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Loss allocation in radial distribution networks with various distributed generation and load models

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ABSTRACT

This paper proposes a new method for loss allocation in radial distribution networks (DNs) considering different models of distributed generation (DG) and load in context of a deregulated environment. In the proposed method, a direct relation between real/reactive power flow in a branch and its losses has been developed without taking any assumption and approximation. Suitable expressions/relations for network power flow have been developed employing power summation algorithm. The developed expressions do not contain any cross-terms. For allocating the losses among network participants, the proposed method uses a circuit based branch oriented approach. Using only power flow results, this method employs a backward sweep network reduction technique to allocate the network losses to load/DG at various nodes. This method does not require additional step of normalization to collect the exact amount of total network losses. In the present study, different types of DG, e.g. DG injecting only real power, DG injecting only reactive power, DG injecting real power and absorbing reactive power, and DG injecting both real and reactive power are considered to allocate losses. In addition to this, various load models based on impact of voltage variation on real/reactive power consumption are also considered. To test the proposed method, modified 9-node and 33-node radial DNs have been considered. In order to show the effectiveness of the proposed method, its numerical results have been compared with those by other methods available in the literature.

Introduction

Nowadays, electrical power system is experiencing major changes and is adopting deregulated operation of electricity market. The vertically integrated systems are being restructured and unbundled into generation, transmission, and distribution segments which has introduced the competition among the network participants (consumers and generators). Unlike the sale of electrical energy by generation companies, activities of transmission and distribution are generally considered as natural monopoly. Therefore, electricity market does not have any control over the cost of services provided by transmission and distribution networks (DNs). Like transmission network, power losses in the DN have large share of service charges. Thus, distribution power losses are to be allocated among network participants, fairly and justifiably.

Distributed generation (DG), when introduced in DN, changes the losses depending on its location and rating [1,2]. Hence, DG should be rewarded/penalized according to its impact on losses of DN. Further, power loss in a branch of DN is a quadratic function of power flowing through it due to loads and DGs [3]. Hence, in bundled power flow [3], it is difficult to trace the exact share of load and DG in the network. The interdependency among network participants is expressed by the cross-terms which also have significant impact on allocated losses to loads and DGs. Hence, the allocation of total network losses cannot be carried out among consumers and DGs in the straightforward way. The critical nature of the loss allocation problem is made evident by the fact that early formulated loss allocation mechanisms, even adopted at the regulatory level, have been found to be inconsistent [4].

Various methods in the literature dealing with the problem of loss allocation are mentioned below:

Based on the proportional principle, Pro rata (PR) method [5,6] allocates the network losses to consumers/DGs based on their real power consumption/injection. While allocating the losses, this method does not consider the location of consumer/DG with respect to (w.r.t.) root node and hence produces unfair result of loss allocation. MW-mile method [7,8] overcomes the drawback associated with PR method by considering the power rating as well as location of a load/DG w.r.t. root node. PR and MW-mile methods are simple and easy to implement. However, these methods do not

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Nomenclature

P_t and Q_t real and reactive power, respectively, available at receiving end of branch t
$P_{D,t}$ and $Q_{D,t}$ real and reactive power, respectively, of load at receiving end of branch t
$P_{0,t}$ and $Q_{0,t}$ real and reactive power, respectively, of load at receiving end of branch t under rated condition
$P_{G,t}$ and $Q_{G,t}$ real and reactive power, respectively, of DG at receiving end of branch t
$V_{s,t}$ and $V_{r,t}$ phasor voltages of sending and receiving nodes, respectively, of branch t
α exponent for different load model
N_t set of branches incident to node t
K_t set of branches ahead of branch t
B_t susceptance of branch t
PS_t and QS_t real and reactive power loss, respectively, in branch t
$\Delta PS_t^{D,u}$ and $\Delta QS_t^{D,u}$ allocated real and reactive power losses, respectively, of branch t to load connected at receiving end of branch u
$\Delta PS_t^{G,u}$ and $\Delta QS_t^{G,u}$ allocated real and reactive power losses, respectively, of branch t to DG connected at receiving end of branch u
$P'^{u}_{D,t}$ and $Q'^{u}_{D,t}$ updated value of $P_{D,t}$ and $Q_{D,t}$, respectively, when connected at receiving end of branch u
$P'^{u}_{G,t}$ and $Q'^{u}_{G,t}$ updated value of $P_{G,t}$ and $Q_{G,t}$, respectively, when connected at receiving end of branch u
$\Delta PS^{D,t}$ and $\Delta QS^{D,t}$ total allocated real and reactive power losses, respectively, to load at receiving end of branch t
$\Delta PS^{G,t}$ and $\Delta QS^{G,t}$ total allocated real and reactive power losses, respectively, to DG at receiving end of branch t

take the power flow into account for loss allocation. Thus, to overcome these limitations of PR and MW-mile methods, marginal loss coefficient (MLC) method [9,10] came into existence for loss allocation. MLC method allocates the losses to a load/DG using the MLCs and power rating of load/DG. This method does not allocate the losses to the root node and therefore, results in over-recovery of total network losses, which is compensated by using suitable normalization procedure. Direct loss coefficient (DLC) method [9] allocates total losses based on the direct relationship between the node power injection and network losses. Z-bus method [11] considers network parameters for loss allocation. It can yield negative allocation to those loads and DGs, which contribute to reduce network losses due to their strategically well positioned in the system. Both MLC and DLC methods are based on the results of Newton–Raphson (NR) power flow, while Z-bus method depends on formation of Z-bus matrix in order to allocate losses. Since a distribution lines have higher R/X ratio in comparison with transmission lines, many times NR method fails to converge for load flow analysis of radial DNs. Also distribution lines have negligible shunt admittance which offers difficulty in formulation of Z-bus. Due to these facts, MLC and DLC methods cannot be applied to radial DN [4].

In the absence of shunt admittance of lines, succinct method [12] is able to calculate allocated losses. However, this method is not able to provide equitable loss allocation in terms of reactive power loads, when the ratio of reactance to resistance of a line is greater than that of reactive to real power available at its receiving node. Substitution method [9] calculates the allocated loss to a consumer/DG by taking the difference of network losses before and after connecting it to the network. In this method, the sum of allocated losses to consumers/DGs is not equal to the total network losses, and therefore additional step of normalization is required.

Proportional sharing method [13,14] uses the results of power flow and linear proportional sharing principle which states that the power flow reaching a bus from the incoming lines is distributed among the outgoing lines proportionally to their corresponding power flows. However, this method does not consider the interdependency of consumers and DGs, and allocates entire network losses to consumers or DGs. The issues related to loss allocation in radial DN with DG are addressed in [15]. It covers the issues such as characteristic of loads and DGs, formulation of the loss allocation problem for radial DNs with respect to transmission networks, and treatment of the root node in radial DNs. A comparison of different practical algorithms is presented in [5] for loss allocation in transmission networks.

In context of deregulated environment, Savier and Das [16] presented an exact method of loss allocation based on the relation between node voltages and branch current in radial DN. They implemented their method for traditional passive DN. Later, Savier and Das [17] extended their method as in [16] for energy loss allocation. Carpaneto et al. [18] presented a branch current decomposition based loss allocation method by representing the power loss in a branch as a function of branch current and load/DG current at various nodes ahead of it in radial DN. Atanasovski and Taleski [4] proposed a power summation method for loss allocation (PSMLA) by establishing a direct relation between loss in a branch and injected real and reactive power at various nodes connected ahead of it. Further, they employed quadratic loss allocation scheme in order to deal with cross-terms. Atanasovski and Taleski [19] presented energy summation algorithm for allocation of energy loss in DN with DG. It is a statistical approach which uses daily load and generation curve. Using quadratic loss allocation scheme for cross-terms, Costa and Matos [20] presented a current based approach, which allocates entire variation of losses to DGs by using upstream looking algorithm.

Brief literature review on various loss allocation techniques presented above shows that these techniques deal with DG having constant real and reactive power injection, and load having constant power model for loss allocation in DNs. Practically, loads normally encountered in low and medium voltage DNs are dependent on the node voltage. Further, real and reactive power injections by DG into network depend on technology employed and resources available at the site. However, to the best of authors' knowledge, the issue of loss allocation in radial DNs with various DG types and voltage dependent load models has not been addressed so far.

The present work proposes a new solution for the problem of loss allocation considering the effects of various DG types and voltage dependent load models. Based on power summation algorithm, the proposed method adopts a branch oriented approach for loss allocation in radial DNs. This method does not make any assumptions and approximations, and hence it is an accurate, simple, efficient, and useful methodology for loss allocation in

Table 1
Different values of exponent.

Load models	Values of α
CP	$\alpha = 0$
CC	$\alpha = 1$
CI	$\alpha = 2$