A Literature Survey on Different Loss Minimization Techniques used in Distribution Network

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ABSTRACT

Due to variable system loads on distribution feeders which are varied time to time the distribution system operation becomes more difficult where load density is higher. Power loss in a distribution network is high due to low voltage and high current. Distribution companies (DISCOs) have an economic enticement to reduce losses in the distribution network. This enticement is the cost difference between the real and standard losses. If real losses are more than the standard losses then DISCOs are penalized, otherwise they obtain profit. Thus loss minimization problem is an important and well researched topic, many researchers proposed different approaches, they are vary with each other by selection of tool for loss minimization and also in problem formulation. The commonly employed methods of loss reduction are capacitor placement, feeder reconfiguration, conductor grading, Distributed Generation (DG) allocation etc. In this paper so many published researched articles are discussed so that further more research can be obtained in this area.

Keywords—Distributed Generation; Distribution System; Network reconfiguration; Capacitor placement; DG allocation.

1. INTRODUCTION

Due to the restructuring in power system, rapid increase in the demand for electricity, environmental constraints and competitive market scenario the distribution systems are operated under heavily loaded conditions so that the distribution system loss has become more concerned in recent days. According to the statistics, the amounts of power losses are varied in various countries. This value in USA was estimated at 6.5% in 2007 [1]. The different studies shows that the distribution system power losses are 70% of the overall losses of power systems [2].To provide acceptable power quality, improved efficiency there must be a climate in favour of loss minimization techniques and innovative operating practices. The distribution system power has been calculated according to the total power generation and the losses in transmission system. Researchers are developed many techniques for distribution system loss minimization and voltage
profile improvement to increase the overall efficiency of the Distribution network. Various methods of the loss minimization for distribution system are available in the literature but the basic methods are (i) Distribution Network Reconfiguration (mostly used in low voltage distribution system). (ii) Optimal Capacitor placement (mostly used for high voltage distribution system). (iii) Distributed Generations (DGs) allocation (mostly used for the interconnected distribution system where small generators are available like diesel engine, micro turbines, wind farms, solar plants.

Traditionally distribution network is designed as a passive network that means no generation at distribution level but the incorporation of the DGs in distribution system changes it from passive to active network. Although the capacitor connected to the distribution system compensates the reactive power, helps in improving power factor, reduces $I^2R$ power losses and also improves voltage profile. However due to planning issues, unavailability of resources Distribution Network operators (DNOs) are limited to accommodate distributed generation in the distribution network, governments are incentivizing low carbon technologies, to meet environmental targets and increasing energy security. DG allocation in distribution system gives the enhanced prospect among all techniques used for loss minimization in distribution system.

### 2. REQUIREMENTS FOR IDEAL LOSS MINIMIZATION TECHNIQUES

Theoretically loss minimization and its allocation is difficult task, because distribution system branch losses are nonlinear functions of generations and loads. Without computing power flow it is difficult to calculate losses. Even after computing the power flow solution there is a strong interdependence between the users and these are expressed by the presence of cross-terms because the losses are nearly quadratic function of power flows. So the loss minimization techniques should be:

- **a)** Easy to understand and based on actual metered data.
- **b)** Loss minimization method should be accurate and consistent.
- **c)** It must be designed to avoid discrimination between users and different time of use.
- **d)** Applicable to different situations and must follow the time evolution of the generation and load patterns.

### 3. NETWORK RECONFIGURATION

The research publications which are related to loss minimization by using Network reconfiguration technique are discussed in this section. These kinds of loss minimization techniques are applicable for the low voltage distribution system. A distribution system is reconfigured by opening or closing of tie switches (normally open) and sectionalizing switches (normally closed) such that the power from main source is redirected. Generally the reconfiguration is obtained by opening a sectional switch and by closing a tie switch. The distribution network has a combination of commercial loads, residential loads, lighting loads. So the distribution substation is subjected to heavily loaded at a certain times and lightly loaded at different
time of the day. Reconfiguration allows smoothing of peak demands, improves voltage profile and increasing the system reliability. Network reconfiguration is also applied for:
a) Service restoration under faulty conditions,
b) Load balancing,
c) Planning outages for maintenance,
d) Minimization of service interruption frequency and
e) Minimization of feeder losses.
The basic key operation for network reconfiguration is switching operation. A tie switch is closed to transfer load from one feeder to another while a sectionalizing switch is opened to restore radial structure. Since there are many candidate configuration of distribution network, due to the discrete nature of switch status the network reconfiguration is considered as a discrete, constrained combinatorial and non-differentiable optimization problem. The well-known methods to solve the reconfiguration problem are classified as follows:

1) heuristic methods such as branch exchange, branch and bound, loop cutting and single loop optimization.
2) metaheuristic algorithms such as ant colony optimization, genetic algorithm, simulated annealing, harmony search algorithm.

The heuristic algorithms are very fast and are appropriate for real time distribution automation; these algorithms also give local optimum solution. In comparison to the metahuristic algorithms it gives global solution, slow and they are not appropriate for real time distribution automation.

3.1 Various reconfiguration techniques
To approach the loss minimization in distribution system Merlin and Bach [3] proposed the first reconfiguration method based on branch and bound method in 1975. This method was modified in 1989 by Shirmohammadi and Hong [4] in which a heuristic approach was used to open the switches at the beginning based on optimal power flow pattern. Civanlar et al. [5] and Baran and Wu [6] proposed a branch exchanged method for feeder reconfiguration. Taylor and Lubkeman [7] implemented a heuristic search strategy for network reconfiguration. So considerable researches have been conducted in the network reconfiguration scheme and they are are discussed as follows

3.2 Heuristic Method Based Approach
The research publications which are based on heuristic method are discussed here. Ji-Yuan Fan et al. in the paper [72] represented a heuristic scheme to implement optimal switch planning with minimum switch operations to optimal switch configuration. Taleski et al. [73] developed a branch exchange technique and that makes maximum energy loss saving. McDermott et al. [74] used a heuristic non-linear constructive method for the loss minimization in a radial distribution network. In the year of 2007 Siti et al. [75] represented a method which is based on neural network in conjunction with heuristic method which helps
different consumers to be connected between different phases to keep phases balanced and the loss of distribution network is minimized.

3.3 Artificial Intelligence Based Approach

Artificial Intelligent based approaches are also have been used in different research papers for network reconfiguration. Kashem et al. used in the paper [76] a trained artificial neural network model to determine an optimum switching status and by using this real power loss was minimized in the radial distribution system. Augugliaro et al. [77] also used neural networks to obtain control strategy of open/closed status of tie-switches in radial distribution network for loss minimization. Queiroz and Lyra [78] proposed an adaptive genetic algorithm for loss minimization. D. Das [80] presented a network reconfiguration for loss minimization based on fuzzy multi-objective approach. Later on Bernardon et al. [79] used a new fuzzy multi-criterion decision making algorithm for the loss minimization in distribution system.

From the above literature survey it is found that the network restructuring method is quite decision making process and it requires quite rigorous numerical computation. Sometimes protection system is affected by the switch operation of the feeder reconfiguration. Rapid changes in network restructuring may lead to transients in the system. Several methods which are mentioned above are having less computation time requirement for that’s why these methods are mostly applicable in smaller distribution systems. Many of them do not provide high quality precise solutions and have been suffered from scaling the problem to a finite number of switches and may not be suitable for real time operation.

4. OPTIMUM CAPACITOR PLACEMENT

The research publications which are related to loss minimization by using Optimum Capacitor Placement Technique are discussed in this section. Shunt capacitors are generally placed near the main substation for power loss reduction, voltage profile improvement, compensation of reactive power and power factor correction. This kind of loss minimization techniques are used for high voltage distribution system. To get the maximum benefit capacitors are connected near to the load. In the recent days due to the availability of pole mounted equipment capacitors are placed near the primary distribution lines [8-12]. In the recent power system scenario blackouts [13, 14] are occurred due to insufficient reactive power and this leads the power system operators towards meeting reactive power demand which is supplied locally using capacitor banks. During low voltage emergencies and scheduling of the generators the capacitors are become the source of reactive power ($Q_c$) by reducing reactance ($X_c$) of the line loading given by the equation (4.1) [15].

$$Q_c = \frac{V^2}{X_c}$$  \hspace{1cm} (4.1)

Various authors have proposed tremendous work in optimum capacitor placement techniques for voltage control and loss minimization in distribution system. These techniques suffered from following challenges:

1) Optimum position of capacitors,
2) Number of capacitors to be allocated,
3) Sizing of capacitors for loss reduction, power flow control and voltage regulation.

4.1 Capacitor Sizing And Cost Equation

It is the basic problem to determine the location and size of fixed shunt capacitor which is to be installed in the distribution system in such way that the total system power loss is minimized, voltage profile of the system is improved but net annual saving is reduced. Regarding investment cost the finite number of maximum capacitor sizes \( Q_{c_{\text{max}}} \) are integer multiple of smallest size of capacitor \( Q_{c_{0}} \) is given by equation (4.2) [16].

\[
Q_{c_{\text{max}}} = L \times Q_{c_{0}} \quad (4.2)
\]

where \( L \) is an integer. The overall cost function with capacitor placement and real power loss can be written by following equation (4.3) [16].

\[
\text{Cost} = K_{p}P_{\text{loss}} + \sum_{j=1}^{k} K_{j}^{c} Q_{j}^{c} \quad (4.3)
\]

where \( K_{p} \) is the annual cost for KW losses in $/KW and \( j = 1,2, \ldots, k \) are indices of selected buses for compensation, \( K_{j}^{c} \) is the corresponding capital investment per kVAR and \( Q_{j}^{c} \) represents the standard capacitor sizes with considering investment cost.

4.2 Review of Various Capacitor Placement Techniques

In previous days when there were not such efficient computing resources and they were expensive various researchers proposed calculus based analytical algorithm. The analytical methods also used for optimum capacitor placement process. The first method was proposed in 1956 by Neagle and Samson [17], they has presented the allocation of single and multiple capacitor in case of uniform and non-uniform distribution of load. Later on in 1959 Cook [18] has presented a research paper in which he showed effects of capacitors in radial system with distributed load and a particular emphasis was placed on an evaluation of the reduction in energy loss taking into account of periodic cycle. Cook extended his work in [19] and developed analytical tools for the proper application of shunt capacitors in primary feeder circuit for load relief and loss reduction. Schmill [20] presented the basic approach for the application of shunt capacitors connected with primary distribution feeders for uniformly distributed load and randomly distributed variable spot load. An iterative method has proposed to solve this problem. Chang [21, 22] extended the previous capacitor placement method to include the optimization of total savings in both the peak loss reduction and energy loss reduction and he also determined the optimal location and size of capacitor. Further generalized equations are developed for the calculation of loss reduction and also found the conditions for optimal loss reductions.

All of these kinds of analytical methods are quite simple, and they require some assumptions to solve the capacitor placement problem. Most of the analytical methods discussed earlier consider that location of capacitor and sizes as continuous variables, therefore the results must be rounded up near to the practical
values. The recent developed methods give more practical values for a distribution system; they can be classified in the following:

4.3 Numerical And Programing Based Approach

Numerical programming approach is used for mathematical problem formulation so that they can solve the arithmetical operations. In this method iterative methods are used to maximize or minimize the objective function of decision variables, decision variables also satisfy a set of constraints. With a great advantage of fast computing skill, availability of large memory the scope of numerical programming based approach has increased. Duran in his paper [23] developed a dynamic programming technique to obtain the optimum number, location and size of shunt capacitor used in radial distribution feeder to increase overall savings. In this paper other algorithms are also used and it extends the work of Schmill [20]. In 1983 Grainger et al. [24] presented a paper for the compensation of reactive power with a continuously controllable capacitive compensation scheme in a primary distribution feeder. The work of [23] was extended by Fawzi et al. [25] in 1983. In this paper two distinct optimization techniques were developed. Later on Baran et al. [26] proposed a mixed integer programming problem for the formulation of capacitor problem.

4.4 Artificial Intelligence Based Approach

Exhaustive search algorithm is the simplest search algorithm for optimization and gives best solution among all the predetermined set of solution. Artificial intelligent (AI) methods are one kind of heuristic search methods [27]. Different Artificial Intelligent based approach have been proposed in finding optimum location and sizing of shunt capacitor used in distribution system. Researchers have used different Artificial Intelligent based approach such as fuzzy based approach [28, 29], particle swarm optimization approach [30], Tabu search method [31], immune algorithm [32], ant colony [33], genetic algorithm [34], and hybrid algorithm [35, 36]. Masoum et al. [37] developed Genetic algorithm based approach (GA) for optimal placement, sizing of capacitor as well as power quality improvement of the radial distribution network. In the paper [38] an iterative nonlinear algorithm was developed for the capacitor problem under linear and nonlinear load in radial distribution network. A fuzzy based approach was used in the presence of voltage and current harmonics for optimal placement and sizing of fixed capacitor banks, the objective function was cost of power loss and energy loss [39]. However in large system AI methods are suffered from large memory requirement and large computation time.

4.5 Heuristic Method Based Approach

Heuristic methods are developed based upon intuition, experience and judgment. Heuristic methods are faster and lead to a solution that is near to the optimal solution. Abdel-Salam et al. [40] proposed a heuristic method for reactive loss reduction in distribution system by connecting a capacitor in that node in which losses due to reactive power is large. Chis et al. [41] extended the work of [40] and proposed a heuristic algorithm in which voltage violation due to addition of capacitor was not allowed. Silva et al. [42] has used
another heuristic constructive algorithm has used for optimal placement of capacitor. In this method the integer variables were represented by sigmoidal function.

5. DG ALLOCATION

The publications which are related with loss minimization using DG allocation technique are discussed in this section. Generally DG allocation techniques are used in the interconnected system where distributed sources are available (it may be renewable source such as wind farms, photovoltaic plants, biomass or may be non-renewable source such as diesel engine, micro turbine). The penetration level of distributed generators in recent days has increased more rapidly. The most distribution networks are operated as passive network with unidirectional power flow. Distributed generators make this passive network into an active network with unidirectional power flow. Installation of DG unit into an existing network has the following advantages:

a) Power loss reduction in the network,
b) Decrease congestion in feeder,
c) Increase total energy efficiency,
d) Stability enhancement,
e) Improvement in voltage profile,
f) Improvement in reliability and security,
g) Encouragement for different renewable sources.

Distributed generators are very much effective in reducing losses as compared to other two methods discussed as before. The reasons behind continuous growth of DG unit in distribution system can be summarized as follows:

a) Environmental concerns,
b) Technical advantages in distributed generators,
c) Reduction in capital investment.

It is also important that improper placement and sizing of DG unit may lead negative effect on distribution system loss minimization. As per the type i.e. renewable and non-renewable DG unit the impacts on distribution system can be written in following Table 1.

5.1 Types of DG Units Used In Distribution System

Based on their characteristics in terms of real and reactive power delivering capability DG units are classified into three major types as follows:

Based on their characteristics in terms of real and reactive power delivering capability DG units are classified into three major types as follows:

**Type 1**: DG unit capable of injecting only active power, such as photovoltaic system, fuel cell, micro turbines. This type of DG unit enhances MWh profit but it may not support improvement of voltage profile
Type 2: DG unit capable of injecting both active and reactive power such as voltage source converter (VSC) based DG unit, synchronous machine based DG unit. Active and reactive power generated from a voltage source inverter (VSI) based PV array can be controlled by varying power angle [44].

Type 3: DG unit capable of injecting active power but consuming reactive power such as induction generator based wind farms.

Table 1: Impacts of distributed generation in distribution system

<table>
<thead>
<tr>
<th>Impact</th>
<th>Renewable type DG</th>
<th>Non-Renewable type DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental concerns</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Voltage profile Improvement</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bidirectional power flow</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Capital cost saving</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DG placement flexibility</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduction of greenhouse gases</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

5.2 Loss Equation

Distribution power losses can be represented for NB number of branches by the following equation (5.1):

\[ P_L = \sum_{i=1}^{NB} I_i^2 R_i \]  (5.1)

where \( I_i \) is the magnitude of current of \( i^{th} \) branch and \( R_i \) is the resistance of \( i^{th} \) branch. Branch current has two components of current on is active component of current \( (I_{act}) \) and another one is reactive component of current \( (I_{rea}) \). So the active power loss \( (P_{LP}) \), reactive power loss \( (Q_{LQ}) \) can be written as:

\[ P_{LP} = \sum_{i=1}^{NB} I_{acti}^2 R_i \]  (5.2)

\[ Q_{LQ} = \sum_{i=1}^{NB} I_{reai}^2 R_i \]  (5.3)

However the losses related to active power can be minimized by optimal placement of DG in the distribution system. Firstly by using a load flow method power loss and voltage deviations are calculated and then the node in which loss is maximum and voltage value is minimum there a DG unit is placed.

5.3 Various Power Flow Methods

Load Flow or Power Flow method is very important for power system planning and operation. There are many conventional power flow methods like Gauss-Siedel, Newton Raphson and Fast Decoupled Load Flow. But all these methods are suitable for transmission systems but not for distribution system because distribution system has high \( R/X \) ratio. Therefore various methods have been proposed by different researchers for power flow solution of distribution system. In recent days so many power flow methods have been developed for distribution systems [45-56]. All these methods are basically based upon node and branch based methods [46]. In case of node based methods the state variables are bus voltage and current.
injection and in case of branch based methods state variables are branch currents to solve the power flow problem [46-49, 55, 57-59]. Rajicic et al. in the year of 1994 [48] developed an efficient forward sweep (calculation of node voltage) and backward sweep (power summation and current summation) method for power flow solution. These sweep based methods were become popular because of its low memory requirement and good convergence characteristics. J.H Teng presented a direct load flow method in his paper [51] and showed that by using bus injection to branch current matrix and branch current to bus voltage matrix a direct load flow solution can be obtained which is time efficient and robust. Further different probabilistic methods have been proposed by different researchers incorporated with Renewable DG units and loads for power flow studies [54-56].

5.4 Various DG Placements And Sizing Method

The problem of DG planning has recently become more important and got much attention by the researchers to obtain maximum benefit from the recent power generation technology. Researchers made various methods for loss reduction in a distribution system using a DG allocation so proper DG allocation and sizing of DG units lead an important role in loss minimization technique. An analytical method was proposed by Wang et al. [57] to find out the appropriate location of DG unit in radial network system for minimization of losses based on unity power factor. Although optimal sizing problem of DG unit was not taken into account. There are faster analytical methods [58, 59, 60] which are basically based on current injection matrix and without use of impedance or inverse admittance matrix optimal place for DG allocation can be obtained [61]. Acharya et al. [62] proposed an exact loss formula based analytical approach to calculate the optimal size and corresponding optimum location of DG in primary distribution system for los minimization. Hung et al. [63] proposed an analytical expression for finding power factor and optimal size of four different types of DG units. This method was rested on different distribution test system and validated using exhaustive test approach. Hung et al. further extended his work in [64] by using an improved analytical method which is more efficient than other method he had used in his paper. In [65, 66, 67] a probabilistic approach had been used as mixed integer nonlinear programming (MINLP) with minimize the annual energy loss as the objective function. In the research paper [66, 67] researchers developed a technique to identify best non-conventional DG unit (solar, biomass, wind) to reduce annual losses in distribution system. In this technique it is considered that DG unit only capable of delivering only active power. The literature represented above considered as DG unit only capable of delivering active power. However to increase the performance of distribution system DG unit should deliver both active and reactive power. So large numbers of DG siting and sizing techniques are analytical and they are based on loss formula mainly suffered from high computational time requirement. So different researchers have focused on so many techniques based on heuristic and artificial intelligent based approach such as Fuzzy-Genetic algorithm [68, 69], Ant colony search [70], Heuristic Curve Fitted Technique [71], Particle swarm optimization for the loss reduction in distribution network using DG unit.
6. EFFECT OF THE THREE LOSS MINIMIZATION TECHNIQUES

The loss minimization techniques mentioned above (categorized as three different types) have the following impacts as shown in the Table 2

Table 2: Various effects of three loss minimization techniques.

<table>
<thead>
<tr>
<th>Impacts of techniques</th>
<th>Network Reconfiguration</th>
<th>Capacitor Placement</th>
<th>DG Allocation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load balancing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voltage profile improvement</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bidirectional power flow</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Cost saving</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Effects on protection system</td>
<td>✓</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss reduction</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Reduction of greenhouse gases</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>✓</td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>

7. RELATIVE ANALYSIS

The literature survey of all above mentioned loss minimization techniques give a relative analysis which is shown in Table 3.

Table 3: Relative analysis of three loss minimization techniques

<table>
<thead>
<tr>
<th>Loss Minimization Techniques</th>
<th>Merits</th>
<th>Demerits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitor placement</td>
<td>Voltage profile improvement. Power factor improvement. Stability enhancement. Source of reactive power. Manage the control of power flow.</td>
<td>Losses due to reactive currents can only be reduced. Quite costly, capacitor size and location are constraints.</td>
</tr>
<tr>
<td>DG allocation</td>
<td>Distribution system loss reduction. Makes distribution system active network. Reduced environmental impacts. Voltage level support. Increase distribution system energy efficiency. Reduce distribution system congestion.</td>
<td>Required proper DG planning. Counter effect may be occurred due to improper sizing and allocation of DG unit. May cause reverse power flow.</td>
</tr>
</tbody>
</table>
8. CONCLUSION

This paper presents a literature survey of three basic loss minimization techniques i.e. (i) Distribution network reconfiguration, (ii) Optimal capacitor placement, (iii) Distributed Generation (DGs) allocation used in distribution system with a fundamental review of apposite background, realistic requirements and adequate techniques. This paper is summarized based on many research articles which were published from the last few decades. The references listed in this literature survey provide a contemporary technical assessment considering improved efficiency of distribution system by achieving power saving through loss minimization.

(i) Network Reconfiguration is generally applicable in low voltage distribution systems. These techniques are economic and require quite complicated controlling arrangement than other methods. These methods are also quite complicated decision-making process.

(ii) Capacitor placement techniques are applicable especially in high voltage distribution systems. These methods are simple and reliable as compared to other two methods. However using capacitor placement simultaneously loss reduction and voltage profile of a distribution system can be improved.

(iii) Distributed Generation (DGs) allocation is more efficient, focused to reduce distribution system losses. It also serves many other benefits as summarized in Table 3. However it suffers from the problem of proper implementation and installation of DG unit in distribution system. In recent days researchers are trying to implement superior techniques to increase all the benefits of DG allocation.

However based on environmental concerns, energy crises, loss reduction using DG allocation method is found to the best solution to minimize the losses in distribution system.

REFERENCES


