI becomes closer to one, all buses become more stable. In this algorithm, SI value is calculated for each bus in the network and sort from highest to lowest value. For the bus having the lowest value of SI, the SCB will be placed at that bus. Once the SCB location has been identified, the size of capacitor bank is calculated based on minimization of active $P_R$
Table 2  
Base case (before capacitor placement).

<table>
<thead>
<tr>
<th>Test system</th>
<th>P-loss (MW)</th>
<th>System loadability</th>
<th>V_{max}/V_{min}</th>
<th>Sum (V/L)</th>
<th>Weakest voltage bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>12-Bus</td>
<td>0.0207</td>
<td>5.32</td>
<td>1/0.9439</td>
<td>0.4204</td>
<td>12</td>
</tr>
<tr>
<td>30-Bus</td>
<td>0.8819</td>
<td>2.79</td>
<td>1/0.8825</td>
<td>8.0290</td>
<td>27</td>
</tr>
<tr>
<td>33-Bus</td>
<td>0.2110</td>
<td>3.41</td>
<td>1/0.9038</td>
<td>3.5228</td>
<td>18</td>
</tr>
<tr>
<td>69-Bus</td>
<td>0.2250</td>
<td>3.22</td>
<td>1/0.9092</td>
<td>3.6191</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 3  
Capacitor placement based on different methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Capacitor position/ size (MVar)</th>
<th>P-loss (MW)</th>
<th>System loadability</th>
<th>V_{max}/V_{min}</th>
<th>Sum (V/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1: Analytical method</td>
<td>12-Bus 9/0.2103</td>
<td>0.0126</td>
<td>5.65</td>
<td>1/0.9563</td>
<td>0.4236</td>
</tr>
<tr>
<td>30-Bus 22/1.13572</td>
<td>0.6831</td>
<td>2.94</td>
<td>1/0.8979</td>
<td>8.1141</td>
<td></td>
</tr>
<tr>
<td>33-Bus 30/1.2298</td>
<td>0.1514</td>
<td>3.6</td>
<td>1/0.9162</td>
<td>3.5651</td>
<td></td>
</tr>
<tr>
<td>69-Bus 61/1.2920</td>
<td>0.1521</td>
<td>3.49</td>
<td>1/0.9302</td>
<td>3.6582</td>
<td></td>
</tr>
<tr>
<td>Method 2: Grid search algorithm</td>
<td>12-Bus 9/0.2106</td>
<td>0.0126</td>
<td>5.65</td>
<td>1/0.9563</td>
<td>0.4236</td>
</tr>
<tr>
<td>30-Bus 21/3.45818</td>
<td>0.6812</td>
<td>2.93</td>
<td>1/0.8979</td>
<td>8.1183</td>
<td></td>
</tr>
<tr>
<td>33-Bus 30/1.265</td>
<td>0.1514</td>
<td>3.6</td>
<td>1/0.9165</td>
<td>3.5662</td>
<td></td>
</tr>
<tr>
<td>69-Bus 61/1.3203</td>
<td>0.1520</td>
<td>3.49</td>
<td>1/0.9306</td>
<td>3.6590</td>
<td></td>
</tr>
<tr>
<td>Method 3: Golden section search algorithm</td>
<td>12-Bus 9/0.2102</td>
<td>0.0126</td>
<td>5.65</td>
<td>1/0.9563</td>
<td>0.4236</td>
</tr>
<tr>
<td>30-Bus 21/3.4347</td>
<td>0.6812</td>
<td>2.93</td>
<td>1/0.8978</td>
<td>8.1178</td>
<td></td>
</tr>
<tr>
<td>33-Bus 30/1.2580</td>
<td>0.1514</td>
<td>3.6</td>
<td>1/0.9165</td>
<td>3.5660</td>
<td></td>
</tr>
<tr>
<td>69-Bus 61/1.3300</td>
<td>0.1520</td>
<td>3.49</td>
<td>1/0.9307</td>
<td>3.6592</td>
<td></td>
</tr>
<tr>
<td>Method 4: Minimization of power losses</td>
<td>12-Bus 9/0.2102</td>
<td>0.0126</td>
<td>5.65</td>
<td>1/0.9563</td>
<td>0.4236</td>
</tr>
<tr>
<td>30-Bus 21/3.4347</td>
<td>0.6812</td>
<td>2.93</td>
<td>1/0.8978</td>
<td>8.1178</td>
<td></td>
</tr>
<tr>
<td>33-Bus 30/1.2580</td>
<td>0.1514</td>
<td>3.6</td>
<td>1/0.9165</td>
<td>3.5660</td>
<td></td>
</tr>
<tr>
<td>69-Bus 61/1.3300</td>
<td>0.1520</td>
<td>3.49</td>
<td>1/0.9307</td>
<td>3.6592</td>
<td></td>
</tr>
<tr>
<td>Method 5: Hybrid (voltage stability + power losses)</td>
<td>12-Bus 12/0.1737</td>
<td>0.0134</td>
<td>5.66</td>
<td>1/0.9561</td>
<td>0.4232</td>
</tr>
<tr>
<td>30-Bus 24/5.15</td>
<td>0.8647</td>
<td>3.06</td>
<td>1/0.9086</td>
<td>8.1562</td>
<td></td>
</tr>
<tr>
<td>33-Bus 12/2.260</td>
<td>0.2733</td>
<td>3.81</td>
<td>1/0.9357</td>
<td>3.6089</td>
<td></td>
</tr>
<tr>
<td>69-Bus 62/2.64</td>
<td>0.2214</td>
<td>3.72</td>
<td>1/0.9493</td>
<td>3.6923</td>
<td></td>
</tr>
<tr>
<td>Method 6: Maximization of system loadability</td>
<td>12-Bus 11/0.4300</td>
<td>0.0263</td>
<td>6.06</td>
<td>1/0.9710</td>
<td>0.4266</td>
</tr>
<tr>
<td>30-Bus 24/5.15</td>
<td>0.8647</td>
<td>3.06</td>
<td>1/0.9086</td>
<td>8.1562</td>
<td></td>
</tr>
<tr>
<td>33-Bus 12/2.260</td>
<td>0.2733</td>
<td>3.81</td>
<td>1/0.9357</td>
<td>3.6089</td>
<td></td>
</tr>
<tr>
<td>69-Bus 62/2.64</td>
<td>0.2214</td>
<td>3.72</td>
<td>1/0.9493</td>
<td>3.6923</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 2. Comparison of voltage profile using different methods of shunt capacitor placement. (a) 12-Bus Test System, and (b) 69-Bus Test System.

where $\lambda$ is a loading factor. $P_0$ and $Q_0$ is initial active and reactive power load, connected with ith bus. $P_{new}$ and $Q_{new}$ is final active and reactive power load, connected with ith bus.

3.1. Simulation and results

The proposed method is tested on 12-bus [127], 30-bus [128], 33-bus [129] and 69-bus [60] radial distribution test systems in all three scenarios. Thukaram load flow method [130] is used to carry out the power flow analysis for the radial distribution system. In base case, when no capacitor is place in the system, following results have been obtained, given in Table 2.

Table 3 is showing the results, when different methods of optimum capacitor placement and sizing are applied on test systems.

4. Discussion

The above methods are compared on the basis of different criterion given in Table 1. Here it is interesting to note that the method 1 to method 4, approximately give the same results. Thus these methods will be discussed simultaneously as “loss reduction methods”. Following important points are concluded:

1. There are significant improvements in reduction in $P_R$ power losses, voltage profile improvement and in maximization of system loadability ($\lambda_{max}$) in comparison with base case (no capacitor). However the method based on loadability...
maximization (method 6) gives higher losses in some cases (12-bus and 33-bus test systems).

2. Here it is also need to be noted that the capacitor size in case of loadability maximization (method 6) have also been significantly increased as compared to other methods. However in case of capacitor placement based on weakest voltage bus (method 5) is much lesser than any other method.

3. The voltage profile improvement in case of loadability maximization (method 6) was found better than the other methods in all test cases, as shown in Fig. 2 (only two bus test system are presented in the result).

4 To visualize the impact of capacitor placement on power loss reduction, voltage profile improvement and maximum loadability improvement, the formulae defined in Table 1 is calculated and plotted in Fig. 3.

From Fig. 3, it can be seen that the losses have been reduced in case of methods 1–5, however the method 6 can increase the system losses. However in terms of VPI and maximum loadability improvement, method 6 was found better than the other methods.

5 To observe the maximum amount of load (kV A) the system can sustain, the load on each bus in 12-bus test system in presence of capacitor is increased till the allowable voltage limit is reached (0.95 < Vbus < 1.05) and the results are summarized in Table 4. Here it can be seen that using the method of loadability maximization, the system can sustain 1.39 times of base load (i.e. 1.39 \times 595.4 \, \text{kV A} = 827.606 \, \text{kV A}), however other methods can sustain only 1.1 times of base load (i.e. 1.1 \times 595.4 \, \text{kV A} = 654.94 \, \text{kV A}).

6 One of the important factors that are needed to be considered in capacitor placement is reactive line current. The placement of capacitor may increase the reactive loading on some of the lines, as shown in Fig. 4. It is interesting to note that the reactive line loading on some of the lines have been increased in case of weakest voltage bus approach (method 5) and maximization of system loadability (method 6) as compared base case and minimization of loss approach. The amount of reactive current can be reduced by placement of multi-capacitor units in the system.

From the above discussion it can be concluded that the capacitor placement and sizing is based on different parameters including minimization of power losses, voltage profile improvement, maximization of system capacity and line limit constraint. Another major factor that is needed to be considered is capital cost, the capital cost will include capacitor cost, protection system used and cost of constructing new lines (if needed). Methods 1–4 of shunt capacitor placement in the system can well handle the minimization of power losses problem considering the line limit constraints, with additional benefits of maximization of system loading and voltage profile improvement.

5. Conclusion

This paper has presented a very detailed overview of optimum shunt capacitor bank (SCB) placement in distribution system. In literature, analytical, numerical programming, heuristic and artificial intelligent based techniques have been proposed. The paper has also presented a comparative study of six different techniques of optimum capacitor placement based on minimization of power losses, weakest voltage bus and maximization of system loadability. The results show that the optimum capacitor placement based on minimization of power losses helps in reducing the reactive current component in total I^2 R losses, in addition to fulfill the line current constraint. The other advantages including voltage profile improvement and maximization of system loadability are also achieved on small scale using power loss reduction technique. Hybrid method (weakest voltage bus and minimization of power losses) and maximization of system loadability must be utilized carefully, such approaches may results in increasing the

![Fig. 3.](image-url) Comparison of six different methods of optimum shunt capacitor placement. (a) Total Line Loss reduction, (b) Voltage Profile Improvement, and (c) System Maximum Loadability Improvement.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Maximum loadability improvement due to single capacitor placement considering voltage limits.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methods</td>
<td>Capacitor position</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------------</td>
</tr>
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<td>Base case</td>
<td>–</td>
</tr>
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<td>Losses</td>
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<td>Loadability</td>
<td>11</td>
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</table>
Fig. 4. Comparison of line current due to loss reduction method, hybrid method and maximization of system loadability. (a) 12-Bus Test System, (b) 30-Bus Test System, (c) 33-Bus Test System, and (d) 69-Bus Test System.
reactive line current in some of the lines if constraints are not defined properly.

Acknowledgment

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Appendix

Particle swarm optimization (PSO) was introduced by [131] to solve the optimization problem, based on social–psychological metaphor behavior. A particle i is represented as \( x_i = (x_{i1}, x_{i2}, x_{i3}, x_{i4}, \ldots, x_{id}) \). The position associated with the best fitness \( pbest_i = (pbest_{i1}, pbest_{i2}, pbest_{i3}, \ldots, pbest_{id}) \) is considered as its current best position. Here \( d \) is a total number of initial particles. The overall best position of the population associated with the current overall best fitness value \( gbest \) is recorded. The rate of the position of the ith particle is represented as \( v_i = (v_{i1}, v_{i2}, v_{i3}, v_{i4}, \ldots, v_{id}) \). During the iteration procedure, the velocity and the position of ith particles are updated according to the Eqs. (A-1) and (A-2):

\[
\begin{align*}
\dot{x}_{id} & = \dot{v}_{id} = c_1 \times r_1 \times (pbest_{id} - x_{id}) + c_2 \times r_2 \times (gbest - x_{id}) \quad (A-1) \\
\dot{v}_{id} & = \dot{x}_{id} = c_1 \times r_1 \times v_{id} + c_2 \times r_2 \times (gbest - x_{id}) \quad (A-2)
\end{align*}
\]

where \( t \) is number of iterations, \( c_1 \) and \( c_2 \) are constants (0.7), \( r_1 \) and \( r_2 \) are random numbers, \( w \) is inertia weight given by Eq. (A-3).

\[
w = \frac{w_{\text{max}} - w_{\text{min}}}{\text{iter}_{\text{max}}} \times t \quad (A-3)
\]

where \( w_{\text{max}} \) and \( w_{\text{min}} \) is 0.9 and 0.4 respectively, \( c_1 \) and \( c_2 \) are constants \( (c_1 = c_2 = 0.7) \).

Table A1 Shows the complete steps of the proposed algorithm for optimum single unit capacitor placement and sizing.

In this paper, PSO is used to achieve the desired fitness function (minimization of power losses or maximization of system loadability). In the present case of shunt placement and sizing, the ith particle \( (x_i) \) is a two dimension vector \( (Q_{\text{SCB}}, Q_{\text{SCB1}, Q_{\text{SCB2}}}) \) representing random shunt capacitor positions \( (Q_{\text{SCB}}) \) and DG sizes \( (Q_{\text{SCB1}, Q_{\text{SCB2}}}) \). The algorithm can also be used for multi SCB placement, considering \( (x_i) \) is a six dimension vector \( (Q_{\text{SCB1}, Q_{\text{SCB2}}, Q_{\text{SCB3}}}) \) representing three SCB position \( (Q_{\text{SCB}}) \) and three SCB size \( (Q_{\text{SCB1}, Q_{\text{SCB2}}, Q_{\text{SCB3}}}) \).

References


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