LOSS ALLOCATION IN RADIAL DISTRIBUTION NETWORK WITH DISTRIBUTED GENERATION

Ph.D. THESIS

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ABSTRACT

The losses in electrical power networks have significant economic implications on its performance. In the traditional vertically integrated power utility systems, operation and control of generation, transmission and distribution segments are under a single authority. The system operator can optimize the total losses in the network by adjusting power output from different generators connected to the system and the cost of losses is included in the overall electricity production cost.

Due to sluggish performance of monopolistic framework of traditional power utility system, the change in power generation technologies and the concept of independent power producers, many power utilities worldwide have restructured their way of operation and business. This restructuring leads to unbundling of generation, transmission and distribution segments into various autonomous business units. The objectives of restructuring are to terminate the monopoly of service providers and to promote competition between them, and to offer choice and economic benefit to consumers. Under restructured power system, generation companies would be in competition with each other to serve more than one distribution utility and generation to each company is assigned by auction or trade contract instead of economic dispatching orders. However, unlike the generation, transmission and distribution segments are generally considered as natural monopoly and are immune to competition as there is no technical and economic logic to introduce it in them. Since these segments are crucial for fair competition among supply and generation, setting of adequate price for transmission and distribution network services becomes very important.

The changed interaction between suppliers and consumers has led to the increased attention towards the economic aspects of the electricity supply system. As a significant portion of network operating cost is due to the power losses, the appropriate allocation of network losses among participants becomes crucial. In the past, loss allocation problem was addressed only to transmission networks, but with increased penetration of Distributed Generation (DG) and introduction of competition among suppliers, this problem becomes very important for distribution networks as well.

DG has significant technical and economic impact on distribution network as it alters the power flows in the network from unidirectional to bidirectional, and by that DG affects the network losses. Therefore, the losses have to be specifically allocated among the

network participants. Efficient loss allocation is a challenging task, because of the nonlinear relationship between losses and power flows. Keeping this in view, this thesis work aims at development of suitable techniques/algorithms for fair allocation of losses of Radial Distribution Network (RDN) among DG and load.

In some of existing techniques for loss allocation in RDN, the reactive power flow in the network has been neglected while assigning the active power loss to network participants. The flow of reactive power also causes active power losses in the network. Hence, it must also be considered for loss allocation. Further, one of the major issues in the loss allocation is the treatment of losses in downstream branches fed by a branch. To tackle this issue, some authors have neglected the losses in downstream branches which leads to incorrect results as losses in downstream branches produce losses in upstream branches. In order to overcome these limitations of existing methods, a suitable technique for loss allocation in RDN is the need of hour.

Therefore, a simple and effective power based branch-oriented approach has been developed in this thesis for loss allocation in RDN. The formulation for this method has been developed from power flow equations without any assumptions and approximations. An expression for branch losses has been derived using node voltages at sending and receiving ends and apparent power at the receiving node of a branch. Further, a backward sweep network reduction technique has been employed to allocate the losses to distributed generators and loads. To show the effectiveness of the proposed method, it has been tested on 33-node and 69-node test RDNs, at two different load levels. The results obtained by proposed method have been compared with those by other methods reported in the literature. By comparing the results, it is observed that in terms of the discrimination between the consumers of same ratings and at different locations, the performance of proposed method is consistent for different load levels. In addition, the proposed method provides moderate cross-subsidises.

The power loss in branch is a quadratic function of current flowing through it. Hence, the expression of branch losses contains two types of terms, first because of square of individual current/power and second because of product of two different currents/powers. The first type of term is referred to as self-term, whereas the second type is referred to as mutual or cross-term. The cross-term reflects the interdependency among network participants and its presence complicates the loss allocation. To unbundle the cross-terms, proportional and quadratic schemes of allocation have been employed in the existing literature. The proportional scheme allocates the cross-term among the participants using a linear function of elements of the cross-term. The allocation of nonlinear cross-terms among participants using a linear function results unfair loss allocation. On the other hand, the quadratic scheme allocates the cross-term among the participants using a quadratic function of elements of the cross-term. Hence, a small variation in power of a participant causes significant change in the allocated cross-term to it. In order to minimize this inconsistency and to effectively deal with cross-terms, the need of a suitable allocation scheme is realized.

In this thesis, a branch-oriented approach has been developed for loss allocation in RDN. In the proposed approach, a geometric scheme of allocation has been employed to deal with cross-terms so as to allocate the losses fairly. This scheme depends neither on the operating point nor on the order in which the trades are entered. In order to check applicability of geometric scheme of allocation, it has been used with both current summation and power summation based formulations of network losses. In current summation based formulation, branch losses are expressed as function of current flow due to network participants, while in power summation based formulation, branch losses are expressed as function of power flow due to network participants. The proposed method has been tested on 33-node and 69-node test RDNs with different load models at two load levels. The results obtained by proposed method have been compared with those by other methods reported in the literature. By comparing the results, it is observed that both current summation based and power summation based proposed approaches encourage DG to participate in the electricity market by assigning more rewards to it. Moreover, the proposed approaches can easily discriminate different conditions of the network (DG connection and load models) while allocating losses to network participants.

Without integration of DG in the RDN, power flow is unidirectional and consumers get power from the sub-station only. However, after integration of DG, the pattern of power flow changes and consumers may get power from both sub-station and DG. Since, in both the cases, total losses in the network are different, loss allocations to consumers are also different. This difference in the allocated loss to a consumer results in its cross-subsidy. Since, in both the cases, power taken by consumers is same, the cross-subsidies of consumers should be minimum. Only few techniques of loss allocation in RDN have mainly focused on cross-subsidies of consumers, however other attributes of a fair loss allocation have not been addressed. Thus, there is a need to develop a new method for loss allocation covering most of the attributes of a fair loss allocation.

A current summation algorithm based branch-oriented approach has been developed for loss allocation in RDN in this thesis to improve the cross-subsidies of consumers and to provide correct signals concerning the size and location of DGs and loads in the network. For this purpose, branch losses have been expressed in terms of branch currents before and after connection of DG. The real and reactive components of the current through a branch have been decomposed into sum of real and reactive components of current by DG and load connected ahead of it. The cross-terms representing the mutual relation among network participants have been allocated by adopting the geometric scheme of allocation. In order to show the effectiveness of the proposed method, it has been tested on 33-node and 69-node test RDNs, at two load levels and the results obtained by proposed method have been compared with those by other methods reported in the literature. The results of proposed method have been found to be consistent with various conditions of the network. Further, it provides moderate cross-subsidies to consumers.

In reality, the end users of electricity are charged for energy consumed. Hence, it is important to deal with allocation of energy rather than power. For an electrical distribution network, time-wise data for generation and load at each node are required to calculate energy losses and thus to allocate the same among network participants. For a practical distribution network, only 20% to 30% of the required data are available through metering. This is because, due to large number of nodes, the installation of meters at all the nodes would become expensive and time consuming process. Even if all data are available, there is a need to perform several load flow and loss allocation calculations, one corresponding to each load level, to allocate the energy losses. Very less work on calculation of energy loss and its allocation has been reported in the literature. Therefore, the need of developing a suitable algorithm for computation of energy losses in absence of actual demand curves is realized.

A new energy summation algorithm based branch-oriented approach is proposed in this thesis for daily energy loss allocation in RDN with DG. It employs the known typical daily generation and daily load curves. Using the statistical characteristics of daily generation and daily load curves, the proposed method calculates their single equivalent values; and allocates the losses among network participants using the equivalent values of generation and load. The proposed method has been tested on 33-node and 69-node test RDNs at different load levels and the results obtained by proposed method have been compared with those by repeated loss allocation method. The error in results obtained by proposed method has been found to be within 10%.

Recently, cooperative game theory based solution concepts, such as Shapley value, Nucleolus value and Aumann-Shapely value have been successfully applied to distribution network for allocation of the network losses. While allocating the losses, Shapley value depends upon the number of permutations, while Nucleolus value depends upon the number of coalitions. If the number of players increases in the game, it requires cumbersome computational efforts to get the solution. On the other hands, Aumann-Shapley value uses the integration of infinitesimal small value of generators and loads which also complicates the computation. Hence, keeping in view the limitations of existing cooperative game theory based solution concepts, there is a need to identify a new cooperative game theory based approach for loss allocation in RDN with DG.

In this thesis, a new cooperative game theory based solution concept, i.e. τ-value, is presented to allocate the network losses among participants in the RDN. In τ-value, the loss allocation is based on the lower and upper vectors of a game. Further, like solutions of Shapley value and Nucleolus value, the solution obtained by τ-value also satisfies all axioms of cooperative game theory. Suitable expressions have been derived to compute the characteristic function of a coalition. The proposed approach uses a two-step method for loss allocation to network participants. In first step, network losses are computed without considering DGs in the network and allocated to all the loads. Then, in second step, network losses are computed considering DGs in the network and loss reduction is allocated to all the DGs. The proposed method has been tested on different test RDNs. The results obtained by τ-value cooperative game theory based proposed method have been found to be in close agreement with those by Shapley value.

The various contributions which have been made through this thesis can be summarized as follows:

- A power based branch-oriented approach has been developed for loss allocation in RDN with DG. Suitable expression for branch losses has been derived using node voltages at sending and receiving ends and apparent power at the receiving node of a branch.
- A branch-oriented approach has been developed for loss allocation in RDN with DG. Both current summation and power summation based formulations of network losses have been presented and a geometric scheme of allocation has been employed to deal with cross-terms.

- A current summation algorithm based branch-oriented approach has been developed for loss allocation in RDN to improve the cross-subsidies of consumers and to provide correct signals concerning the size and location of DG sources and loads in the network. The branch losses have been expressed in terms of branch currents before and after connection of DG.
- An energy summation algorithm based branch-oriented approach has been proposed for daily energy loss allocation in RDN with DG. Using the statistical characteristics of daily generation and daily load curves, the proposed method allocates the energy losses among network participants.
- A τ-value cooperative game theory based solution concept has been used to allocate the network losses among participants in the RDN. Suitable expressions have been derived to compute the characteristic function of a coalition. A two-step method has been used for loss allocation to network participants.