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Branch current decomposition method for loss allocation in contemporary distribution systems

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A B S T R A C T

The presence of distributed generation (DG) units in reconfigured distribution systems introduces complexity in loss allocation (LA). DG integration alters feeder power losses so DG owners (DGOs) may be incentivized or penalized accordingly, whereas network reconfiguration alters feeding path of network user's thus further increases complexity in LA. The LA method should judiciously allocate losses among load points and simultaneously reward DGOs and distribution network operator (DNO) for their contribution towards loss reduction. Moreover, the LA method should take care of the reactive power transactions of network users. This paper proposes a branch current decomposition method (BCDM) based upon circuit theory for allocating losses in active reconfigured distribution system while giving due consideration to reactive power transactions of network users. BCDM considers virtual branch voltage drops which is well supported by analytical treatment. In addition, Superposition is utilized to incentivize/penalize DGOs. A new LA strategy is proposed for fair allocation of loss/loss incentives among network users and DNO. Proposed method is thoroughly investigated under varying loading, load power factors and under varying network topologies. The comparison results obtained on standard test distribution system highlights the importance of proposed method.

1. Introduction

Wide spread deployment of distributed generations (DGs), remote controlled switches and the competitive deregulated environment in power distribution industries are the key factors which have completely revolutionized the electricity tariff calculations for the network users. The assessment of charges incurred against the Joule's heating in distribution feeders is of utmost importance from the network users' as well as from the utility point of view. The Joules heating depends upon the amount of active and reactive power transaction by network users and the network topology of distribution system. The loss allocation (LA) methodology must differentiate among the actual contributions of consumers/DG owners (DGOs), distribution network operators (DNOs) for feeder power. This essentially involves fair allocation of loss penalties/incentives to all entities. In fact, each entity will realize the true costs that it causes in each element of the network [1]. However, allocation of true cost is highly challenging on the account of non-linearity, presence of DGs and the system operation under varying network topologies. Furthermore, since Joule's heating equally depends upon active and reactive power flows, the LA method should reflect a strong signal for each power transactions conducted by network users. The distribution loss allocation method must address all such concerns so that the loss penalties/incentives may be fairly allocated to various entities of distribution system.

In literature many methods of loss allocation are available. Among them, the popularly known methods are: *pro-rata* [2,3], quadratic procedure [1,4], proportional sharing [5–7], substitution method [8], incremental method [9–10], direct loss coefficient method [11], analytical methods [12–14], circuit theory-based methods [15–23], etc. *Pro-rata* is a simplest method but does not consider network topology thus the method has not gained general acceptance [24]. This limitation is overcome in quadratic and proportional LA methods which consider network topology, but are based upon heuristic formulations. In substitution method the impact of DG on losses are determined by the difference of system losses while connecting and disconnecting the DG unit. However, the results obtained are inconsistent and with lack in economic foundation [11,25]. The incremental methods assign incremental change in power loss w.r.t. incremental change in nodal power injection, thus they have gained wider acceptability in market environment. But, this method suffers from negative LA (cross-subsidies), dependency over the slack bus, and over recoveries [25], therefore needs normalization. Direct loss coefficient method directly relates losses to the nodal injections thereby avoid reconciliation. However, the method does not seems to be able to do the allocation of the cross-

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Nomenclature

$\alpha(ij)$ and $\beta(ij)$	components of current phasor $\bar{I}(ij)$
ij	branch number
$\bar{I}(ij)$	current phasor of ij branch
$\bar{I}'(ij)$	current phasor of ij branch with DG
$\bar{I}_{DG}(ij)$	DG current phasor of ij branch
$\bar{I}(ij,k)$	current contributed by kth node in ij branch
$\bar{I}(k)$	current phasor of the kth contributing node
$\bar{I}_{DG}(ij,p)$	current contributed by pth DG in ij branch
k	node number
N	total number of system nodes
NB	total number of system branches
NDG	total contributing DG
P_i	active power injection by ith load point
$ploss(k)$	power losses allocated to kth node
$ploss(ij,k)$	power loss of $n(ij,k)$ node in branch ij
$Ploss(ij)$	power loss in branch ij
PL	system loss
Q_i	reactive power injection by ith load point
$R_{DG}(p)$	remuneration to pth DG
$R(ij)$	resistance of branch ij
$\bar{V}_i$	node voltage of sending end in branch ij
$\bar{V}_j$	node voltage of receiving end in branch ij
$\Delta\bar{V}(ij)$	voltage drop in ij branch
$\Delta\bar{V}'(ij)$	virtual voltage drop in ij branch
$\Delta\bar{\gamma}(ij)$	constrained virtual branch voltage drop in ij branch
$\Delta\bar{\upsilon}(ij)$	fictitious branch voltage drop in ij branch
$x(ij)$	reactance in ij branch
$z(ij)$	impedance in ij branch
$\Omega(ij)$	set of contributing nodes in ij branch
$\omega(k)$	set of branches that connect kth node to the root node
$\theta(ij)$	impedance angle in ij branch
$\phi(ij)$	phase angle of $\bar{I}(ij)$ in ij branch
$\phi_{DG}(ij)$	phase angle of $\bar{I}_{DG}(ij)$ in ij branch
$\phi(ij,k)$	phase angle of $\bar{I}(ij,k)$ w.r.t. $\bar{V}_1$
$\psi(ij)$	phase angle of $\Delta\bar{\gamma}(ij)$ w.r.t. $\bar{V}_1$
$\delta(ij)$	phase angle of the phasor $\Delta\bar{V}(ij)$ with the phasor $\bar{V}_1$
$\zeta(ij)$	phase angle of $\Delta\bar{\upsilon}(ij)$ in ij branch

terms of losses [3]. Several analytical methods have been reported which suggest different participation factor to allocate cross-term in current, power or energy summation approaches. Atanasovski and Taleski [13] proposed power summation method where the participation factor used is based upon quadratic approach. The current summation algorithm developed in [12] to allocate losses in transmission systems. Recently, a novel approach for loss allocation of distribution networks with DGs is proposed in [14]. In this method the cross-terms can be decomposed using logarithmic scheme provided the participation factors to be positive and lie within the range [0–2]. However, such restriction may be violated in practical distribution system having disproportionate load or DG sizes. Refs. [15–19] employed Shapley value and linear circuit theory for simultaneous loss allocation/incentives to network users. However, distribution loads are usually considered as constant power type so these methods are not appropriate. Conejo et al. [20] allocate loss by employing bus impedance matrix, but can allocate negative losses to users that are strategically well positioned in the network thus causes cross-subsidies. Later on, Succinct method [21] and Exact method [22] were proposed by developing analogous linear relationship between loss allocated and the power delivered. Ref. [23] has pointed out the paradox present in the Succinct method, due to which it is unable to give meaningful loss allocation for specific load condition, and is eliminated by suggesting virtual voltage drop in a branch obtained by considering reactance free branches. Although the paradox is removed but the loss allocation becomes inconsistent w.r.t. variation in power factor of load as virtual voltage drop phasor remains in phase with the nodal current phasor.

In active distribution system the active components can alter both magnitude and direction of power flow in distribution feeders thereby affects feeder power losses. Refs. [13,14,23] proposed methods for allocating loss in active distribution systems where the loss reduction caused by DGs is allocated to load points. However, the benefit from the reduced amount of system losses is allocated to each DG as a reward, which will encourage DGs to supply a more effective power system [18]. The LA strategy therefore should reward DGOs who have actually contributed towards feeder power loss reduction.

Distribution networks are generally structured in mesh configuration but operated in radial topology to reduce fault level and the cost of protective schemes [26]. Contemporary distribution systems are equipped with remote controlled switches so may be operated at desirable network topology by exchanging the status of sectionalizing and tie-switches. This process is called as network reconfiguration (NR). However, NR causes alteration in the spatial location of end users so affects their loss/remuneration allocations. Ref. [4] has pointed out this aspect and thereby recommended modified tariff structure, but the study was restricted to the passive distribution systems. In practice, both DGOs and unbundled distribution network operators (DNOs) are subjected to remunerations for loss reduction and penalties for increase in comparison with a target level [27]. However, a conflict usually occurs regarding the share of these loss incentives. DNOs should be encouraged to carry out the essential investment to reduce power losses [27] so may be remunerated against the loss reduction caused by NR. In this way the conflict may be resolved. Nevertheless, correct determination of the loss reduction caused separately by either DGs or NR is cumbersome task.

Keeping in view the above discussion, this paper proposes loss allocation method based upon circuit theory suitable for both passive and active distribution systems. Proposed method fairly allocates losses and loss incentives among network users while giving due consideration to reactive power transactions. The salient contributions of the present work may be stated as:

(1) Development of new LA method by suggesting virtual branch voltage drops that takes care of both active and reactive power transactions of network users. Proposed method is well supported by analytical treatment.
(2) Superposition is employed for accurate allocation of loss incentives/penalties to DGOs.
(3) A new strategy is suggested for the fair allocation of loss and loss incentives among the network users and DNO in active reconfigured distribution systems (ARDS).

The proposed methodology is applied to 33-bus test distribution system and the results of investigation are presented and compared with other established methods.