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Loss allocation to consumers before and after reconfiguration of radial distribution networks

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ABSTRACT

This paper presents allocation of power losses to consumers connected to radial distribution network before and after network reconfiguration in a deregulated environment. Loss allocation is made in a quadratic way, which is based on identifying the real and imaginary parts of current in each branch and losses are allocated to consumers. Comparison of loss allocation after multi-objective approach based distribution network reconfiguration is made with those before reconfiguration. For network reconfiguration, multiple objectives are considered for minimization of system real power loss, deviations of nodes voltage, branch current constraint violation and transformer loading imbalance and they are integrated into an objective function through appropriate weighting factors which is minimized for each tie-switch operation. The effectiveness of the proposed approach is demonstrated through an example.

1. Introduction

Deregulation of the power industry was intended to introduce competition and to bring down prices, improve efficiency and generate an all out improvement in the industry. It was primarily aimed at demolishing the monopolistic, protective and vertically integrated structure of the industry and providing a chance for the new entrants to make their contributions to the business in general. Unlike generation and sale of electrical energy, activities of transmission and distribution are generally considered as a natural monopoly. The cost of transmission and distribution activities needs to be allocated to the users of these networks. Allocation can be done through network use tariffs, with a focus on the true impact they have on these costs. Among others, distribution power losses are one of the costs to be allocated. The main difficulty faced in allocating losses is the nonlinearity between the losses and delivered power which complicates the impact of each user on network losses [1].

Different techniques have been published in the literature for allocation of losses, most of them dedicated to transmission networks and can be classified into three broad categories – pro rata procedures, marginal procedures, proportional sharing procedures, and circuit-based procedures. Pro rata procedure [2,3] is the simplest one in which the total losses are first assigned to generators and loads, generally 50% of losses are assigned to each category. Then the losses are allocated to individual generators proportional to their active power generated or consumed irrespective of their location within the network. Thus remotely located generators or loads will be benefited at the expense of the others. In marginal procedures [4–7], losses are assigned to generators and demands through the so-called incremental transmission loss (ITL) coefficients. This method depends on the location of the slack bus. Hence, different slack buses will give different ITL coefficients. The method has the disadvantage that it results in over recovery and needs normalization. The ITL coefficients can be positive or negative. The negative ones can be interpreted as cross subsidies [5]. In proportional sharing procedures [8–13], losses are allocated to the generators and consumers by using the results of a converged power flow. The losses are then allocated to different generators or consumers based on a linear proportional sharing principle. Conejo et al. [14] have proposed a circuit-based procedure for allocating transmission losses to generation and loads based on the networks Z-bus matrix. Z-bus loss allocation technique can also yield negative allocation to those participants who contribute to reduce network losses due to their strategically well positioned location in the system, which again can be interpreted as cross subsidies. Conejo et al. [15] have also presented a comparison of different practical algorithms available for loss allocation in transmission systems. Costa and Matos [16] have addresses the allocation of losses in distribution networks with embedded generation by considering quadratic loss allocation technique.

In recent years, considerable research has also been conducted for loss minimization in the area of network reconfiguration of distribution systems. Distribution system reconfiguration for loss reduction was first proposed by Merlin and Back [17]. They have

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Nomenclature

p	node number
$IL(p)$	load current at pth node
PL_p	real power load at pth node
QL_p	reactive power load at pth node
V_p	voltage at pth node
NB	total number of nodes in the system
jj	branch number, jj = 1, 2, ..., NB − 1
$I(jj)$	current of branch-jj
$N(jj)$	total number of nodes (consumers) beyond branch-jj
$ie(jj, i)$	nodes (consumers) beyond branch-jj, for i = 1,2, ..., $N(jj)$
$IL\{ie(jj, i)\}$	load current of consumer at node $ie(jj, i)$
$ILD\{ie(jj, i)\}$	real component of load current at node $ie(jj, i)$
$ILQ\{ie(jj, i)\}$	reactive component of load current at node $ie(jj, i)$
$\alpha\{ie(jj, i)\}$, $\beta\{ie(jj, i)\}$	loss allocation factors for the consumer at node $ie(jj, i)$
$PLOSS(jj)$	real power loss of branch-jj
$R(jj)$	resistance of branch-jj
$ploss(jj, \ell)$	real power loss of branch-jj allocated to consumer ℓ
$Tploss(\ell)$	real power loss supported by consumer ℓ
V_s	voltage at the substation
N_k	total number of branches in the loop including the tie branch, when kth tie-switch is closed
$V_{i,j}$	voltage of node j corresponding to the opening of the ith branch in the loop
$Ploss(i)$	total real power loss when ith branch in the loop is opened
$Ploss^0$	total real power loss in the network before reconfiguration
$\lvert I(i, m)\rvert$	magnitude of current of branch-m when the ith branch in the loop is opened
$I_c(m)$	line capacity of branch-m
kVA_j	kVA rating of jth transformer
$ITr_{i,j}$	current of jth transformer when the ith branch in the loop is opened
N_t	total number of transformers
$ITr^{Opt}_{i,j}$	optimal value of the current to be shared by the jth transformer when the ith branch in the loop is opened = $\frac{kVA_j}{\sum_j kVA_j}\sum_j ITr_{i,j},\ j=1,2,\ldots,N_t$

used a branch-and-bound-type optimization technique to determine the minimum loss configuration. In this method, all network switches are first closed to form a meshed network. The switches are then opened successively to restore radial configuration. Based on the method of Merlin and Back [17], a heuristic algorithm has been suggested by Shirmohammadi and Hong [18]. Here also, the solution procedure starts by closing all of the network switches which are then opened one after another so as to establish the optimum flow pattern in the network. Many approximations of the method of Merlin and Back [17] have been overcome in this algorithm. Borozan et al. [19] have presented a network reconfiguration technique which contains three main parts: real-time load estimation, effective determination of minimum power loss configuration, and cost/benefit evaluation. Civanlar et al. [20] have proposed a heuristic method to determine a distribution system configuration which would reduce line losses by using a simplified formula to calculate the loss reduction as a result of load transfer between two feeders. Baran and Wu [21] have made an attempt to improve the method of Civanlar et al. [20] by introducing two approximation formulas for power flow in the transfer of system loads. The power flow equations used by Baran and Wu [21] were defined by recursive approximation of P, Q and V at each node. Liu et al. [22] have proposed two algorithms to minimize the real power loss in distribution networks. To obtain global optimal or, at least near global optimal solutions, Chiang and Jean-Jameau [23,24] and Jeon et al. [25] have proposed new solution methodologies using the simulated annealing algorithm for the reconfiguration. Taleski and Rajicic [26] have proposed a method to determine the configuration with minimum energy losses for a given period. Lin et al. [27], Jeon and Kim [28], Shin et al. [29], Hsiao and Chien [30], Hsiao [31], Hong and Ho [32], Huang [33] and Huang and Chin [34] have proposed artificial intelligence based applications in a minimum loss configuration. Das [35,36] has presented two different algorithms for network reconfiguration based on heuristic rule and fuzzy multi-objective approach.

The configurations of the distribution networks may be varied with manual or automatic switching operations so as to reduce power loss, increase system security, and enhance power quality. Even though the main objective of network reconfiguration is to reduce power loss, in the deregulated environment, it is important that the reconfiguration algorithm consider the objectives such as nodes voltage deviation, branch current constraint violation, and transformer loading imbalance. Also, in the deregulated environment, the losses are allocated to different consumers in the network. In this work, impact of network reconfiguration on loss allocation in radial distribution networks is presented. This work formulates loss allocation based on quadratic loss allocation scheme to consumers in a radial distribution network. It is assumed that consumers have to pay for losses. The network reconfiguration problem is formulated as a multi-objective problem subject to operational and electric constraints. Four objectives, namely, minimization of the system power loss, minimization of the deviations of the nodes voltage, minimization of branch current constraint violation, and minimization of transformer loading imbalance are considered and they are integrated into an objective function through appropriate weighting factors which is minimized for each tie-switch operation. The problem formulation proposed herein considers the following aspects:

1. Loss allocation to consumers before network reconfiguration.
2. Network reconfiguration using multi-objective approach and at the same time, the radial structure of the network must remain after reconfiguration in which all loads must be energized.
3. Loss allocation to consumers after network reconfiguration.

2. Methodology for quadratic loss allocation

For the purpose of explanation, consider a sample distribution network as shown in Fig. 1. In Fig. 1, branch numbers are shown in (·). The branch number, sending end and receiving end nodes are given in Table 1.

The load current at any node p, is given as:

$$IL(p) = \frac{PL_p - jQL_p}{V_p^*}, \quad p = 2, 3, \ldots, NB \tag{1}$$

Consider branch-5 of Fig. 1. Number of node beyond branch-5 is one and this is node 6. Therefore, current through branch-5 is:

$$I(5) = IL(6) \tag{2}$$

Now consider branch-4. The total number of nodes beyond branch-4 is two and these nodes are 5 and 6, respectively. Therefore, current through branch-4 is: