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A Simple and Practical Method for Loss Minimization in Restructured Distribution Systems

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Abstract: - Energy losses arise as power flows through the network to meet customer load demands. Some of the input energy is dissipated in the conductors along the delivery route. These losses are inherent in the processing and delivery of power but can be minimized to maximize returns. These losses represent a considerable operating cost, estimated to add 6 to 8 percent to the cost of electricity and some 25 percent to the cost of delivery. Hitherto, electric utilities operating as government monopoly institutions in rigid grid structures, have in the past paid little attention to reducing the losses because they did not constitute major operational or quality of supply problems. In market-driven economies and deregulated electricity industry environments, the minimization of these losses has assumed greater importance. From the utility perspective, these losses need to be reduced to their optimal level. This paper focuses on copper loss minimization in a deregulated power network. The paper presents a simple and practical method to achieve the loss minimization through reactive power compensation by means of optimal locating and sizing of the capacitor banks. The proposed method is performed in Tabriz distribution network as verification and the results are reported in the paper.

Key-Words: - Deregulation; Loss minimization; Optimization; Reactive power; Identification; Fitting.

1 Introduction

In the past, distribution systems have not received as much attention as generation and transmission systems. Restructuring of the electric utility industry is causing widespread changes in the power distribution sector. The growing needs of individual customers and the innovative technologies being developed to meet such requirements coupled with regulatory supervision are the driving forces that are bringing about a new revolution in distribution systems.

Customer demand for good-quality power delivered with a high level of reliability is greater now than ever before. Effective automated planning and operational tools are necessary to make the emerging distributions systems robust, efficient and cost effective. This is a necessary condition imposed by deregulation. A variety of technological solutions must be developed and perfected to cater to these diverse demands. Distribution companies must be flexible in order to compete efficiently and effectively with their competitors. So distribution systems must be optimally designed and operated [1,2,3].

In this paper, in view point of economical matter, a simple and practical procedure is presented for loss minimization through a distribution feeder by optimal sizing and locating of capacitor banks along the feeder. The procedure is based on the identification of reactive power along the feeder. In the proposed method reactive power of the capacitor bank located in a point is proportional to the reactive power consumed in the point. Therefore reactive power compensation is almost perfectly performed and loss minimization is achieved.

The paper is organized as follows. In section 2, we explain how the size and location of a capacitor bank that must be installed along a distribution feeder can be determined optimally in order to minimize the losses in the distribution feeder. Identification of reactive power is presented in section 3. In section 4, we discuss how an arbitrary feeder may be divided into subsections in an optimal method, i.e. *fitting of a parabola with closest lines.* Section 5 and 6 present economic cost function and its minimization, respectively. A case study is presented in section 7 that have been performed in the Azerbaijan distribution networks. This is followed by conclusions in section 8.

2 Location and Sizing for Optimal Line Loss Reduction [4,5]

A simple distribution system is shown in Fig.1. Reactive load current at the beginning and the end of the line is designated I_1 and KI_1, respectively. The reactive load current is assumed to be uniformly distributed along the length of the line and is considered to be a lumped load at the end of the line . The equation for the reactive load current as a function of x can be expressed as:

$$i(x) = \frac{KI_1 - I_1}{l} x + I_1 \tag{1}$$

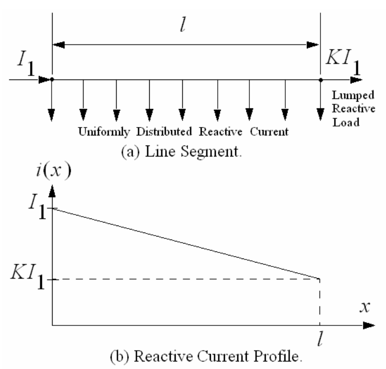

Fig.1. Reactive load current distribution.

The active power loss per phase due to the reactive component of load current is:

$$P_{Loss} = \int_0^l i^2(x) R dx \tag{2}$$

After some calculations we can write:

$$P_{Loss} = \frac{l}{3} I_1^2 (K^2 + K + 1) R \tag{3}$$

By using equation $Q = \sqrt{3} V_L I_L$ we have:

$$P_{Loss} = \frac{l}{9V_L^2} Q_1^2 (K^2 + K + 1) R \tag{4}$$

where, R is the resistance per unit length of the line.

If a single capacitor bank is added to the circuit, the reactive load profile is modified as shown in Fig.2. The reactive component of load current can be expressed as:

$$i(x) = \frac{KI_1 - I_1}{l} x + I_1 - I_c \quad for \quad 0 \le x \le x' \tag{5}$$

and

$$i(x) = \frac{KI_1 - I_1}{l} x + I_1 \quad for \quad x_1 \le x \le l \tag{6}$$

The power loss per phase with installation of the capacitor bank can be obtained by (2) as:

$$P_{Loss} = \{ \frac{x'^2}{l} \left(I_1 I_c (1-K) \right) + x'(I_c^2 - 2I_1 I_c) + \frac{l}{3} \left[I_1^2 \left(K^2 + K + 1 \right) \right] \}.R \tag{7}$$

By using equation $Q = \sqrt{3} V_L I_L$ the result is:

$$P_{Loss} = \frac{1}{3V_L^2} \{ \frac{x'^2}{l} \left(Q_1 Q_c (1-K) \right) + x'(Q_c^2 - 2Q_1 Q_c) + \frac{l}{3} \left[Q_1^2 (K^2 + K + 1 \right] \}.R \tag{8}$$

To determine the optimum capacitor size and location to minimize the circuit losses, partial derivatives of (7) or (8) are taken with respect to I_c and x' and equated to zero as:

$$\frac{\partial P_{Loss}}{\partial x'} = 0 \tag{9}$$

$$\frac{\partial P_{Loss}}{\partial I_c} = 0 \tag{10}$$

The results are as follows:

$$x' = \frac{2/3}{1-K} l \tag{11}$$

$$I_c = \frac{2}{3} I_1 \tag{12}$$

If $K \geq \frac{1}{3}$ the results will be as follows:

$$x' = l \tag{13}$$

$$I_c = \frac{K+1}{2} I_1 \tag{14}$$

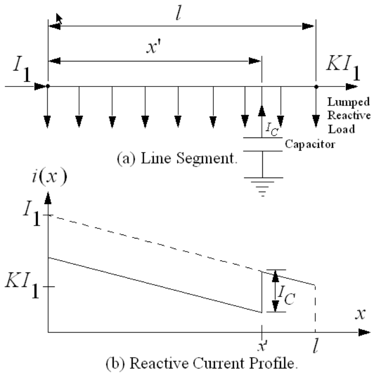

Fig.2. Reactive load current distribution with capacitor added.

3 Identification of Reactive Power [6]

Reactive powers are measured at a number of points along the feeder. Then, reactive power profile is shown in Fig.3. The Q_i is the reactive power measured at point x_i. The reactive power equation can be expressed as:

$$Q_i(x_i) = ax_i^2 + bx_i + c + e_i \tag{15}$$

where a, b and c are constant parameters of the model, and e_i is the error term.

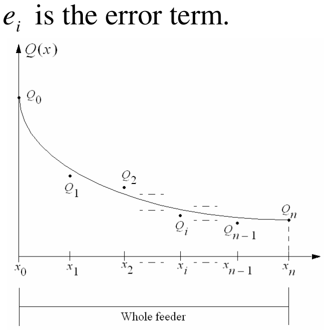

Fig.3. Profile of reactive power along the feeder.

Now, we define:

$$\theta \triangleq \begin{bmatrix} a & b & c \end{bmatrix}^t \tag{16}$$

$$Y \triangleq \begin{bmatrix} Q_0 \, Q_1 \ \ldots \ Q_i \ \ldots \ Q_N \end{bmatrix}^t \tag{17}$$

$$U = \begin{bmatrix} 0 & x_1^2 & \ldots & x_i^2 & \ldots & \ell^2 \\ 0 & x_1 & \ldots & x_1 & \ldots & \ell \\ 1 & 1 & \ldots & 1 & \ldots & 1 \end{bmatrix}^t \tag{18}$$

We can write all the data in matrix form as:

$$Y = U\theta + e \tag{19}$$

Cost function of the error is defined as:

$$S \triangleq e^t e \tag{20}$$

Derivative of (20) is taken with respect to the θ and equated to zero as:

$$\frac{\partial S}{\partial \theta} = 0 \tag{21}$$

The result is as follows:

$$\theta = \left(U^t U\right)^{-1} U^t Y \tag{22}$$

Now the a, b and c parameters are determined and the reactive power model can be expressed as:

$$Q = ax^2 + bx + c \tag{23}$$

4 Fitting of a Parabola with Closest Lines [7]

In order to fitting a parabola with the closest lines so that two ends of each line are on the parabola as shown in Fig.4, we define the following area function:

$$\begin{aligned} S(x_1, x_2, \ldots, x_{i-1}, x_i, \ldots x_{n-1}) &= \frac{x_1}{2}(ax_1^2 + bx_1 + 2c) + \\ &\frac{x_2 - x_1}{2}[a(x_1^2 + x_2^2) + b(x_1 + x_2) + 2c] + \\ &\ldots + \frac{x_i - x_{i-1}}{2}[a(x_i^2 + x^2_{i-1}) + b(x_i + x_{i-1}) + 2c] + \ldots + \\ &\frac{l - x_{n-1}}{2}[a(x_{n-1}{}^2 + l^2) + b(x_{n-1} + l) + 2c] \end{aligned} \tag{24}$$

where S is the overall area under the all lines.
The following derivatives are taken:

$$\frac{\partial S}{\partial x_1}=0, \dots , \frac{\partial S}{\partial x_i}=0 \dots , \frac{\partial S}{\partial x_{n-1}}=0 \qquad (25)$$

Following set of equations can be obtained:

$$x_1=\frac{1}{n}l, \dots , x_i=\frac{i}{n}l, \dots , x_{n-1}=\frac{n-1}{n}l \qquad (26)$$

Briefly, if the length of l is equally divided, fitting of a parabola with the closest lines is achieved.

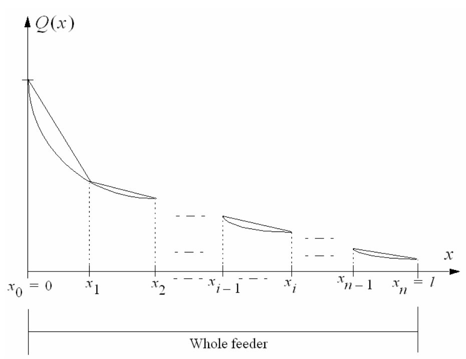

Fig.4. Fitting of parabola with closest lines.

5 Cost Function

Cost function is defined as follows:

$$J(n)=C_{Loss}(n)+C_{cap}(n) \qquad (27)$$

and

$$J(0)\triangleq C_{Loss,0} \qquad (28)$$

where

n is the number of subsections or capacitor banks;

$C_{Loss,0}$ is the cost of feeder losses before installation of any capacitor banks;

$C_{Loss}(n)$ is the cost of feeder losses after installation of n capacitor banks during their lifetime;

$C_{cap.}(n)$ is the cost of purchasing, installation, maintenance, and repair of capacitor banks during their lifetime.

6 Minimization of the Cost Function

The following difference in cost functions is calculated until the difference becomes negative. Then, the last n is the number of optimum subsections which minimizes the cost function. The procedure is illustrated in Fig.5.

$$\Delta J(n)=J(n)-J(n+1) \ , \ n=0,1,2,... \qquad (29)$$

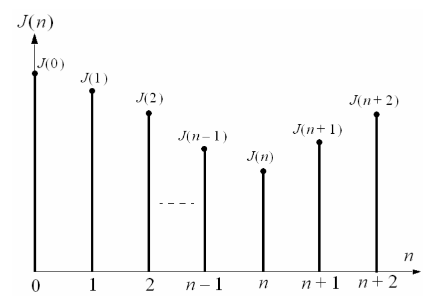

Fig.5. Diagram of cost function minimization.

7 A Case Study in Tabriz Distribution Feeder

In a typical three phase distribution system in Tabriz city, the measurements of distance and reactive power at several points are shown in Table 1. The reactive power equation is modeled by (23) as:

$$Q(x)=-0.0227x^2-115.7044x+7.9751\times10^4 \ \ VAR$$

Firstly, based on the result of section 4, the overall line length of the feeder is equally divided into n line subsections. The correct procedure is to begin for locating and sizing the capacitors at the line subsection farthest away from the source, i.e. subsection n. Next, the reactive profile of all the line subsections closer to the source, i.e. subsections $n-1,...,1$ will be modified. The same procedure is repeated till the line subsection 1 is reached. This procedure will result in the minimizing of losses for all line subsections of the feeder. Therefore, line subsection n will be analyzed first, followed by line subsection $n-1$ and so on.

For the reason that the capacitor banks must be installed on the poles, the actual position for the installation of the capacitor banks are usually other than calculated ones. The actual position for installation of capacitor banks is given by:

$$x_{act.} = [\frac{x_{cal.}}{d} + \frac{1}{2}].d \qquad (30)$$

where

[ ] is the operator of *Greatest Integer Function* for its operand;

$x_{act.}$ is the actual position for installation of the capacitor banks;

$x_{cal.}$ is the calculated position for installation of the capacitor banks;

d is the distance between two nearby poles.

The procedure for minimization of cost function presented in section 6 is applied on the distribution system and the results are mentioned in table 2. For n=4 the optimal result is obtained. Feeder loss reduction and reactive power compensation in percent are also shown in Table 3.

Table 1
The measurements of distance and reactive power at several points in a typical distribution system

x (m)	*Q(x)* (kVAr)	*x* (m)	*Q(x)* (kVAr)	*x* (m)	*Q(x)* (kVAr)
0	79.5	240	50.5	510	17.0
30	76.0	300	44.0	540	7.5
90	69.5	360	37.5	610	2
150	63.0	390	28		
180	57.0	450	23		

Table 3
Reduction of loss and compensation of reactive power in a typical feeder for several subsections

Number of subsections	Reduction of loss (%)	Compensation of reactive power (%)
n=1	88.6	62.9
n=2	91.1	78.6
n=3	94.5	94.3
n=4	96.1	95.3
n=5	97.5	96.1
n=6	98.4	97.3

8 Conclusions

In this paper a simple and practical procedure is presented for loss minimization in the distribution networks in order to economically operating it in the new power markets. The method uses the installation of capacitor banks along the feeders which are determined optimally in view point of size and location. The method is based on the identification of reactive power by a parabola equation. Then, the feeder is divided by subsections until the cost function is minimized. A case study in Tabriz distribution network is performed as verification and the effectiveness of the proposed method is practically proved.

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Table 2
Number of subsections and the specifications of installed capacitor banks in the typical feeder; l_C is the distance of capacitor installation point from the beginning of the feeder; Q_C is the reactive power of installed capacitor bank

Number of subsections	Location and size of capacitor banks	First capacitor bank	Second capacitor bank	Third capacitor bank	Fourth capacitor bank	Fifth capacitor bank	Sixth capacitor bank
n=1	l_C (m)	410	-	-	-	-	-
	Q_C (kVAr)	4×12.5	-	-	-	-	-
n=2	l_C (m)	512	298	-	-	-	-
	Q_C (kVAr)	2×12.5	3×12.5	-	-	-	-
n=3	l_C (m)	347	395	169	-	-	-
	Q_C (kVAr)	2×12.5	2×12.5	2×12.5	-	-	-
n=4	l_C (m)	563	455	280	152	-	-
	Q_C (kVAr)	12.5	2×12.5	12.5	2×12.5	-	-
n=5	l_C (m)	573	473	366	244	122	-
	Q_C (kVAr)	12.5	12.5	12.5	2×12.5	2×12.5	-
n=6	l_C (m)	580	488	393	297	199	98
	Q_C (kVAr)	12.5	12.5	12.5	12.5	12.5	12.5