LOSS ALLOCATION STRATEGIES FOR DISTRIBUTION NETWORK USAGE CHARGES: SOME INVESTIGATIONS

Ph. D. Thesis

PANKAJ KUMAR

(I.D. No. 2014 REE 9058)

DEPARTMENT OF ELECTRICAL ENGINEERING

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This thesis is submitted in
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Pankaj Kumar
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Under the Supervision of

Dr. Nikhil Gupta and Prof. K. R. Niazi

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CANDIDATE'S DECLARATION

I, Pankaj Kumar (I.D. No. 2014REE9058) declare that this thesis titled, "***Loss Allocation Strategies for Distribution Network Usage Charges: Some Investigations***" and work presented in it is my own, under the supervision of Dr. Nikhil Gupta and Prof. K.R. Niazi, Department of Electrical Engineering, Malaviya National Institute of Technology, Jaipur (Rajasthan), India. I confirm that:

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Date: (2014REE9058)

DEPARTMENT OF ELECTRICAL ENGINEERING
MALAVIYA NATIONAL INSTITUTE OF TECHNOLOGY JAIPUR

CERTIFICATE

This is to certify that the thesis entitled, "***Loss Allocation Strategies for Distribution Network Usage Charges: Some Investigations***", submitted by ***Pankaj Kumar*** (Student ID 2014 REE 9058) is a bonafide research work carried out under my supervision and guidance in fulfilment of the requirement for the award of the degree of **Doctor of Philosophy** in the **Department of Electrical Engineering,** Malaviya National Institute of Technology, Jaipur, India. The matter embodied in this thesis is original and has not been submitted to any other University or Institute for the award of any other degree.

(Dr. Nikhil Gupta)
Supervisor & Associate Professor
Department of Electrical Engineering
MNIT Jaipur

(Prof. K. R. Niazi)
Joint-Supervisor & Professor
Department of Electrical Engineering
MNIT Jaipur

Place: Jaipur
Date:

This thesis is dedicated to my parents ***Mr. Raghuvir Singh & Mrs. Sarla Devi*** *who taught me the virtues of discipline, honesty and sincerity.*

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For any glitches or inadequacies that may remain in this work, the responsibility is entirely my own.

(Pankaj Kumar)

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ABSTRACT

The competitive deregulated environment in electric supply industries has completely revolutionized the tariff structure for network users. The cost of distribution charges now has to be allocated judiciously via suitably designing the network use tariff. Apart from other network use charges, the evaluation of the charges incurred against loss allocation is highly complex and challenging task in contemporary distribution systems. This is primarily attributed to the nonlinear relationship between losses and delivered power, complex distribution flows caused by stochastic nature of load demand and power generation from renewables, and topological variations occurred by network reconfiguration. The loss allocation becomes complex as the losses being recorded are due to the joint effect of several entities such as customers, DGOs and DNO, and the latter two entities may cause loss reduction. A fair extraction of losses or incentives to respective entities, however, becomes tedious specifically under varying network topologies of distribution networks. Any unfair extraction may lead to cross-subsidies which may arise serious conflicts among concerned entities. Moreover, it is imperative to address power factor of end users while developing loss allocation methods. The developed method should be simple, accurate and robust, and must prevails good degree of fairness so that can common acceptance.

This thesis addresses the development, investigation and analysis of three different circuit theory-based loss allocation methods, namely Branch Current Decomposition Method (BCDM), Crossed-Term Decomposition Method (CTDM) and Exact Crossed-Term Decomposition Method (ECTDM) while considering aforementioned issues and concerns of modern distribution systems. All proposed methods employ branch oriented approach and suggests analytically driven loss allocation factors. Attempts have been made to develop fair and efficient loss allocation to different concerned entities which are logically convincing and simple to implement. The loss allocation is extracted with either positive or negative sign that depends whether the stake holder is contributing towards losses or loss reduction. The principle of Superposition is employed, in a different way, to allocate losses to DGOs. In addition, the loss allocation strategy suggested in order to avoid conflict among different concerned entities. Proposed methods are applied to standard as well as practical distribution systems. Proposed methods are thoroughly investigated while considering realistic operational conditions such as variation in system loading, load power factor and reactive power injection from DG units. The application results reveal the importance of proposed methods in the context of contemporary distribution systems.

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NOMENCLATURE

$CN(ij)/CDG(ij)$	Set of contributing node/DG current in branch *ij*
$CT(ij)$	Cross-terms of current in branch *ij*
$CT(ij, k)$	Cross-terms of each contributing node current $\boldsymbol{I}(ij,k)$ in branch *ij*
$CT^a(ij)$/ $CT^r(ij)$	Crossed-term for active/reactive component of contributing currents in branch *ij*
$CT^a(ij, k)$/ $CT^r(ij, k)$	Crossed-term related to active/reactive component of contributing node current $I(ij, k)$ in branch *ij*
$CT_{DG}^{a}(ij, p)$/ $CT_{DG}^{r}(ij, p)$	Crossed-term for active/reactive component of contributing *p*th DG currents in Branch *ij*
ij	Branch number
$\boldsymbol{I}(ij)$	Current phasor of *ij* branch
$\boldsymbol{I'}(ij)$	Current phasor of *ij* branch with DG
$\boldsymbol{I_{DG}}(ij)$	DG current phasor of *ij* branch
$\boldsymbol{I}(ij, k)$	Current contributed by *k*th node in *ij* branch
$\boldsymbol{I}(k)$	Current phasor of the *k*th contributing node
$\boldsymbol{I_{DG}}(ij, p)$	Current contributed by *p*th DG in *ij* branch
k, q	Node number
$Lf(ij, k)$	Loss allocation factor for $CT(ij,k)$
$Lf^a(ij,k(q))$/ $Lf^r(ij, k(q))$	Loss allocation factor for crossed-terms from *k*th and *q*th active/ reactive nodal injections
$MT(ij)$	Mixed terms of current in branch *ij*
$N/NB/N_{DG}$	Total nodes/ branches/DGs in the distribution system
p, r	DG number
P_i	Active power injection by *i*th load point
$ploss(k)$	Power losses allocated to *k*th node
$ploss(ij,k)$	Power loss of *k*th node in branch *ij*
$ploss(ij)$	Power loss in branch *ij*
$Ploss$	System loss
Q_i	Reactive power injection by *i*th load point
$Ru^a(ij, p(r))$/ $Ru^r(ij, p(r))$	Remuneration allocation factor for crossed-terms from *p*th and *r*th active/ reactive DG power injections

$Ru(ij, p)$	Remuneration allocation factor to bifurcate $CT^{DG}(ij, p)$
$R_{DG}(p)$	Remuneration to pth DG
$R(ij)$	Resistance of branch ij
$\Re\{\boldsymbol{x}\}/Im\{\boldsymbol{x}\}$	Real/imaginary part of complex quantity $\boldsymbol{x}$
$ST(ij)$	Sum of squared-term of contributing node currents in branch ij
$ST_{DG}(ij, p)$	Squared-term of contributing pth DG current in branch ij
V_k	Voltage at kth node
$\Delta\boldsymbol{V}(ij)$	Voltage drop in ij branch
$\Delta\boldsymbol{V}'(ij)$	Virtual voltage drop in ij branch
$\Delta\boldsymbol{\gamma}(ij)$	Constrained virtual branch voltage drop in ij branch
$\Delta\boldsymbol{\upsilon}(ij)$	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 $\boldsymbol{I}(ij)$ in ij branch
$\phi_{DG}(ij)$	Phase angle of $\boldsymbol{I_{DG}}(ij)$ in ij branch
$\phi(ij, k)$	Phase angle of $\boldsymbol{I}(ij, k)$ w.r.t. $\boldsymbol{V}_1$
$\psi(ij)$	Phase angle of $\Delta\boldsymbol{\gamma}(ij)$ w.r.t. $\boldsymbol{V}_1$
$\delta(ij)$	Phase angle of the phasor $\Delta\boldsymbol{V}(ij)$ with the phasor $\boldsymbol{V}_1$
$\zeta(ij)$	Phase angle of $\Delta\boldsymbol{\upsilon}(ij)$ in ij branch

ABBREVIATIONS

ACO	Ant Colony Optimization Algorithms
ADN	Active Distribution Network
BCDM	Branch Current Decomposition Method
BCDLA	Branch Current Decomposition Method for Loss Allocation
BESS	Battery Energy Storage Systems
CTDM	Crossed-Term Decomposition Method
CVBVD	Constrained Virtual Branch Voltage Drop
DER	Distributed Energy Resource
DG	Distributed Generation
DGO	DG Owner
DN	Distribution Network
DNO	Distribution Network Operator
ECTDM	Exact Crossed-Term Decomposition Method
EM	Exact Method
ESMLA	Energy Summation Method for Loss Allocation
EV	Electric Vehicle
FBVD	Fictitious Branch Voltage Drop
GA	Genetic Algorithm
LA	Loss Allocation
LAF	Loss Allocation Factor
LAL	LA to load
LAS	Loss Allocation Strategy
LI	Loss Incentive
Max.	Maximum Value
Min.	Minimum Value
MLC	Marginal Loss Coefficient
NC	Nominal Configuration
NLA	Net LA
NR	Network Reconfiguration
NRU	Net Revenue to Utility
OC	Optimal Configuration
PSMLA	Power Summation Method for Loss Allocation

PSO	Particle Swarm Optimization Algorithm
RADN	Reconfigured Active Distribution Network
RBD	Reconfiguration Benefit to DNO
RDG	Remuneration to DGO
RCS	Remote Controlled Switches
RN	Reconfigured Network
SD	Standard Deviation
SM	Succinct Method
SV	Shapley Value
TPC	Tai Power Corporation Distribution
VBV	Virtual Branch Voltage

CHAPTER 1
INTRODUCTION

The deregulation and consequent unbundling of electric power industries resulted into the formation of generation, transmission and distribution companies. These changes brought competition in electricity business. Conventionally, the transmission and distribution of electrical power are the activities, which are generally considered as a natural monopoly and their cost analysis of network usage was based on heuristics. However, with the competition in electricity business, the focus of the transmission and distribution companies shifted towards identifying the actual network usage cost of every individual entity. The larger portion of network usage cost lies on account of power loss occurring in the network. The power loss in transmission and distribution systems is mainly on account of consumer loads or network users. The network loss allocation is basically the distribution of total network power loss among the network users. The network usage costs involved in transporting electrical power to the network user are allocated to network users via network use tariffs. With the advent of electricity markets, the distribution system loss allocation has assumed significant importance in the context of contemporary distribution systems on account of involved economics. Therefore, the focus of the thesis is on loss allocation in distribution systems.

The distribution system loss allocation is a very complex problem especially in the context of modern distribution systems which are equipped with distributed generations (DGs). The distribution systems losses are due to the flow of load currents in the network branches. The difficulties in loss allocation arise due to the non-linear relationship between losses and currents in the branches of the network. This problem is further complicated due to spatially distributed loads. The network topology as well as the presence of distributed generations (DGs) can alters line flows and thus further complicates the loss allocation problem. The presence of DGs normally causes a reduction of distribution loss and therefore their loss allocation should be in the form of revenue reward. With these concerns, the loss allocation (LA) of modern distribution system becomes highly complex problem. The competition and distribution system economics demands the fair allocation of losses among different entities contributing towards net power losses. Though true loss allocation is not possible due to complexity of the problem, no matter the method of loss allocation, a set of fundamental principles must be respected in order to guarantee a correct allocation [1].

The legacy (passive) distribution systems are now transforming into active distribution systems by the widespread deployment of DGs owing to social and techno-economic concerns. The growing presence of local generation sources in radial distribution systems has modified the flow of power and some-times it may reverse the power flows in some distribution system branches [2]. This affects feeder power losses and consequently affects the LA to consumers. Moreover, the DG owners (DGOs) who are contributing towards loss reduction may ask for revenue reward. Furthermore, distribution networks may frequently undergo topological changes through network reconfiguration (NR). Distribution system automation has facilitated topological variation in network and is usually done by distribution network operator (DNO) to achieve one or more operational objectives. However, NR causes spatial changes of end users within the distribution network (DN) thus affects their LA. Since NR balances load among distribution feeders, it may be reflected in loss reduction. In view of this DNO should also be incentivized for any loss reduction caused by NR. The LA method therefore should penalize or incentivize the network users depending upon their effect on the total distribution loss. However, loss allocation in the presence of DGs, consumers and DNO due to NR becomes a tedious task as losses are occurring due to the simultaneous presence of these three entities, and both the magnitude and sign of the losses incurred by an individual entity becomes dynamic due to complex variations in line flows as well as spatial location of the end users.

Several loss allocation methods have been proposed in the literature. These methods may be broadly categorized in three main families, namely pro rata procedures, marginal procedures and proportional procedures. Most of these methods have been attempted for distribution systems but suffers from disproportionate allocation, singularity of bus-admittance matrix or over recovery, etc., and ignores reactive power flow while allocating losses. However, transmission and distribution systems are different with reference to the selection of slack bus, *R*/*X* ratio of lines, characteristic of load and load profile, penetration level of DGs, nature of power transactions, range of power factor, operating topology of network, etc. Some other methods such as Succinct method [3], Costa's method [1], Exact method [4], power summation method [5], energy summation method [6], branch current decomposition method for loss allocation [7], Jharomi's method [8] and several other methods have been proposed by focusing attention on distribution systems. Most of these methods are very interesting as they have employed different circuit theory-based approach, but are unable to precisely allocate losses considering operational realities of modern distribution systems. In fact, distribution systems must be seen at length before devising any LA method.

Some of the above mentioned circuit theory-based methods employed branch oriented approach while allocating losses. In this approach, the loss contribution in each DN branch from all the downstream nodes is determined separately and then LA is evaluated for each end user. Though the branch oriented approach is quite straightforward in understanding and implementation for passive DN with fixed configuration, but becomes highly complex in the presence of DGs or when distribution network is reconfigured. This is probably the reason that the approach is yet not comprehensively attempted while allocating losses or incentivizing different entities of distribution systems.

Distribution systems have diverse customers with reference to power and power factor. The power factor may be exceptionally poor at certain nodes. The low power factor causes increased power loss and may result in heavy voltage sag along the distribution feeder. This increases congestion in distribution feeders, reduces energy efficiency of the system and sometimes creates very difficult operating conditions. On the contrary, DGOs should maintain better power factor to avoid deficiency of reactive power with in distribution system. The LA method specifically devised for distribution systems must address this issue while allocating losses among end users.

This thesis addresses the development, investigation and analysis of three different circuit theory-based LA methods using branch oriented approach while considering aforementioned issues and concerns of modern distribution systems. A brief literature survey about the subject is presented in chapter 2 and critical reviews are extracted. On the basis of critical reviews, the research objectives for the thesis are framed.

The well-established method proposed by Carpento *et al*. [7] is modified by proposing branch current decomposition method (BCDM) in chapter 3. The method of [7] has fully neglected line reactance in order to overcome paradox presented in Succinct’s method [3], but the method not duly considers power factor of network users. In BCDM, the line reactance is made dynamic by suggesting constrained virtual branch voltage drop that considers power factor of end users while allocating losses. In addition, a novel idea of using Superposition is suggested while incentivizing DGOs. It has been shown that Superposition can be applied, in a different manner, to modern distribution systems being well equipped with distributed energy resources (DERs). A loss allocation strategy (LAS) is finally proposed so that the benefit of loss reduction can be judiciously disbursed among DGOs and DNO to resolve any conflicts in this regard.

In this thesis work three different loss allocation methods have been proposed. Developed methods have been thoroughly investigated under wide range of operating conditions and network topologies. The real power loss in a branch of an ac system can be expressed using two fundamental approaches, viz., real part of the product of branch voltage drop with complex conjugate of branch current or the product of square of magnitude of branch current with branch resistance. In chapter 3, a loss allocation method has been developed using branch current decomposition. The method also enables to incentivize or penalize DGOs and DNO under dynamic network topology. In chapter 4, the second approach is used by proposing cross-term decomposition method (CTDM) for LA in distribution systems. However, this approach imposes difficulty while decomposing crossed-terms pertaining to LA. A loss allocation factor (LAF) is suggested in CTDM. LAF is established analytically and it allocates crossed-terms among all the downstream customers of distribution feeder.

The power factor of end users varies through wide limits in distribution systems. Poor power factor causes more feeder power loss to transport same amount of active power. That is why electric utility consistently encourages end users to maintain better power factor at their premises. Since both reactive and active component of line flow are equally responsible for feeder power loss, a new cross-term decomposition method, called exact cross-term decomposition method (ECTDM) is proposed in chapter 5. The ECTDM method independently considers active and reactive components thus judiciously allocates losses to end users by truly considering power factor. The LAF suggested for this method is also derived analytically.

All the developed methods have been thoroughly investigated on standard/modified 33-bus test distribution system and 83-bus Tai Power Company practical distribution system. The accuracy of all the methods is deeply investigated by varying system loading, power factor of load and reactive power injection from DG units. The accuracy of the methods is compared with established LA methods by conducting statistical error analysis. The results of proposed LA strategy to disburse remuneration against loss reduction among DGOs and DNO are also presented.

In chapter 6, a comparative study of the developed methods has been carried out. The conclusions drawn from the thesis work are presented. This chapter also presents future scope of the thesis work.

CHAPTER 2
LITERATURE REVIEW

In the present scenario, there is rising trend towards DG integration and system automation with more emphasis on efficiency and economy in power delivery to the consumers. The competitive deregulated environment in electric supply industries has completely revolutionized the tariff structure for network users. The cost of transmission and distribution charges now has to be allocated judiciously via suitably designing the network use tariff. Apart from other network use charges, the evaluation of the charges incurred for loss allocation is highly challenging on account of nonlinear relationship between losses and power delivered. The allocation of losses should be fair, consistent and judicious with regard to customers as well as network operator. Moreover, the loss allocation scheme should be simple to understand and easy to implement, and should be judicious to satisfy customers. For the given load demand, the system losses are also the function of load power factor. It is imperative to give due consideration to load power factors while designing a loss allocation method, yet maintaining appropriate fairness in loss allocation is highly appreciated. Since the advent of deregulation of electricity market, several loss allocation methods have been proposed and are in practice from more than a couple of decade. A brief literature review about LA in distribution systems is presented while addressing several issues and concerns pertaining to contemporary distribution systems including critical analysis of existing LA methods. On the basis of literature review, some research gaps have been identified and research objectives of the thesis are framed. A brief literature about loss allocation without DG, with DG and impact of NR on loss allocation is presented in the subsequent section.

2.1 LOSS ALLOCATION

The loss allocation was first introduced in transmission systems. Several transmission loss allocation methods employed may be broadly categorized as: *Pro-rata* [9]-[10], Proportion sharing procedures [11]-[13], Quadratic schemes [1], [14], Geometric allocation [14]-[16], Marginal loss coefficient (MLC) [17], [18], etc. With the advent in deregulation, the competitive business environment evolved. Distribution losses are significant owing to relatively low operational voltages, a fair distribution loss allocation becomes an important issue for the survival of utilities in the competitive market. Though, true loss allocation of these losses is not possible on account of non-linearity between power losses and the power delivered, but some very interesting distribution loss allocation methods such as Exact Method [4], Power Summation Method for Loss Allocation (PSMLA) [5], Energy Summation Method for Loss Allocation (ESMLA) [6], Branch Current Decomposition Loss Allocation (BCDLA) [7], Jharomi's Method [8], etc. Aforementioned methods have employed different approaches in order to provide a strong economic signal for loss allocation. These methods have their own advantages and disadvantages. A brief literature review about various loss allocation methods is presented here.

Pro-rata methods were first used to allocate losses in transmission systems in mainland Spain, and England and Wales against transportation of power from generating unit to the suppliers. The word Pro-rata is originally a Latin word that means 'according to the rate'. With these methods, losses are first divided equally between generators and demands, and then an allocation within each category is made based on the level of power or current injection [19]. Pro rata methods are one of the most common procedures which are simple to understand and implement [20], [21]. However, the loss allocation process emphasizes current rather than power injections, an approach that is intuitively reasonable and leads to a natural separation of system losses among the network [20]. Nevertheless, these methods "ignore" the network topology [5], [8], [20]-[25] therefore they becomes unreliable.

The branch power loss may be considered as the sum of squared and crossed-terms of load currents for all the nodes beyond the branch. The squared-terms allocated directly to concerned nodes, but the allocation of crossed-terms imposes real challenge. This allocation is suggested using various heuristic approaches such as proportional sharing, quadratic and geometric allocation.

The limitation of *Pro-rata* methods is overcome in *Proportion sharing procedure.* This procedure is based upon the principle which states that "the power flow reaching a bus from any power line splits among the lines evacuating power from the bus proportionally to their corresponding power flows," [21]. This approach was used in New Zealand and Poland. However, the procedure does not provide any theoretical foundation [12], also without approximation simultaneous allocation to end users is not possible [22].

The quadratic schemes developed considers network topology while allocating losses. The loss allocation factors employed with the assumption that power losses grow squarely with power flows. A. G. Expósito *et al.* **[**14**]** first presented quadratic scheme for transmission losses allocation. For multiple transaction frameworks, the Ref. [26] presented ''physical power-flow-based'' approach which considers quadratic loss approximation for loss allocation. Quadratic sharing procedures consider reactive power transactions and network topology, but loss allocation factors were based upon heuristics.

In Geometric Allocation [14] the decomposition of crossed-terms is proposed using a logarithmic scheme. The authors admitted that for fair loss allocation, the participation factor should be positive and must lie within the range of 0–2. This, however, true for transmission systems, but not for distribution systems.

Pro-rata, marginal and proportional sharing procedures ignore reactive power flow in the process of loss allocation [1]. So these methods are not suitable for distribution systems having customers with diverse power factors.

It is the most commonly used procedure, for example PJM market. Marginal or Incremental transmission loss methods [18], [27], [28], employed incremental change in losses with per unit change in the power injected at each node to allocate losses to generators and loads. The sensitivity analysis taken into account the problem constraint, network topology and power transactions with system buses. The sensitivity analysis, however, does not answer the question where the power goes; it answers the question how would line flows change following a change in the nodal generation demand [29]. However, these methods suffer from the issues like dependency on the slack bus, cross-subsidies and over recovery. It happened because losses are also allocated to slack bus which is fair for transmission systems but unfair for distribution systems where no losses should be allocated to substation bus acting as the slack bus.

Game theory is a mathematical study to optimizing the agents or players involve in an objective. Many researchers [30]-[34], have addressed the problem of loss allocation using Game theory. They combined basic circuit theory with the game theory for fair division of the branch power flow and losses among the generators and loads. However, these methods demand huge data storage and a substantial computational burden and as such these methods are not suitable for real-time applications. The lack of a physical and economic justification for this allocation ratio obtained using these methods causes its specification to be arbitrary, which is not satisfactory for market participants [35]. The limitation of these methods is that they are based upon linearized circuit models to employ Shapley value (SV), therefore cannot be applied to distribution systems.

A. Elmitwally *et al.* [36] proposed an analytical method for loss allocation in restructured transmission systems. It is based on circuit laws and the concept of the transmission network usage. The method employed the division of line current into two components by using Superposition principle. The first one is due to the power transfer from GENCOs to DISCOs and the second component due to the voltage difference between GENCO buses.

M. Khosravi *et al.* [25] proposed an algorithm to allocate transmission losses to consumer loads and generators of the network in a fair manner. This method can be applied to any topologies of the system. This algorithm is based on the active and reactive power exchange in the network. Therefore, the loss of each line is composed of two terms and the power loss of each line is allocated to loads and generators. This method can penalise or reward a market participant in accordance to positive or negative impact on energy loss reduction. However, the method suffers from the over-recovery thus need normalization.

Several loss allocation methods have been devised using circuit theory-based approach. The approach is straight forward though it needs power flow tracing in the system. The circuit-based methods are defined on the basis of the system structure, expressed by the bus impedance matrix and of the results of a power flow calculation [7]. Some of these methods are presented here.

The method proposed in [20] is based upon the Z-bus matrix of the network. The method impetus for the current-based loss allocation to provide a natural mathematical separation of system losses among network buses. Though the method considers network topology but sometimes yields negative allocation to strategically well positioned customers. Moreover, it allocates significant amount of losses to the slack bus owing to its high current injection thus results in cross-subsidy. Instead of using *Z*-bus, the method of [37] employed modified *Y*-bus matrix by proposing a strategy to allocate the active power losses. However, these method depend upon the non-singularity of *Y*-bus matrix. Since distribution systems are characterized by negligible shunt reactance, these methods are not suitable for distribution systems consists of overhead lines [5], [38].

In substitution method [39], the impact of a network user on the system losses is assessed by calculating the difference in losses when the user is connected and when it is disconnected from the network. The substitution method was used at Electricity Pool in England and Wales. Although the method is simple to understand and easy implement, but is found to be inconsistent so gives unfair loss allocation as reported in [40].

The Succinct's method [3] presented an interesting linearized model for loss allocation using branch oriented approach where the allocated losses are indicated by the projections of all contributing load current phasors onto the voltage drop phasor of the branch considered. The method needs only one assumption that is to maintain node voltage profile of the power system at an acceptable level. The advantage of the method is that it is free from loss allocation factor thus provides fair loss allocation. However, the method presents a paradox according to which it is unable to provide a meaningful loss allocation under specific circumstances concerning the reactive power loads [7].

Earlier, most of the distribution tariff structures were incurred fixed charges, a portion of which against feeder power losses, using two-part tariff. The scheme was highly simplified but was not fair because the losses incurred is the function of load supplied and the feeding path, both cannot be identical to different network users. With the advent of deregulated electricity market, the distribution utilities have got more attention towards loss allocation on account of significant annual losses incurred. Therefore, transmission loss allocation methods were employed to allocate distribution losses. However, most of the transmission LA methods suffer from disproportionate allocation, singularity of bus-admittance matrix, over recovery, etc., and also ignores the reactive power flow the consideration of which is very crucial while allocating distribution losses. In fact, transmission and distribution systems are different with reference to the selection of slack bus, R/X ratio of lines, characteristic of load and load profile, penetration level of DGs, nature of power transactions, range of power factor, operating topology of network, etc. in recent past several remarkable distribution loss allocation methods are suggested. A brief review of some of these methods is presented below.

The Exact method [4] proposed is based upon circuit theory where the losses are allocated to each customer by determining its actual contribution using branch oriented approach. The only disadvantage of this method, it has been developed only for radial distribution system [38]. However, the method is analogous to Succinct's method thus suffers from the same limitation which is crucial while dealing with distribution systems.

2.1.1 LOSS ALLOCATION WITH DISTRIBUTED GENERATIONS

The alarming global warming, depletion in fossil fuel reserves, congestions in transmission lines and cost cutting in renewable energy sources may be called as the prominent reason that enforces self-sustainability in distribution systems by integrating dispersed or distributed generations (DGs). Thus a passive distribution system gradually transforms into active distribution systems. As a consequence, contemporary distribution systems can be seen with varying degree of DG penetrations. Uncounted benefits are associated with DG integration, but it leads to the shift of paradigm of unilateral power flow in distribution feeders that primarily makes complex operations of distribution systems. In fact, the integration of DG units alters power flow in DNs thus affects losses and node voltage profiles. This not only introduces sign in loss allocation, as the power generation from DG units may decrease or increase losses, but also makes loss allocation a challenging task. Therefore, researchers attempted distribution loss allocation while duly addressing the presence of DGs.

J. Mutale *et al.* [41] presented marginal loss coefficients (MLC) and direct loss coefficients (DLC) methods for allocating losses in generic distribution systems with embedded generation. The DLC method uses Taylor series expansion at an operation point to relate losses directly to the nodal injections and therefore does not require reconciliation. In contrast, the MLC method allocates marginal losses whereas the DLC method allocates total losses [41]. Both of these methods, however, rewarded customers in some situations, instead of paying for losses thus are incapable in providing allocation to the crossed-terms of losses [1]. Furthermore, the complexity increases due to evaluation of Hessian matrix and the results have imprecisions on account of the truncation error while expanding Taylor series.

The branch current decomposition method for loss allocation (BCDLA) method is proposed by [7] which is based upon branch oriented approach. The method assumes reactance-free in order to overcome the limitations of well-established methods, e.g. Succinct's method [3] and Exact method [4].The method allocates losses to each bus of the network as a product of bus current injection and the voltage drop between the slack bus and the node under consideration [5]. This method have limitation in terms of reduced losses of customer who are actually creating the losses and then consequently reduces the loss incentives to DGOs, even some DGs are assigned with losses for reducing system losses. Moreover, this method is applicable to those end users which are placed individually, but not simultaneously, at different nodes. Later on, the same authors in [2] have employed this method for loss partitioning among the phase currents in three-phase distribution systems.

The branch power losses in quadratic form consists of squared and crossed-terms of nodal injections. The squared-terms provides loss allocation, but the crossed-terms needs a fair allocation among contributed nodes. Several LA methods [1], [5], [6] have adopted quadratic scheme to allocate losses in active distribution system using different strategies. Ref. [1] suggested loss incentives to DGOs against actual amount of loss reduction caused by injected DG power. The authors have pointed out that node voltage profiles are significantly improved in the presence of DG units therefore the power losses incurred while delivering power in active distribution systems will not be same as that obtained in the absence of DG units. Therefore, the method suggested reconciliation against the node voltage variations. PSMLA [5] and ESMLA [6] methods have also employed quadratic scheme while allocating crossed-terms of losses by separately considering active and reactive component of currents. ESMLA [6] employs statistical representation of daily load and generation curves. However, the implementation of the latter method can be on ex-post or ex-ante basis. In ex-post application ESMLA is much better alternative than PSMLA if no metered data is available, while in case when metered data is available PSMLA can be more effective [6]. Both of these methods attempted to minimize cross subsidies so may divert some loss incentives towards customers which are actually incurred these losses.

Ref. [8] presented a loss allocation method for radial distribution systems where the allocation is carried in three steps. In the first step, LA is done where generation was more than consumption, losses are allocated to the loads owing to active flows and then due to reactive flows. In the next step, losses are allocated to DGs where the consumption was more than generation while assigning zero losses to loads at those nodes where DG power is more than the load. The over-recovery of the losses incurred needs normalization which is being executed in the final step.

Geometric method was considered in [15]-[16]. Originally the approach was suggested for transmission systems [14] but is attempted for distribution systems. This approach employed current summation algorithm to allocate losses. In these methods, there is a limitation that the participation factor should be positive and must lie within the range of 0–2. But, this limitation may be violated in practical distribution systems having disproportionate sizing of loads and/or DGs.

Recently, Ref. [38] presented a method to allocate losses in weakly meshed distribution systems using Shapley value. In [42] a method is presented for loss allocation in DNs based on Game theory. More specifically, it was based on Aumann-Shapley theory and circuit laws and offers an analytical solution that is easy to implement and results in fair allocation of losses among the participants. However, the procedure equally divides crossed-terms of losses among the different players. Some other researchers [43], [44] employs Game theory approach for loss reduction allocation using Cooperative Game theory. But, Game theory approach needs linearized circuit modelling, which in fact non-linear thus may leads to unfair loss allocation.

2.1.2 LOSS ALLOCATION WITH NETWORK RECONFIGURATION

The Smart Grid philosophy enforces distribution automation in distribution systems to achieve optimum operation. Contemporary distribution systems have remote controlled switches (RCSs) for distribution lines so that the system can be operated at optimum reliability and energy efficiency during normal and abnormal states of operations. Distribution systems are structure in mesh but operated in radial configuration to reduce the cost of protective schemes [45]. Distribution systems have sectionalisation switches (normally closed) and tie switches (normally open). There are several radial topologies but one of them may optimize desired objectives(s). The desired radial topology of a DN may be obtained by exchanging the status of these line switches and the process is known as network reconfiguration (NR) [46]. Numerous works have been reported [45]-[55] where NR is performed for loss minimization besides other objectives. The distribution system automation facilitates distribution network operator (DNO) to perform NR using RCSs operation which is now becomes a usual task. NR transfers loads from heavily loaded feeders to lightly loaded feeders to achieve load balancing thus reduces feeder power losses. Thus power flows among distribution lines alters in both magnitude and direction whenever performing NR. Moreover, the topological variations in radial DN caused by NR alter spatial location of end users from the substation. Therefore, LA becomes tedious and challenging task in reconfigured active distribution networks (RADNs).

Limited works have been reported where attempts have been made for loss allocation in distribution systems. Ref. [4], [55] allocates losses among customers in radial distribution system before and after NR by employing quadratic-loss allocation scheme. The authors have pointed out that NR causes loss reduction to customers, however, some times the reverse may be true. Since NR conducted by DNO, therefore any benefit of loss reduction cannot be granted to customers. The analysis is limited to passive distribution systems.

2.2 CRITICAL REVIEW

From the aforementioned literature review, following research have been identified:

1. Most of the transmission LA methods suffer from disproportionate allocation, singularity of bus-admittance matrix, over recovery, etc., and ignores the reactive power transactions of end users while allocating losses in distribution systems.
2. In fact, transmission and distribution systems are different while considering the selection of slack bus, *R*/*X* ratio of lines, characteristic of load and load profile,

penetration level of DGs, nature of power transactions, power factor of end users, operating topology of network, etc.

3. Some established LA methods, e.g. Succinct's method, Costa's method, Exact method, PSMLA method, ESMLA method, BCDLA method, Jharomi's method, etc. have employed different circuit theory-based approaches, but are unable to precisely allocate losses considering operational realities of modern distribution systems.
4. Some of the circuit theory-based methods have employed branch-oriented approach to determine the contribution of downstream nodes in branch power loss. Though the branch- oriented approach is quite straightforward for passive DNs, but becomes highly complex for RADNs. This probably the reason that the approach is yet not comprehensively attempted.
5. The transportation of power to customers causes definite power loss. On the other hand, the integration of DG units may reduce or increase power losses. However, NR usually results in loss reduction. These aspects have not been yet comprehensively addressed while devising LA method for distribution systems.
6. Distribution systems have end users with diverse power factors. The low power factor causes increased power losses to deliver same amount of active power. This causes more power losses and also results in heavy voltage sag. On the other hand, DG units should maintain appropriate power factor otherwise the deficit of reactive power will results in voltage sag besides increased power losses. Therefore, power factor is an important issue while allocating losses or loss incentives to end users.
7. Practically, exact loss allocation is extremely difficult, not only because of the non-linear relationship between losses and the power delivered but also on account of the fact that the net losses recorded by the utility is due to the combined effect of load supplied to customers, power injected by DG units and the loss reduction caused by reconfigured DN. With these concerns, there is a pressing need to identify the contribution of different entities which are contributing toward the loss recorded by the utility.
8. The LA method devised should addresses the issues discussed pertaining to contemporary distribution systems and must allocates losses or loss incentives against the actual amount of losses incurred or the loss reduction caused by different entities in a judicious manner to avoid conflicts among the entities. Moreover, the LA method should be simple to understand and easy to implement for its common acceptance from utilities and/or concerned authorities.

2.3 RESEARCH OBJECTIVES

On the basis of aforementioned critical review, the following research objectives have been framed for the thesis work.

1. To carry out an extensive literature survey in the area of loss allocation, DG penetration, network reconfiguration, loss allocation strategies (LASs), etc. in the context of contemporary distribution systems. To understand about the general aspects, structures and behaviour of contemporary distribution systems.
2. To develop suitable circuit theory-based LA methods for contemporary distribution systems which takes into account power factor of consumers, active and reactive power transactions from DG units, and topological aspects of the DNs.
3. To develop a method to remunerate DGOs against the actual amount of loss reduction caused by individual DG unit.
4. To develop suitable LAS for contemporary distribution systems in order to avoid conflict among customers, DGOs and DNO while disbursing loss allocation/loss incentives, as the case may be.
5. To investigate the applicability of developed LA methods and LAS on standard test and practical distribution systems.

This thesis presents three circuit theory-based LA methods for RADNs while duly considering above mentioned vital issues of contemporary distribution systems. The prominent features of these methods lies on the theme that end users should maintain better power factor to avoid penalties and facilitate judicious extraction of loss or loss incentives for DGOs and DNO from the net system losses being recorded by the utility.

Chapter 3 presents Branch Current Decomposition Method (BCDM) for loss allocation. The method overcomes the limitations of established BCDLA method by analytically deriving virtual branch voltage drop. Superposition principle is suggested, in a different way, to remunerate DGOs and finally a LA strategy (LAS) is suggested to avoid conflicts among different entities cause loss or loss reduction in RADNs. The method is thoroughly investigated on standard test and practical distribution systems and the obtained results are presented and discussed.

Another LA method, i.e. Cross-term Decomposition Method (CTDM) is proposed in Chapter 4 using different circuit-theory-based approach as employed in proposed BCDM. In this method, the crossed-terms of losses are decomposed by deriving separate loss allocation factors (LAFs) for customers and DGs. The method is thoroughly investigated on standard test and practical distribution systems and the obtained results are presented and discussed.

In Chapter 5, an Exact Cross-term Decomposition Method (ECTDM) is presented. The method is different from proposed CTDM as it specifically considers active and reactive transactions of end users by suggesting separate LAFs for these transactions. The method is thoroughly investigated on standard test and practical distribution systems and the obtained results are presented and discussed.

Finally, a comparison of all the three proposed methods is presented in Chapter 6. The chapter also addresses salient contributions and conclusions along with prospective future scope of the present work.

CHAPTER 3
BRANCH CURRENT DECOMPOSITION METHOD

The distribution system loss allocation is basically the distribution of total distribution loss among the consumers. It is a variable part of distribution usage tariff which is levied by the consumers over and above other charges. Contemporary distribution systems unlike conventional distribution systems are complex network with widespread deployment of renewable DG units on account of techno-economic and environmental concerns. The DG units may be owned by private DG operators (DGOs). With the advent of electricity markets, the distribution system loss allocation has assumed significant importance in the context of contemporary distribution systems on account of economics involved. The direct stake holders of distribution loss allocation are consumers, distribution network operators (DNOs), and DGOs. The distribution system loss allocation could be positive or negative depending whether the stake holder are contributing towards increase or decrease of the total loss respectively. The deployment of DG normally contributes towards loss reduction. Similarly network reconfiguration (NR), which is an effort of DNO also contributes towards loss reduction. On the other hand, consumers are the source of distribution loss. Under such conditions the distribution LAS becomes a difficult task on account of complexity of distribution network and nonlinear nature of loss allocation problem. In fact no unique and perfect loss allocation method exists in the literature. Attempts are being made to develop fair and efficient loss allocation methods which are logically convincing and simple to implement.

Several loss allocation methods have been suggested in literature as discussed in Chapter 2, which have employed different approaches and provide loss allocation in close proximity. These methods have different logics and philosophies, and sometimes conflict in allocating remuneration among DGOs and DNO providing marginal differences in loss allocation. However, loss allocation and LAS devised must be judicious enough to provide true reflection of the realistic facts of distribution systems under all operating conditions to satisfy various stake holders by a good degree.

This chapter proposes a new Branch current Decomposition Method (BCDM) for contemporary distribution systems. The method is based upon circuit theory and is more realistic as it give due consideration to reactive power transactions which has been ignored in most of the methods developed. The salient features of the method are application of constrained virtual branch voltage drop (CVBVD) to allocate losses, the application of

Superposition principle to remunerate individual DGO and LAS for reconfigured active distribution network (RADN). The proposed methodology is first applied to 33-bus test distribution system and then to the 83-bus practical distribution system. The method is thoroughly investigated under varying conditions of load, power factor and reactive power injection from DG units. The application results of the proposed method are presented and compared with other established methods.

3.1 PROPOSED BRANCH CURRENT DECOMPOSITION METHOD

Initially, many transmission loss allocation methods [1], [3], [9]-[14], [17], [18], [20], [41] have been studied to allocate losses in distribution systems, as well. However, these methods have limitations due to one or more reasons such as over recovery, cross subsidy, consideration of reactive power transaction, etc. This leads to the development of several interesting approaches for distribution loss allocation in which the circuit theory based methods [7], [4], [5], [6] become the centre of attraction for researchers due to their simplicity in understanding and application. However, the exact determination of LA is impossible due to non-linear relationship between power losses and nodal power injections. Therefore, each of these developed methods, though are good enough, have faced strong imputation on fairness of LA which may be briefly explained as below.

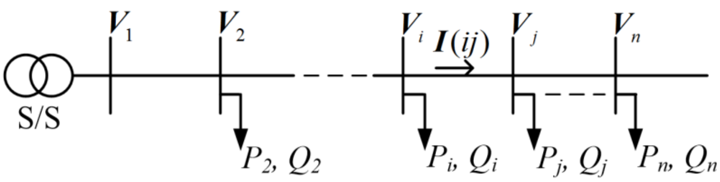


Fig. 3.1 Single line diagram of a distribution feeder

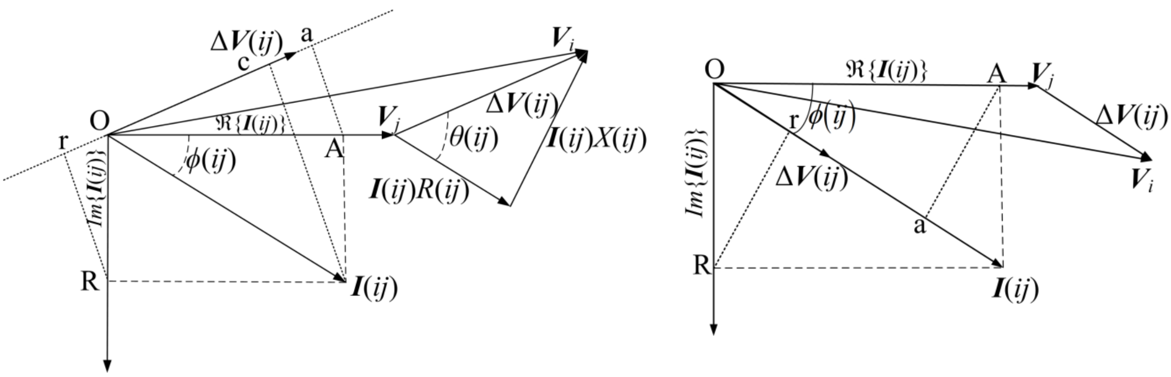
Let us consider branch *ij* of a simplified distribution feeder as shown in Fig. 3.1. For this branch, the power loss using Succinct Method (SM) [3] or Exact Method (EM) [4] is given by the product of $\Delta\boldsymbol{V}(ij)$ and the projection of $\boldsymbol{I}(ij)$ on the branch voltage drop $\Delta\boldsymbol{V}(ij)$ as given below

$$ploss(ij)= \Re\{\Delta\boldsymbol{V}(ij)\boldsymbol{I}(ij)\} = \Delta V(ij)I(ij)\cos\theta(ij);\ \Delta\boldsymbol{V}(ij)= \boldsymbol{V}_i - \boldsymbol{V}_j \tag{3.1}$$

where, $\theta(ij)$ is impedance angle of branch *ij*.

According to [7], the power loss $\Delta\boldsymbol{V}(ij).\boldsymbol{I}(ij)$ can be seen in a different way. The phasor $\boldsymbol{I}(ij)$ can be resolved into two rectangular components R{$\boldsymbol{I}(ij)$} and *Im*{$\boldsymbol{I}(ij)$} about the source voltage phasor $\boldsymbol{V}_1$, as shown in Fig. 3.2 (a). Since $I(ij)\cos\theta(ij)$ is the component of $\boldsymbol{I}(ij)$ about $\Delta\boldsymbol{V}(ij)$, therefore it will be given by the sum of projections of R{$\boldsymbol{I}(ij)$} and *Im*{$\boldsymbol{I}(ij)$} about $\Delta\boldsymbol{V}(ij)$, i.e. Oa and Or. Thereby, LA is proportional to Oa – Or, i.e. Oc.

However, it would be Oa if $Im\{\boldsymbol{I}(ij)\}$ is zero. Thus Succinct method allocates less LA when the same active power load is drawing reactive power. In this way, Succinct method presents a paradox according to which, it is unable to provide a meaningful loss allocation under specific circumstances concerning the reactive power loads [7]. In order to remove this paradox, Carpento *et al*. proposed branch current decomposition method for loss allocation (BCDLA), where they suggested virtual branch voltage (VBV) $\Delta\boldsymbol{V'}(ij)$ by assuming reactance-free branches. With this assumption, the phasor $\Delta\boldsymbol{V'}(ij)$ aligns with $\boldsymbol{I}(ij)$ as shown in Fig. 3.2 (b). The figure also shows elimination of paradox as Oa and Or are become additive.



(a) (b)

Fig. 3.2 Phasor interpretation of the reactive power paradox

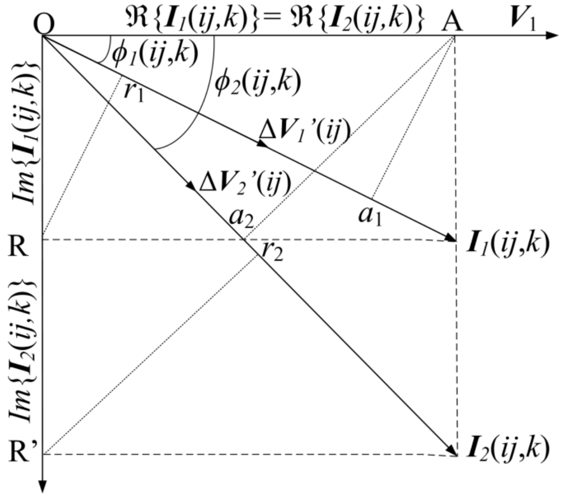


Fig. 3.3 Inconsistency of BCDLA under varying reactive power transactions

Though, BCDLA overcomes the limitation of SM [3] and EM [4], however, the method is found to be inconsistent with respect to variation in reactive power transactions of load. This can be explained through Fig. 3.3, which is compares the projections of active and reactive components of current using BCDLA. It can be observed from the figure that Or_1 and Or_2 are consistent with the increase in reactive power demand. But the same is not true while comparing Oa_1 and Oa_2, because for identical active power demand, these two projections must be equal. Thus, BCDLA shows inconsistency while considering reactive power transactions of network users. Distribution systems have witnessed extensive variations in nodal power factor on account of diversity in network users. Therefore, branch current decomposition method (BCDM) is proposed to allocate losses in distribution system which can be explained as below.

It is a well-known fact that both active and reactive components of the node current are equally responsible for feeder power loss. One of the major differences among transmission and distribution nodal injections is, variation in reactive power transaction is more for distribution system nodes. Therefore, these two components should be given impartial weightage while devising any loss allocation method for distribution systems. In this view, these components must provide true signals for LA under varying active and reactive power transactions of the distribution network users. The distribution network has been assumed reactance-free in BCDLA [7], however, the LA method to be devised may assume any value for branch reactance in order to retain consistency for fair allocation. With this philosophy, BCDLA [7] is extended by proposing BCDM while suggesting constrained virtual branch voltage drop (CVBVD) $\Delta\boldsymbol{\gamma}(ij)$, instead of VBV$\boldsymbol{\Delta V'}(ij)$, as suggested in [7]. The phase angle of CVBVD is proposed to keep a fixed angle of $\psi(ij)$ by constraining branch reactance, for each system state. However, the magnitude of CVBVD is modified to satisfy system losses. Referring to Fig. 3.4, the loss allocated to kth contributing node of branch ij using BCDM is therefore given by

$$ploss(ij,k) = \Delta\boldsymbol{\gamma}(ij)\left[\Re\{\boldsymbol{I}(ij,k)\}\cos\psi(ij) + Im\{\boldsymbol{I}(ij,k)\}\sin\psi(ij)\right] \tag{3.2}$$

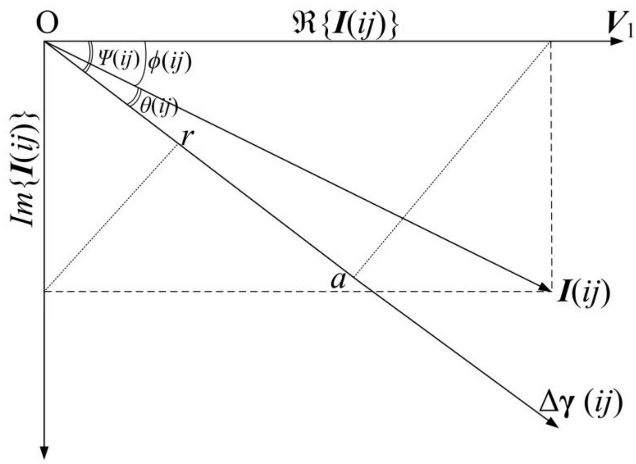


Fig. 3.4 Projection of current component over proposed CVBVD

3.1.1. DERIVATION OF CVBVD

Considering Fig. 3.2 (a), the projections of $\Re\{\boldsymbol{I}(ij)\}$ and $Im\{\boldsymbol{I}(ij)\}$ about $\Delta\boldsymbol{V}(ij)$ are given by

$$P\alpha(ij) = \Re\{\boldsymbol{I}(ij)\}\cos\left(\theta(ij)-\phi(ij)\right) = I(ij)\cos\phi(ij)\cos\left(\theta(ij)-\phi(ij)\right) \tag{3.3}$$

$$P\beta(ij) = Im\{\boldsymbol{I}(ij)\}\sin\left(\theta(ij)-\phi(ij)\right) = I(ij)\sin\phi(ij)\sin\left(\theta(ij)-\phi(ij)\right) \tag{3.4}$$

Since $$I(ij)^2 R(ij) = \Re\{\boldsymbol{I}(ij)\}^2 R(ij) + Im\{\boldsymbol{I}(ij)\}^2 R(ij) = Ploss^a + Ploss^r \tag{3.5}$$

where, $Ploss^a$ and $Ploss^r$ denote the loss contributions of active and reactive component of the branch current. Thus,

$$\frac{Ploss^a}{Ploss^r} = \frac{\Re\{\boldsymbol{I}(ij)\}^2}{Im\{\boldsymbol{I}(ij)\}^2} \tag{3.6}$$

However, the projections $P\alpha(ij)$ and $P\beta(ij)$ for the fair loss allocation considering power factor should be such that

$$\frac{P\alpha(ij)}{P\beta(ij)} = \frac{\Re\{\boldsymbol{I}(ij)\}}{Im\{\boldsymbol{I}(ij)\}} \tag{3.7}$$

By replacing $\Delta\boldsymbol{V}(ij)$ with $\Delta\boldsymbol{\gamma}(ij)$, as shown in Fig. 3.4, the projections of $\Re\{\boldsymbol{I}(ij)\}$ and $Im\{\boldsymbol{I}(ij)\}$ about $\Delta\boldsymbol{\gamma}(ij)$ are given by

$$P\alpha'(ij) = Oa = \Re\{\boldsymbol{I}(ij)\}\cos\psi(ij) \tag{3.8}$$

$$P\beta'(ij) = Or = Im\{\boldsymbol{I}(ij)\}\sin\psi(ij) \tag{3.9}$$

$$\frac{P\alpha'(ij)}{P\beta'(ij)} = \frac{\Re\{\boldsymbol{I}(ij)\}}{Im\{\boldsymbol{I}(ij)\}}\cot\psi(ij) \tag{3.10}$$

In order to satisfy (3.7)

$$\psi(ij) = \frac{\pi}{4}, \frac{3\pi}{4} \tag{3.11}$$

The first solution is considered because the second one is not practical due to negative allocation. For the considered value of $\psi(ij)$, the sum of projections is given by

$$P\alpha'(ij) + P\beta'(ij) = I(ij)\cos\left(\phi(ij) - \frac{\pi}{4}\right) \tag{3.12}$$

For $P\alpha'(ij) + P\beta'(ij) = I(ij)\cos\theta(ij)$ yields

$$\theta(ij) = \phi(ij) - \frac{\pi}{4} \tag{3.13}$$

Thus the proposed CVBVD is given by

$$\Delta\boldsymbol{\gamma}(ij) = (R(ij) + jX(ij))\boldsymbol{I}(ij);\ X(ij) = R(ij)\tan\left(\left|\phi(ij)\right| - \frac{\pi}{4}\right);\ \forall ij \in NB \tag{3.14}$$

The loss allocation at kth node and power loss to the system is given by following expressions, respectively.

$$ploss(k) = \sum_{ij=1}^{NB} ploss(ij,k) \tag{3.15}$$

$$Ploss = \sum_{k=1}^{N} ploss(k) \tag{3.16}$$

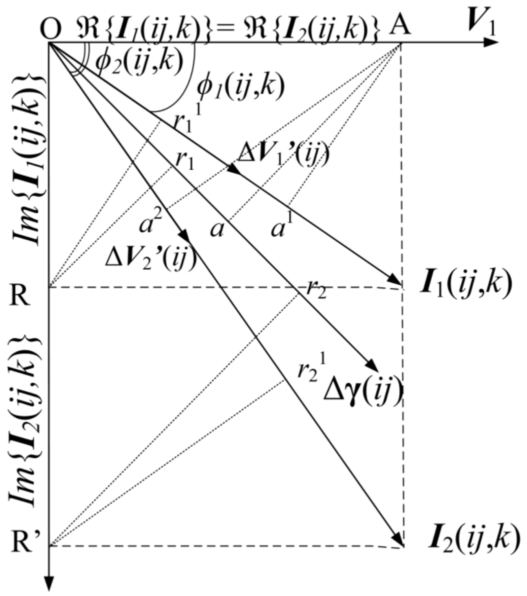


Fig. 3.5 Projections of current components about constrained virtual voltage drop

The importance of proposed $\Delta\boldsymbol{\gamma}(ij)$ over $\Delta \boldsymbol{V'}(ij)$ can be understood from Fig. 3.5, which shows the effect of variation in power factor on the projected components of load current over the branch voltage drop phasors. Considering *k*th contributing load current of branch *ij* with initial value of $\boldsymbol{I}_1(ij, k)$ having OA and OR as active and reactive components, respectively, about the source voltage $\boldsymbol{V}_1$. Using BCDLA, the respective projections of these components over $\Delta \boldsymbol{V}_1'$ are found to be Oa^1 and Or_1^1. Let $\boldsymbol{I}_2(ij, k)$ is the load current at same node having higher reactive power transaction while maintaining active power. The projections of component OA and OR' are now taken over $\Delta \boldsymbol{V}_2'$, which are found to be Oa^2 and Or_2^1. It can be observed that Oa^2 < Oa^1, which is not rational since the active power demand of the load remain unchanged. As a consequence, Or_2^1 will not be fair though Or_2^1 > Or_1^1. However, the projected component Oa about proposed $\Delta\boldsymbol{\gamma}_1(ij)$ or $\Delta\boldsymbol{\gamma}_2(ij)$ remains unchanged for an identical value of OA. Thereby, provides true projecting components Or_1 and Or_2. It can be observed that Or_1 > Or_1^1 whereas Or_2 < Or_2^1. These relations seem to be consistent with the prevailing variation in reactive power transactions. This shows the importance of proposed BCDM over BCDLA [7] while allocating losses under varying load power factor.

The equation 3.15 provides loss allocation to *k*th node using proposed BCDM assuming no DG penetration and nominal network configuration.

Illustration

For illustration purpose a 23 kV test distribution system is considered, as shown in Fig. 3.6. The proposed BCDM is applied to the given system. The details line and bus data of this system may be referred from Table 3.1.

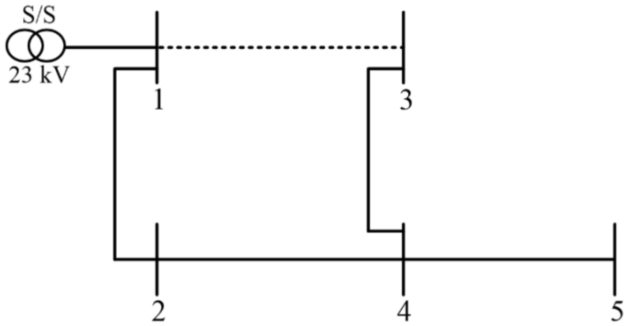


Fig. 3.6 Single line diagram of small 5-bus test distribution system

Table 3.1 Line and bus data of small test distribution system

Branch	$R(ij)+jX(ij)$ (Ω)	MW-MVAr*	Contributing nodes
1-2	0.03+j0.03	3.4-1.4	2, 3, 4
1-3	0.02+j0.02	10.0-4.0	-
2-4	0.02+j0.02	6.7-2.7	3, 4, 5
4-3	0.01+j0.01	-	3
4-5	0.01+j0.01	10.0-4.0	5

*Power at the end node of the line.

The step-wise calculation for the proposed BCDM is presented in Table 3.2-Table 3.4. The branch currents $\boldsymbol{I}(ij)$ obtained using load flow which is then employed to determine $X(ij)$ and $\Delta\boldsymbol{\gamma}(ij)$ using (3.14), shown in Table 3.2. Thereafter, the components $\Re\{\boldsymbol{I}(ij,k)\}$ and $Im\{\boldsymbol{I}(ij,k)\}$ of $\boldsymbol{I}(ij,k)$ are determined using $\boldsymbol{V}_j$, as shown in Table 3.3. Finally, the loss allocations to system node for each branch $ploss(ij, k)$ are determined using (3.2), and (3.14), as shown in Table 3.4 in kW. Table also shows loss allocation to each node $ploss(k)$ and total system loss which can be determined using (3.15) and (3.16), respectively.

Table 3.2 Calculation for constrained branch voltage drop

ij	$R(ij)$ (p.u.)	$I(ij)\angle\phi(ij)$ (p.u.)	$X(ij)$ (p.u.)	$\theta(ij)$	$\Delta\boldsymbol{\gamma}(ij)$ (p.u.)
1-2	0.03	0.0616∠-21.99	-0.0127	-23.01	0.0020∠-45.00
2-4	0.02	0.0546∠-21.94	-0.0085	-23.06	0.0012∠-45.00
4-3	0.01	0.0204∠-21.90	-0.0043	-23.10	0.0002∠-45.00
4-5	0.01	0.0204∠-21.90	-0.0043	-23.10	0.0002∠-45.00

Table 3.3 Calculation for the components of contributing nodal currents

k	$\boldsymbol{V}_{\mathrm{j}}$	$\boldsymbol{I}(k)$	$\Re\{\boldsymbol{I}(ij,k)\}$				$Im\{\boldsymbol{I}(ij,k)\}$			
			1-2	2-4	4-3	4-5	1-2	2-4	4-3	4-5
1	1.0000∠0	0∠0.00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
2	0.9976∠-0.0586	0.0070∠-22.32	0.0064	0.0000	0.0000	0.0000	0.0027	0.0000	0.0000	0.0000
3	0.9959∠-0.1001	0.0204∠-21.70	0.0190	0.0190	0.0190	0.0000	0.0076	0.0076	0.0076	0.0000
4	0.9962∠-0.0935	0.0137∠-21.86	0.0127	0.0127	0.0000	0.0000	0.0051	0.0051	0.0000	0.0000
5	0.9959∠-0.1001	0.0204∠-21.70	0.0190	0.0190	0.0000	0.0190	0.0076	0.0076	0.0000	0.0076

Table 3.4 Calculation for loss allocation to distribution nodes

ij / *k*	*ploss*(*ij*, *k*) 1-2	2-4	4-3	4-5	*ploss*(*k*)
1	0.00	0.00	0.00	0.00	0.00
2	6.83	0.00	0.00	0.00	6.83
3	19.96	11.81	2.21	0.00	33.98
4	13.40	7.92	0.00	0.00	21.32
5	19.96	11.81	0.00	2.21	33.98
ploss(*ij*)	60.15	31.54	2.21	2.21	*PL*= 96.11

In the following section simulation results of the proposed method is presented.

3.1.2. REMUNERATION TO DGOs

The legacy passive distribution systems are now transforming into active distribution systems by more and more penetration of DGs. The DGs are relatively small generating units to meet local supply within the distribution systems. However, the introduction of DG units makes bilateral power flow among distribution feeders. This increases complexity in LA while employing circuit theory based methods. The complexity arises not only owing to bilateral power flow but also due to on the fact that the nodal injections of DG units, either upstream or downstream, cannot be determined using conventional branch injection matrix. As discussed earlier, the presence of DG causes variation in the total distribution loss. Therefore, DGOs should be remunerated or penalized depending upon their impact on distribution system losses.

It is known that DG units also support voltage of the distribution system. Therefore the voltage profiles of the contemporary distribution system with many DG units may be assumed to be practically constant. In such situations, the principle of Superposition can be applied to determine DG flows among distribution feeders. With this assumption, the DGOs may be remunerated or penalized in active distribution networks (ADNs).

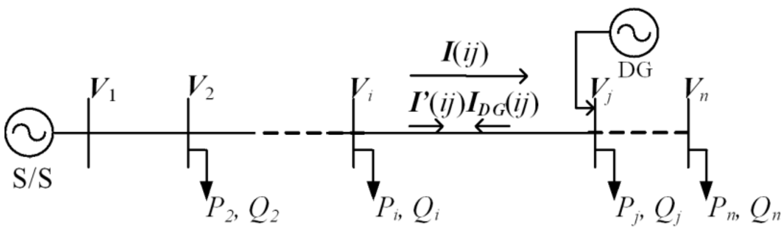


Fig. 3.7 Currents flowing through a distribution feeder

Consider branch *ij* of a distribution network, as shown in Fig. 3.7. If $\boldsymbol{I}(ij)$ and $\boldsymbol{I'}(ij)$ denotes current through branch *ij* without and with DGs, respectively, then following relation may hold for contemporary distribution systems

$$\boldsymbol{I}(ij) = \boldsymbol{I'}(ij) - \boldsymbol{I}_{DG}(ij) \qquad (3.17)$$

Where, $\boldsymbol{I}_{DG}(ij)$ is the phasor sum of contributing DG currents in branch *ij*. The currents

$\boldsymbol{I}(ij)$ and $\boldsymbol{I}'(ij)$ are determined using load flow conducted without and with DGs, whereas $\boldsymbol{I}_{DG}(ij)$ can be evaluated using Superposition and can be written as

$$I_{DG}(ij) = \sum_{p=1}^{N_{DG}} I_{DG}(ij, p) \tag{3.18}$$

However, it is important to note that the way in which Superposition applied is quite different to the conventional one. In proposed method, the contributing current of the *p*th DG in branch *ij* is determined by using the following relation

$$\boldsymbol{I}_{DG}(ij, p) = \sum \boldsymbol{I}(ij, m) - \sum \boldsymbol{I}(ij, n);\ \forall m \in \mathrm{CDG}(ij),\ \forall n \in CDG(ij),\ n \neq p \tag{3.19}$$

Where, $\boldsymbol{I}(ij, m)$ denotes current in branch *ij* with all *m* DGs in the system.

The sum of loss incentives to all contributing DGs in branch *ij* against loss reduction can be expressed as

$$R_{DG}(ij) = \Delta\boldsymbol{\gamma}'(ij).\boldsymbol{I}'(ij) - \Delta\boldsymbol{\gamma}(ij).\boldsymbol{I}(ij) \tag{3.20}$$

where, $\Delta\boldsymbol{\gamma}(ij)$ and $\Delta\boldsymbol{\gamma}'(ij)$ are CVBVDs for the branch *ij* without and with DGs.

Eq. (3.20) provides the total amount of remuneration to be dispersed among contributing DGs of branch *ij* which can be determined using load flows without and with DGs. While considering disbursement of loss incentives among concerned DGs, difficulty would arise on account of unknown value of branch voltage drop corresponding to the known value of contributing DG currents. In order to overcome this difficulty, a novel idea of fictitious branch voltage drop (FBVD) $\Delta\boldsymbol{\upsilon}(ij)$ is suggested such that the following relation is satisfied

$$R_{DG}(ij) = \Delta\boldsymbol{\upsilon}(ij).\boldsymbol{I}_{DG}(ij);\ \Delta\boldsymbol{\upsilon}(ij) = \Delta\upsilon(ij)\angle\zeta(ij) \tag{3.21}$$

Since, the phase angle of the FBVD, i.e. $\zeta(ij)$ can be kept fixed at $-\pi/4$ so that DGOs can be encouraged to inject appropriate amount of reactive power in the system. This is very important from practical consideration as this reactive power injection can support node voltage profiles and also reduce feeder power losses, consequently DGOs can be incentivized. Using Eqns. (3.20) and (3.21), the magnitude of proposed FBVD can be determined using following expression

$$\Delta\upsilon(ij) = \frac{\Delta\boldsymbol{\gamma}'(ij).\boldsymbol{I}'(ij) - \Delta\boldsymbol{\gamma}(ij).\boldsymbol{I}(ij)}{I_{DG}(ij)\cos(\zeta(ij) - \phi_{DG}(ij))};\ \zeta(ij) = -\frac{\pi}{4} \tag{3.22}$$

Thus, the loss incentive to the *p*th DG for loss reduction in branch *ij* can be evaluated using

$$R_{DG}(ij, p) = \Delta\upsilon(ij) I_{DG}(ij, p)\cos\left(\zeta(ij) - \phi_{DG}(ij, p)\right) \tag{3.23}$$

A small error, as given by (3.24), may arise while remunerating DG units. It occurs due to the variation in node voltages while applying Superposition. However, this variation will be insignificant in contemporary distribution system having large number of DGs. In proposed method, this insignificant error is adjusted among contributing DG units in proportional to their respective loss reduction using (3.25). The proposed method therefore produces zero error from the utility point of view while incentivizing DGOs. The adjusted value of the loss incentive to each DGO can be evaluated using (3.26).

$$\varepsilon = \sum_{ij=1}^{NB} \left[R_{DG}(ij) - \left(\Delta\boldsymbol{\gamma}'(ij).\boldsymbol{I}'(ij) - \Delta\boldsymbol{\gamma}(ij).\boldsymbol{I}(ij) \right) \right] \tag{3.24}$$

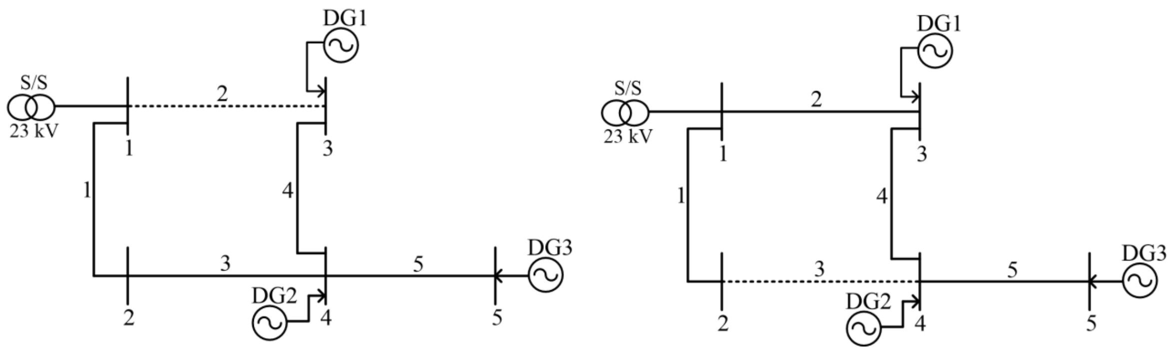
$$\varepsilon_p = \varepsilon \left(\frac{\sum_{ij=1}^{NB} R_{DG}(ij,p)}{\sum_{ij=1}^{NB} \sum_{p=1}^{N_{DG}} R_{DG}\left(ij,p\right)} \right) \tag{3.25}$$

$$R_{DG}(p) = \sum_{ij=1}^{NB} R_{DG}(ij,p) + \varepsilon_p \tag{3.26}$$

The equation 3.25 provides the formula for DGO incentive/penalty to *p*th DG.

3.1.3. LOSS INCENTIVE STRATEGY FOR DNO

Distribution networks are frequently reconfigured from one to another radial topology by distribution network operator (DNOs) to optimize different performance indices of the system. In fact, NR is one of the popular traditional distribution system operation strategy. DNO may operate distribution network in desired topology by performing NR to reduce feeder power losses during both normal and abnormal operating conditions. The NR transfers load from heavily loaded to lightly loaded feeders thus alters power flow and feeder power losses. It has been observed that NR plays very effective role in loss reduction during high load conditions. Since NR is performed by exchanging the status of



(a) Single line-diagram of small distribution system (b) Reconfigured distribution network

Fig. 3.8 Single line diagram of modified 5-bus test distribution system tie and sectionalizing switches, it involves system automation thus a definite investment and switching operation cost arises while conducting NR. In this view, DNO should be incentivized against any loss reduction caused by NR.

Distribution systems are structured in mesh but operated in radial configuration. For a given distribution network, there may be several possible radial topologies even for small distribution systems as shown in Fig. 3.8. Practical distribution systems are large and complex and therefore there exist a very large number of possible radial topologies. The NR problem involves the determination of one optimal radial topology of the network out of huge set of radial topologies to achieve desired objective(s).

NR is therefore one of the complex combinatorial optimization problem of distribution systems. The NR problem has been solved efficiently using any population-based heuristic technique such as GA [56], ACO [57], PSO [58], etc. While optimizing NR problem using these techniques, the radiality constraint imposes the biggest hurdle. Several methods [59]-[62] have been reported in literature to deal with this tedious task. In the present work, the rule-based codification proposed by [62] is used to handle radiality constraint. The codification is efficient to check and correct the infeasible radial topologies whenever appeared during the computational process. According to this codification, following three rules are used to identify and correct infeasible radial topologies.

Rule 1: Each candidate switch must belong to its corresponding loop vector.

Rule 2: Only one candidate switch can be selected from one common branch vector.

Rule 3: All the common branch vectors of a prohibited group vector cannot participate simultaneously to form an individual. For further details about the loop vector, common branch vector and prohibited group vector is available in [62].

Since feeder power losses are independently affected by DG power injection and NR, the loss incentives to DGOs and DNO are separable. Another noticeable issue is that, NR causes spatial change of end users within the distribution network thus both magnitude and the sign of the loss incentives may be affected. This increases complexity in LA method. Whatever are the repercussions of NR, the repercussion on loss reduction/ increase should be duly addressed while devising LA method for RADNs. Ideally speaking, both DGOs and DNOs should be rewarded against their respective loss reduction to avoid any conflicts. On the contrary, DGOs should be penalized for any increase in feeder power losses. Therefore, load points or consumer should be penalized for the amount of losses actually incurred to transport power from the source node to their strategic locations. On the other hand, if the network user is playing as a DG, the remuneration/penalty should be imposed for the actual loss reduction/enhancement incurred while injecting power into the system. With this philosophy, the loss and remuneration/penalty may be allocated to load points and DGOs, respectively by assuming them as separate entities though actually are contributing towards feeder power losses as a single entity. This leads to stronger economic signals, because each user will realize the true costs that he causes in each element of the network [1]. In this context, the reduced losses occurred in the presence of DGs and NR cannot be allocated to consumer points. Instead, the losses that would occur in the absence of DGs and NR should be allocated to load points. Therefore, following strategy is proposed while allocating losses or loss incentives among different entities.

"The losses awarded to loads are equal to the amount of losses that would occur to supply power to the load while assuming distribution network in base case minimum loss configuration and without DGs. The remuneration awarded to DGO or DNO is against their respective contribution towards loss reduction." The strategy proposed not only provides rational allocation of losses among different entities but also avoids conflicts between DGOs and DNO while sharing loss incentives.

The step-wise explanation of the proposed BCDM is discussed with the following illustration.

3.2 Simulation Results

Two test systems have been used to examine the applicability of proposed method. The application results of proposed method for loss allocation to different entities are presented and discussed.

3.2.1 Case study 1

The proposed method is now applied to a well-known 12.66 kV, 33-bus test distribution system [50]. The system has 32 sectionalizing and 5 tie-lines. The nominal active and reactive power loading of the system are 3.715 MW and 2.3 MVAr respectively and the detailed line and bus data can be referred from the Appendix. The base configuration of the distribution network is obtained by opening tie-lines 33-37. In this configuration the feeder power loss at the nominal loading is 202.67 kW.

A. Loss Allocation to Loads

The propose LA method is applied to this system for nominal loading condition. It has been observed that total loss allocation using proposed method is 202.67 kW. Ref. [16] has shown this loss as 202.59 kW using Exact method [4], 202.67 kW using BCDLA [7], 202.68 kW using PSMLA [5] and 202.68 kW using methods of [15], [16]. This show that total loss allocated using proposed method is nearly the same as obtained by other established methods. The loss allocated to various loads using proposed method is presented and compared with these methods in Fig. 3.9. It can be observed from the figure that proposed method produces comparable results with other methods. However, LA is different at node 30 using these methods. It may be due to exceptionally poor power factor, i.e. 0.30 lag at this node.

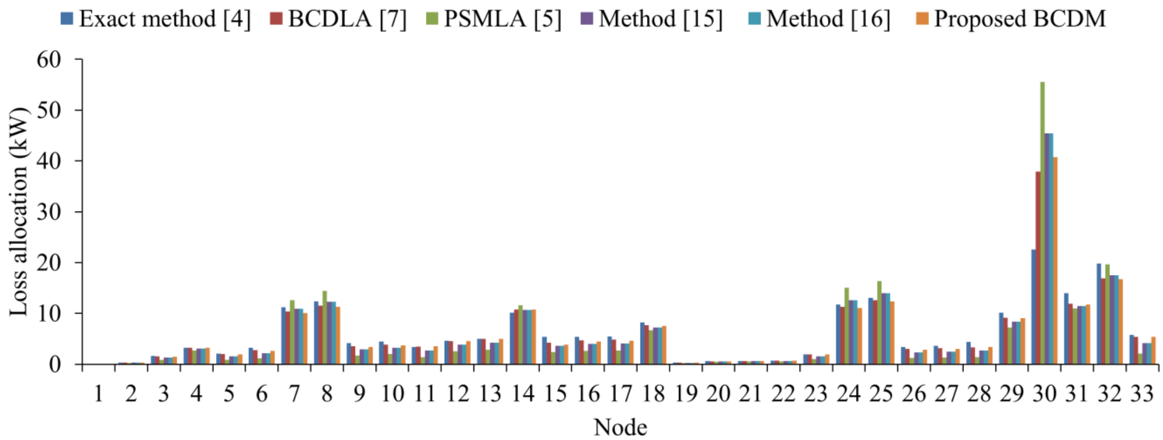


Fig. 3.9 Comparison of LA using BCDM with established methods

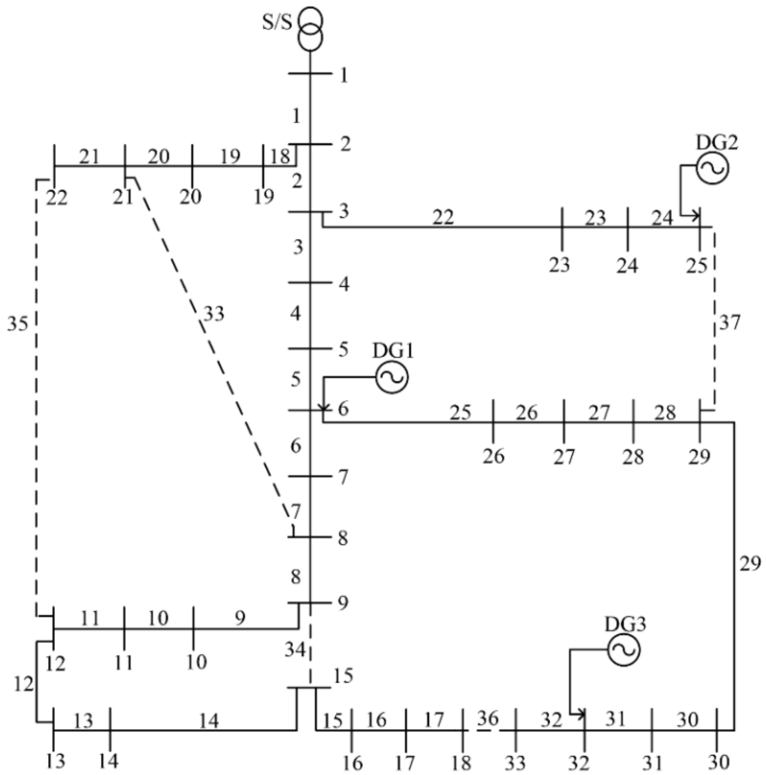


Fig. 3.10 Single line diagram of modified 33-bus test distribution system

B. Remuneration to DGOs

In order to investigate the applicability of proposed method to active distribution systems, the system is modified by placing three DGs as in [16]. The schematic single line diagram of this modified 33-bus test distribution system is shown in Fig. 3.10.

Table 3.5 Power generation and siting of DGs

Particular	DG1	DG2	DG3
Node	6	25	32
Active power (kW)	2058.71	738.39	499.55
Reactive power (kVAr)	997.10	457.60	0.00

The figure shows the network in base configuration with DGs as shown in Table 3.5. With this DG placement, the power loss of the modified system is found to be reduced from 202.67 kW to 43.44 kW at nominal load condition. The presence of DGs therefore causes a significant loss reduction of 159.23 kW. According to proposed methodology, DGOs are remunerated by disbursing this reduction of power loss using application of Superposition. The detailed calculation for determining the contributing currents for DG units using Superposition may be referred from Table 3.6. The last two columns, i.e. columns X and Y of the table shows a close match between the sum of contributing branch currents by DG units as obtained using load flow to that obtained using proposed method. This is true with regard to magnitude as well phase angle. This shows the simplicity and effectiveness of the proposed application of Superposition to determine the contributing branch currents of individual DGs.

The remuneration allocated to DGOs is then evaluated as shown in Table 3.7. The table shows that the calculated value for total remuneration is 155.81 kW against the true loss reduction of 159.23 kW. This shows an error of -3.42 kW. Which is quite obvious since the Superposition is applied to a non-linear system. However, the small error so produced is divided among DGOs using (3.24). The adjusted values for remuneration so obtained are then allocated to DGOs as shown in the table. It can be observed from the table that the difference between the calculated and adjusted values of remuneration to all DGs is small enough and may be acceptable from practical point of view. Thus the utility or the network operator has to remunerate against a loss reduction of 159.23 kW so will not be affected using proposed method.

Table 3.7 Remuneration allocated to DGOs using proposed BCDM

Remuneration to DGOs (kW)	DG1	DG2	DG3	Total remuneration (kW)
Calculated	102.85	23.76	29.21	155.81
Adjusted	105.11	24.27	29.85	159.23

The comparison results of proposed method with other existing methods for active distribution systems are presented in Table 3.8. The table shows the results of other methods available in [16] under identical system conditions, where all figures are in kW. It can be observed from the table that

Table 3.6 Validation of contributing currents from DGs

ij	Base case without DGs		Node (DG capacity in kW)								Node (Contributing DG capacity in kW)						X		Y	
			DG1 DG2 DG3		DG2 DG3		DG1 DG3		DG1 DG2		DG1		DG2		DG3					
	(a)		(b)		(c)		(d)		(e)		(f) =(b)-(c)		(g) =(b)-(d)		(h)=(b)-(e)		(i) = (b)-(a)		(j)=(f)+(g)+(h)	
	M	P	M	P	M	P	M	P	M	P	M	P	M	P	M	P	M	P	M	P
1	364.25	-0.56	78.50	-1.09	255.58	-0.64	143.24	-0.84	104.09	-0.74	188.01	2.69	69.95	2.59	40.39	3.12	299.24	2.72	294.36	2.72
2	324.01	-0.57	52.05	-1.57	215.97	-0.67	106.96	-0.98	66.43	-0.92	187.95	2.69	69.93	2.59	40.38	3.12	299.14	2.72	294.26	2.72
3	233.07	-0.62	54.29	-2.00	197.05	-0.73	54.49	-1.99	53.26	-1.23	187.73	2.69	0.21	1.37	40.34	3.13	228.93	2.76	224.93	2.76
4	221.40	-0.62	53.67	-2.21	185.60	-0.74	53.87	-2.21	44.61	-1.38	187.55	2.69	0.20	1.17	40.32	3.13	228.68	2.76	224.68	2.76
5	216.00	-0.62	54.86	-2.30	180.40	-0.75	55.06	-2.30	41.61	-1.48	187.43	2.69	0.20	1.07	40.30	3.13	228.51	2.76	224.52	2.76
6	101.05	-0.45	95.94	-0.44	99.83	-0.44	96.30	-0.44	96.64	-0.44	3.92	2.58	0.36	2.79	0.81	2.16	5.19	2.52	5.02	2.53
7	82.43	-0.44	78.20	-0.43	81.41	-0.44	78.50	-0.43	78.78	-0.44	3.23	2.59	0.30	2.80	0.67	2.17	4.28	2.54	4.13	2.54
8	63.67	-0.44	60.38	-0.43	62.88	-0.43	60.62	-0.43	60.83	-0.43	2.51	2.59	0.23	2.80	0.52	2.18	3.34	2.54	3.22	2.54
9	58.37	-0.45	55.35	-0.44	57.64	-0.44	55.56	-0.44	55.76	-0.44	2.31	2.58	0.21	2.79	0.48	2.17	3.07	2.53	2.96	2.53
10	53.04	-0.46	50.29	-0.45	52.38	-0.45	50.48	-0.45	50.66	-0.45	2.10	2.58	0.19	2.78	0.43	2.16	2.79	2.52	2.69	2.52
11	48.48	-0.45	45.97	-0.44	47.88	-0.44	46.14	-0.44	46.31	-0.44	1.93	2.59	0.18	2.79	0.40	2.17	2.55	2.53	2.47	2.54
12	42.59	-0.43	40.37	-0.43	42.06	-0.43	40.53	-0.42	40.67	-0.43	1.69	2.59	0.16	2.80	0.35	2.18	2.25	2.54	2.17	2.54
13	36.66	-0.42	34.76	-0.41	36.20	-0.41	34.89	-0.41	35.02	-0.41	1.46	2.60	0.13	2.81	0.30	2.19	1.93	2.55	1.87	2.55
14	24.56	-0.33	23.28	-0.32	24.25	-0.33	23.37	-0.32	23.45	-0.32	0.98	2.69	0.09	2.90	0.20	2.28	1.30	2.64	1.25	2.64
15	19.41	-0.37	18.39	-0.36	19.16	-0.37	18.46	-0.36	18.53	-0.37	0.78	2.65	0.07	2.85	0.16	2.24	1.03	2.60	0.99	2.60
16	13.96	-0.39	13.23	-0.38	13.78	-0.39	13.28	-0.38	13.33	-0.38	0.56	2.63	0.05	2.83	0.12	2.22	0.74	2.57	0.71	2.58
17	8.51	-0.43	8.07	-0.42	8.41	-0.42	8.10	-0.42	8.13	-0.42	0.34	2.60	0.03	2.80	0.07	2.19	0.45	2.54	0.44	2.55
18	31.33	-0.42	31.25	-0.42	31.30	-0.42	31.27	-0.42	31.26	-0.42	0.05	2.70	0.02	2.80	0.01	2.27	0.08	2.67	0.08	2.67
19	23.52	-0.42	23.46	-0.42	23.50	-0.42	23.48	-0.42	23.47	-0.42	0.04	2.70	0.01	2.80	0.01	2.27	0.06	2.67	0.06	2.67
20	15.69	-0.42	15.65	-0.42	15.67	-0.42	15.66	-0.42	15.65	-0.42	0.02	2.70	0.01	2.80	0.01	2.27	0.04	2.67	0.04	2.67
21	7.85	-0.42	7.83	-0.42	7.84	-0.42	7.83	-0.42	7.83	-0.42	0.01	2.70	0.00	2.80	0.00	2.27	0.02	2.67	0.02	2.67
22	83.97	-0.45	15.26	0.04	15.41	0.04	82.95	-0.45	15.29	0.04	0.15	-3.13	69.83	2.59	0.03	2.72	70.86	2.59	69.99	2.59
23	75.68	-0.45	9.28	0.51	9.38	0.51	74.76	-0.44	9.30	0.51	0.09	-2.67	69.78	2.59	0.02	-3.10	70.71	2.59	69.84	2.59
24	37.90	-0.45	32.33	2.46	32.65	2.46	37.44	-0.44	32.39	2.46	0.32	-0.70	69.30	2.59	0.07	-1.14	69.76	2.59	68.93	2.59
25	113.13	-0.79	83.59	-1.13	86.97	-1.14	83.90	-1.13	108.10	-0.79	3.39	1.92	0.32	2.13	40.65	3.11	44.16	3.03	42.21	3.03
26	108.16	-0.81	79.90	-1.18	83.13	-1.18	80.20	-1.18	103.35	-0.81	3.24	1.88	0.30	2.08	40.62	3.11	43.92	3.03	41.98	3.04
27	103.24	-0.84	76.39	-1.23	79.48	-1.23	76.68	-1.23	98.63	-0.83	3.10	1.83	0.29	2.04	40.59	3.12	43.66	3.03	41.73	3.04
28	98.64	-0.86	73.44	-1.28	76.41	-1.28	73.72	-1.28	94.23	-0.86	2.98	1.78	0.28	1.99	40.54	3.12	43.39	3.04	41.47	3.04
29	87.55	-0.91	65.92	-1.40	68.58	-1.40	66.17	-1.40	83.64	-0.90	2.66	1.67	0.25	1.87	40.44	3.12	42.82	3.05	40.93	3.05
30	40.41	-0.46	18.09	-1.91	18.82	-1.91	18.16	-1.91	38.60	-0.45	0.73	1.16	0.07	1.37	40.67	-3.14	42.24	3.12	40.37	3.13
31	26.18	-0.47	21.64	-2.57	22.51	-2.57	21.72	-2.57	25.01	-0.47	0.87	0.50	0.08	0.70	40.50	-3.13	41.50	3.14	39.67	3.14
32	6.21	-0.58	5.81	-0.56	6.04	-0.57	5.83	-0.56	5.93	-0.58	0.24	2.50	0.02	2.71	0.15	1.94	0.42	2.29	0.40	2.30

M: Magnitude (A), P: Phase angle (radian), X: Branch currents contributed by DGs using load flow, Y: Branch currents contributed by DGs using proposed method.
Difference quantities showing phasor differences.

Table 3.8 Comparison results of proposed BCDM with existing methods

Node	BCDLA [7]	PSMLA [5]	Method [15]	Method [16]	Proposed BCDM
1	0.00	0.00	0.00	0.00	0.00
2	0.06	0.21	0.16	0.17	0.31
3	0.13	0.82	0.68	0.73	1.46
4	0.27	2.51	1.53	1.68	3.26
5	0.08	0.78	0.89	0.98	1.92
6	-0.07	1.06	1.20	1.34	2.58
7	0.35	11.02	4.82	5.52	10.09
8	1.35	12.68	6.00	6.84	11.25
9	0.62	1.57	1.85	2.06	3.36
10	0.91	1.81	2.14	2.39	3.69
11	0.95	1.27	1.90	2.11	3.51
12	1.29	2.32	2.59	2.90	4.56
13	1.63	2.60	2.93	3.27	4.98
14	3.66	10.40	6.87	7.74	10.77
15	1.35	2.12	2.50	2.79	3.86
16	1.61	2.36	2.81	3.14	4.49
17	1.70	2.43	2.90	3.24	4.60
18	2.80	6.00	4.90	5.50	7.52
19	0.08	0.19	0.17	0.18	0.29
20	0.36	0.47	0.45	0.46	0.57
21	0.41	0.52	0.50	0.51	0.62
22	0.45	0.56	0.54	0.55	0.66
23	0.20	0.94	0.80	0.86	1.90
24	1.02	11.17	4.34	4.85	11.05
25	-0.02	11.35	3.59	4.14	12.38
26	0.03	1.16	1.32	1.48	2.86
27	0.11	1.20	1.39	1.56	3.03
28	0.30	1.25	1.52	1.72	3.40
29	1.59	6.37	4.23	4.89	9.07
30	14.78	43.13	25.31	29.52	40.75
31	1.86	9.40	5.28	6.19	11.74
32	2.58	16.18	7.62	9.01	16.72
33	1.05	1.88	2.29	2.64	5.41
LAL	**43.49**	**167.73**	**106.02**	**120.96**	**202.67**
DG1	0.04	71.90	45.19	56.28	105.11
DG2	0.05	20.05	6.77	8.37	24.27
DG3	-0.04	32.34	10.62	12.87	29.85
RDG	**0.05**	**124.29**	**62.58**	**77.52**	**159.23**
NRU	**43.44**	**43.44**	**43.44**	**43.44**	**43.44**

NRU: Net revenue to utility; RDG: Remuneration to DGOs; LAL: LA to load

(1) total LA to load (LAL) is ranging from 43.49 kW to 202.67 kW whereas the total remuneration to DGO (RDG) is varying from 0.05 kW to 159.23 kW using different methods. This shows that the application of different LA methods can produce diverse results in active distribution systems.

(2) the net revenue to utility (NRU) is found to be identical using each of these methods. This is against the actual amount loss, i.e. 43.44 kW that occur in distribution feeders

in the presence of DGs. This shows that none of these methods will cause under or over recovery from the utility side.

Therefore, some of these methods definitely allocate erroneous LA/remuneration. This discrepancy may be explained as below. In fact, system losses are 202.67 kW without DGs which is reduced to 43.44 kW with DGs. Since the presence of DGs causes a loss reduction 159.23 kW, for which loads are not responsible. With this fact, RDG should be against a loss reduction of 159.23 kW as obtained using proposed BCDM. It can be observed from the table that, RDGs obtained using other methods are less than this amount. It happened because RDG is partially diverted toward the LA of loads. Thus DGOs will receive less remuneration and consequently loads will be allocated less losses. This cannot be said judicious allocation as DGOs will suffer whereas loads will get undue rebates against the loss reduction. This fact can be validated from the table while comparing RDG and LAL. This shows the supremacy of the proposed BCDM over other established methods while subjected to active distribution systems.

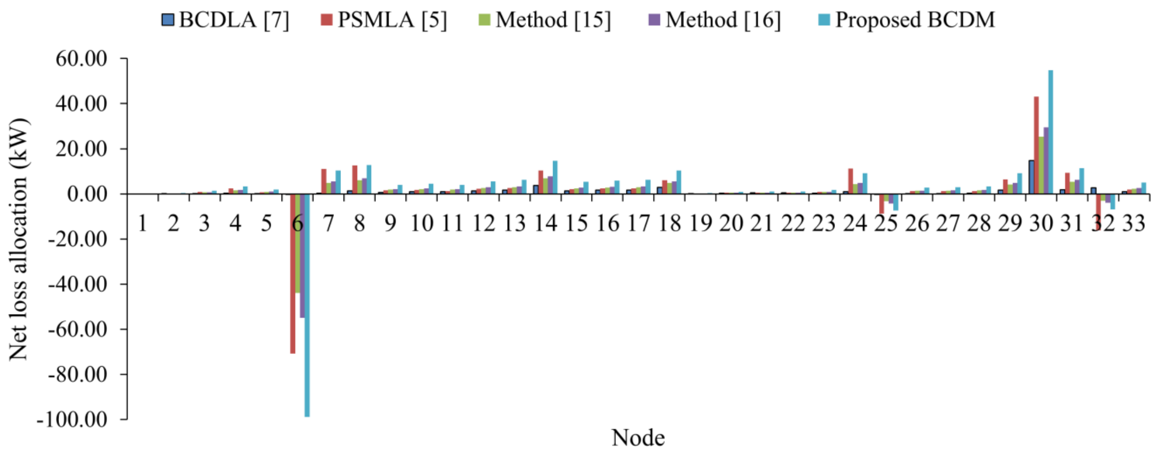


Fig. 3.11 Comparison of NLA to prosumers for different methods

The comparison of net LA (NLA) to prosumers is presented in Fig. 3.11. The figure shows variance in the results produced by different methods considered due the reasons discussed above. In particular, it has been observed that the NLA or LA at node 30, as there is no DG at this location, is different using various methods. It may happen as the node has very poor power factor of 0.30 lag. It can be seen that LA is highest at this node using proposed method, therefore, the method is seems to be taking more care of power factor than other methods. This could be an added advantage of proposed method, however, it will be thoroughly analysed later in this section.

C. Loss Incentives to DNO

In order to investigate the applicability of proposed method to RADNs, a more realistic load profile is created. For this purpose, feeders are classified in the distribution system to exclusively supply residential, industrial and commercial customers [63] as shown in Table 3.9. The table shows various types of customers connected to particular group of nodes in accordance to the feeder classification, and also the load factors and load duration assigned to each category of customers. The system load profile is therefore composed of nine different states owing to diversity of load among distribution buses. For each of these states, the feeder power losses are determined by conducting load flow while ignoring DGs. Another load flow is then conducted by considering DGs. However, the distribution network topology is assumed to be in base case minimum loss configuration (BMLC), i.e. by opening switch at 7, 9, 14, 32 and 37, in these two situations. The power losses incurred for each system state are presented in Table 3.10. The distribution network is then optimally reconfigured to minimize power loss using the method of [62] and the results obtained are also presented in Table 3.10. The energy loss reduction caused by DGs or NR is evaluated separately and is presented in the Table 3.11. The strategy adopted is that first the feeder power losses are determined for the passive network assuming it to be operated in initial topology. Thereafter, the loss reduction in the presence DGs is evaluated. Finally, the distribution network is optimally reconfigured with DGs and the further loss reduction on account of NR is determined. The table shows the economic equation for each state of the reconfigured RADN using proposed LAS.

Table 3.9 Load factors and load duration for daily load profile

State	Residential (N1-N15)	Industrial (N22-29)	Commercial (N16-21, N30-33))	Duration (h)
1	0.40	0.80	0.40	7
2	0.40	1.00	0.40	1
3	0.60	1.00	0.40	3
4	0.60	1.00	0.60	3
5	0.80	1.00	0.80	5
6	0.80	0.80	0.80	1
7	0.80	1.00	1.00	1
8	1.00	1.00	1.00	2
9	1.00	0.80	0.40	1

Table 3.10 An Illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	35.69	61.79	32.13	13,18,22,34,35
2	45.35	56.38	25.86	13,15,18,22,35
3	53.26	56.77	21.80	13,15,18,22,35
4	69.19	56.01	21.21	13,18,23,30,35
5	100.46	61.97	24.10	13,19,24,31,35
6	87.59	64.87	22.64	13,20,23,31,35
7	125.14	68.27	27.54	13,20,24,31,35
8	139.55	74.58	29.18	13,24,31,33,35
9	62.07	65.68	19.44	12,18,22,30,35

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

Table 3.11 Economic equation for RADN

S	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	249.8	432.6	224.9	249.8	-182.7	207.7
2	45.4	56.4	25.9	45.4	-11.0	30.5
3	159.8	170.3	65.4	159.8	-10.5	104.9
4	207.6	168.0	63.6	207.6	39.5	104.4
5	502.3	309.9	120.5	502.3	192.4	189.3
6	87.6	64.9	22.6	87.6	22.7	42.2
7	125.1	68.3	27.5	125.1	56.9	40.7
8	279.1	149.2	58.4	279.1	129.9	90.8
9	62.1	65.7	19.4	62.1	-3.6	46.2
Total	**1718.7**	**1485.1**	**628.3**	**1718.7**	**233.6**	**856.8**

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

The table shows that energy losses are reduced at each state by considering DGs, except at state 1 due to over generation form DGs under light load condition. Therefore RDG is with negative sign for state 1. This shows that proposed method can remunerate or penalize DGOs, as the case may be. It can be observed from the table that for the sample day, DNO receives an amount from loads against feeder power loss of 1718.7 kWh which is reduced to 1485.1 kW by DG placement and is then further reduced to 628.3 kW by optimally reconfiguring the distribution network. Therefore, the loss reduction caused by DG units is 233.6 kWh (1718.7 kWh–1485.1 kWh) and that by NR is 856.8 kWh (1485.1 kWh – 628.3 kWh). With this fact, DGOs being remunerated against the loss reduction of 233.6 kWh whereas a loss incentive against the loss reduction of 856.8 kWh is to be kept with DNO. In other words, DNO receives an amount from loads against the losses of 1718.7 kWh, out of which it will pay remuneration to DGOs against the loss reduction of 233.6 kWh and compensate an amount against the system losses of 628.3 kWh that actually incurred and the balance amount remains is against loss reduction of 856.8 kWh which is on account of optimally reconfiguring the distribution network. This economic equation equally holds good for each system state as can be verified from the table. Thus proposed LA strategy provides judicious allocation of loss incentives among DGOs and DNO which may be very useful to avoid conflicts between them.

The application results obtained using proposed BCDM method have been found satisfactory with other established methods. The distribution system undergoes dynamically varying states. Therefore, it is interesting and important to analyse the accuracy of developed LA method against the variation in system loading, load power factor and reactive power injection from DG units.

D. Accuracy of Proposed BCDM

Distribution systems characterized by diverse variety of customers so faces significant variations in load demand and load power factor. These variations become more acute in RADNs where active and reactive power demands with DG units have to be continuously adjusted for smooth operation of the system. The application result of LA methods provides LA for a single snap-shot. However, it become essential to investigate the developed method under diverse varying conditions that may exist in distribution systems.

Variation in Load Demand

In order to address the accuracy of the proposed application of superposition, system loading is varied from 0.2 p.u. to 2.0 p.u. The value of true remuneration to DGOs is determined by conducting two load flows, without and with DGs. The calculated value of remuneration is then determined using proposed application of superposition. The results obtained for each system loading are in Table 3.12. The table shows losses in kW for each loading. It can be observed from the table that the percentage error in remuneration to DGOs increases with the system loading and is kept within 3.04%. This shows that the accuracy of the proposed method is good enough while remunerating DGOs. It can also be observed that DGOs are penalized (negative remuneration) under light load conditions as they increase power losses. This shows that proposed method can remunerate or penalize DGOs whatever the case may be.

The error in remuneration produced due to the variation in nodal voltages while employing superposition to evaluating contribution branch currents of DG units. The node voltage deviations increases with the increase in system loading, however, the maximum deviation remains within in a range of 3-5%, as shown in table. This reflects in small error while calculating remuneration.

Table 3.12 Accuracy of Superposition for Remuneration allocation to DGOs

Load Factor	Loss without DGs	Loss with DGs	True	Calculated	Error (%)	DVmax (%)
0.2	7.23	84.31	-77.08	-76.29	-1.02	3.55
0.4	29.72	53.99	-24.28	-23.94	-1.38	3.64
0.6	68.74	36.42	32.32	31.66	-2.05	3.73
0.8	125.81	32.53	93.27	91.39	-2.02	3.83
1	202.67	43.44	159.23	155.81	-2.15	3.94
1.2	301.42	70.40	231.02	225.63	-2.33	4.06
1.4	424.53	114.86	309.67	301.65	-2.59	4.20
1.6	575.40	178.55	396.84	385.54	-2.85	4.34
1.8	757.46	263.50	493.97	481.53	-2.52	4.55
2	975.78	372.30	603.48	585.13	-3.04	4.73

Variation in Load Power Factor

Next, the accuracy of proposed method is evaluated against variation in load power factor. Therefore, the distribution system is assumed passive. Arbitrarily, system nodes are divided into three groups; Group-A contains top five nodes with good power factor i.e. nodes 6, 9, 10, 15 and 16, the Group-B contains bottom five node with poor power factor, i.e. nodes 4, 11, 14, 30 and 33, and the remaining system nodes constitutes Group-C, as shown in Table 3.13. Two scenarios are considered to vary power factor of nodes assigned to Group-A and Group-B, as shown in the table. In both scenarios, the power factor is decreased for Group-A, whereas it is increased for Group-B. This strategy is adopted to critically analysing the proposed method. While varying power factor, the active power demand at the node is kept unchanged. The nodal power factor considered for this study may be referred from Table 3.14. The proposed BCDM is applied for both scenarios of varying load power factors. The result obtained is compared by applying Exact method [4] and BCDLA [7] and may be referred from Table 3.15. In order to have a better comparison among LA methods, per-cent change in loss allocation by varying power factor is determined and is presented in Fig. 3.12 (a) and Fig. 3.12 (b), where just for the sake of better understanding system nodes are arranged in the descending order of power factor.

Table 3.13 Grouping of system nodes and scenarios considered for case study 1

Group	Nodes	Change in power factor	
		Scenario 1	Scenario 2
A	6,9,10,15,16	-10%	-20%
B	4,11,14,30,33	+10%	+20%
C	2,3,5,7,8,12,13,17,18,19,20,21,22,23,24,25,26,27,28, 29,31 and 32	No change	No change

Table 3.14 Load power factors for base case and scenarios considered for case study 1

Node	Group-A			Node	Group-B		
	X	Y	Z		X	Y	Z
6	0.9487	0.8538	0.7589	4	0.8321	0.9152	0.9985
9	0.9487	0.8538	0.7589	11	0.8321	0.9152	0.9985
10	0.9487	0.8538	0.7589	14	0.8321	0.9152	0.9985
15	0.9864	0.8878	0.7891	30	0.3162	0.3478	0.3795
16	0.9487	0.8538	0.7589	33	0.8321	0.9152	0.9985
Node	Group-C			Node	Group-C		
	X	Y	Z		X	Y	Z
2	0.8575	0.8575	0.8575	21	0.9138	0.9138	0.9138
3	0.9138	0.9138	0.9138	22	0.9138	0.9138	0.9138
5	0.8944	0.8944	0.8944	23	0.8742	0.8742	0.8742
7	0.8944	0.8944	0.8944	24	0.9029	0.9029	0.9029
8	0.8944	0.8944	0.8944	25	0.9029	0.9029	0.9029
12	0.8638	0.8638	0.8638	26	0.9231	0.9231	0.9231
13	0.8638	0.8638	0.8638	27	0.9231	0.9231	0.9231
17	0.9487	0.9487	0.9487	28	0.9487	0.9487	0.9487
18	0.9138	0.9138	0.9138	29	0.8638	0.8638	0.8638
19	0.9138	0.9138	0.9138	31	0.9062	0.9062	0.9062
20	0.9138	0.9138	0.9138	32	0.9029	0.9029	0.9029

X: Base case, Y: Scenario 1, Z: Scenario 2

Table 3.15 Comparison of loss allocation methods for case study 1

Group-A

Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
6	-0.11	14.60	20.02	-2.88	25.53	36.74
9	-1.08	14.28	20.21	-5.07	25.01	37.16
10	-1.19	14.14	20.26	-5.53	24.63	37.24
15	-2.16	19.10	29.54	-7.08	30.97	50.07
16	-1.48	13.87	20.27	-6.39	24.09	37.37

Group-B

Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
4	-3.68	-11.06	-14.21	-8.95	-28.56	-37.97
11	1.23	-9.96	-13.79	1.39	-27.11	-37.32
14	2.23	-9.57	-13.68	3.31	-26.36	-37.12
30	-9.41	-10.61	-9.86	-19.41	-20.45	-18.51
33	-4.89	-13.31	-15.56	-9.79	-32.92	-39.68

Group-C

Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
2	-1.18	-0.68	-0.49	-3.61	-2.10	-1.36
3	-1.15	-0.63	-0.55	-3.53	-1.94	-1.59
5	-1.27	-0.74	-0.65	-3.95	-2.27	-1.91
7	-0.91	-0.63	-0.59	-3.68	-2.11	-1.85
8	-0.59	-0.42	-0.49	-3.15	-1.79	-1.64
12	0.20	-0.02	-0.28	-2.47	-1.48	-1.31
13	0.40	0.07	-0.23	-2.42	-1.43	-1.24
17	0.75	0.17	-0.20	-1.20	-0.77	-1.06
18	0.83	0.23	-0.19	-1.33	-0.88	-1.07
19	-0.91	-0.50	-0.41	-2.77	-1.50	-1.17
20	-0.49	-0.26	-0.21	-1.49	-0.80	-0.61
21	-0.46	-0.24	-0.19	-1.39	-0.73	-0.56
22	-0.43	-0.24	-0.18	-1.30	-0.68	-0.53
23	-1.07	-0.62	-0.47	-3.28	-1.88	-1.34
24	-0.79	-0.44	-0.36	-2.42	-1.34	-1.04
25	-0.72	-0.40	-0.33	-2.19	-1.21	-0.94
26	-1.33	-0.72	-0.77	-4.03	-2.12	-2.16
27	-1.51	-0.82	-0.97	-4.34	-2.29	-2.50
28	-2.21	-1.01	-1.58	-5.44	-2.52	-3.58
29	-3.18	-1.68	-2.01	-7.46	-4.01	-4.38
31	-3.19	-1.60	-2.16	-7.41	-3.77	-4.63
32	-3.25	-1.63	-2.16	-7.57	-3.85	-4.61

The per-cent change in loss allocation in kW with respect to the base case condition is evaluated from Table 3.15 and the comparison results obtained for scenario 1 and scenario 2 are presented in Fig. 3.12(a) and Fig. 3.12(b), respectively. It can be observed from the figure that proposed method allocates higher losses to nodes of Group-A, where power factor has been decreased and simultaneously allocates less losses to nodes of Group-B, where power factor has been increased. Moreover, the LA remains almost unaffected for almost all nodes of Group-C. Similar results are produced by BCDLA [7]. This is found to be true for both scenarios. It can also be observed from the figure that Exact method [4] is showing inconsistency against the variation in load power factor for all nodal groups.

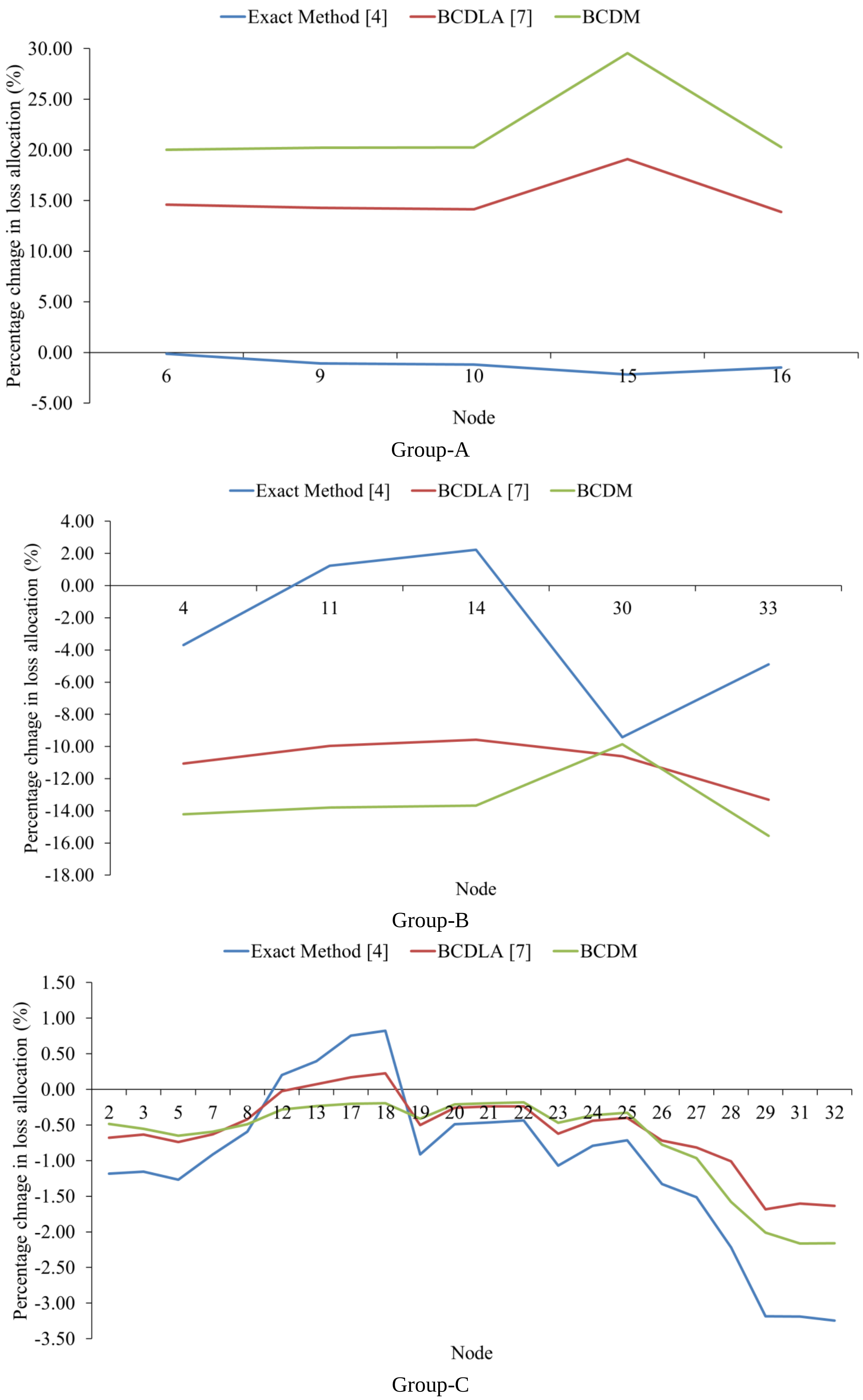
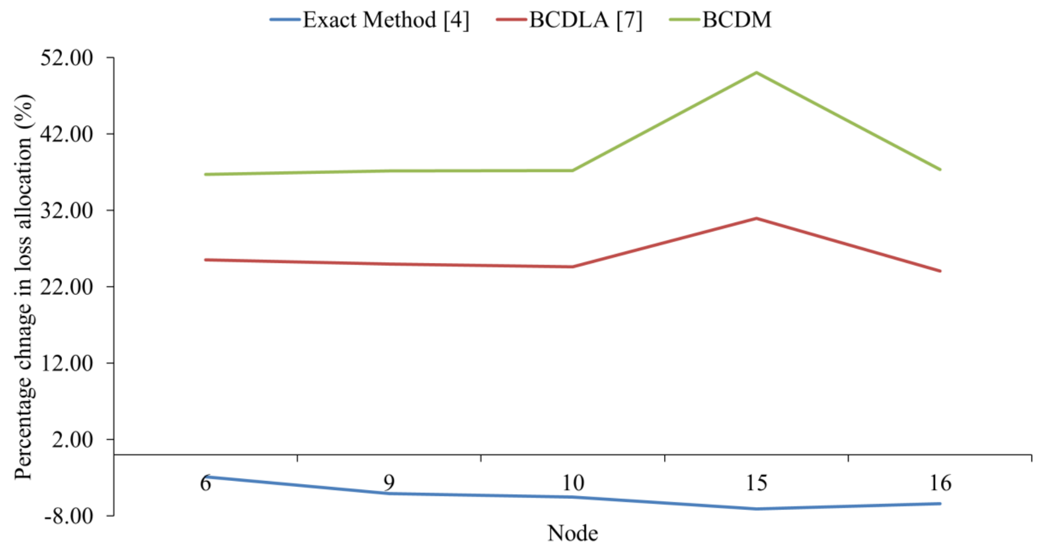
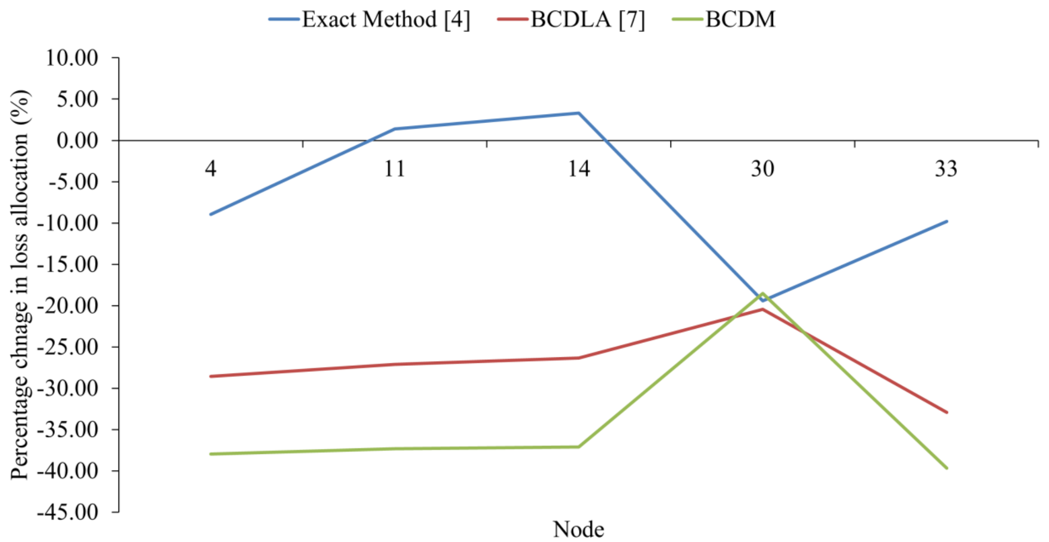


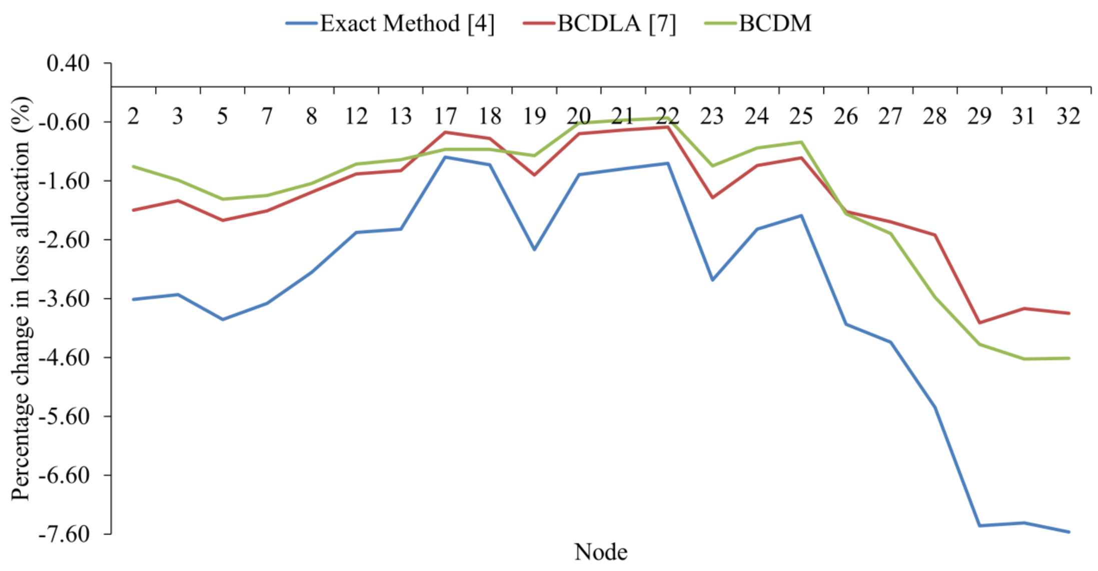
Fig. 3.12 (a) Comparison of proposed methods with established methods for scenario 1



Group-A



Group-B



Group-C

Fig. 3.12 (b) Comparison of proposed methods with established methods for scenario 2

Table 3.16 Statistical Error Analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
Max.	3.245	1.683	2.163	7.565	4.009	4.628
Min.	0.204	0.022	0.181	1.196	0.684	0.527
Mean	1.219	0.625	0.704	3.475	1.884	1.867
SD	0.899	0.472	0.640	1.926	0.960	1.254

The LA to nodes of Group-C should not be affected while varying power factors of other system nodes. But, some discrepancy is observed from Fig. 3.12. In order to compare the performance of different LA methods, a statistical error analysis is carried while considering both scenarios. The results obtained are presented in Table 3.16. The table shows absolute values of the maximum and minimum value of the per-cent change in loss observed from Group-C nodes using different methods. The table also shows mean and standard deviation (SD) of these sampled data. Smaller values of these statistical indices are desired. It can be observed from that the performance of BCDLA [7] is better than the Exact method [4], but is comparable with that of proposed BCDM.

Variation in DG power factor

In order to investigate the effect of varying power factor of DG unit on remunerations allocated by LA method, power factor of the DG, i.e. DG1, having highest MVA rating is varied from unity to 0.707 (leading), keeping active power generation constant. The results obtained using proposed BCDM are presented in Fig. 3.13. The figure shows the remuneration allocation to all the three DG units while keeping power factor of the DG1 at unity, 0.95, 0.90, 0.85, 0.80 and 0.707. It can be observed from the figure that remuneration to DG1 increases consistently while increasing its reactive power. However, remuneration to other DGs remains more or less the same. It is noteworthy that the proposed method is encouraging DGOs for injecting reactive power into the system.

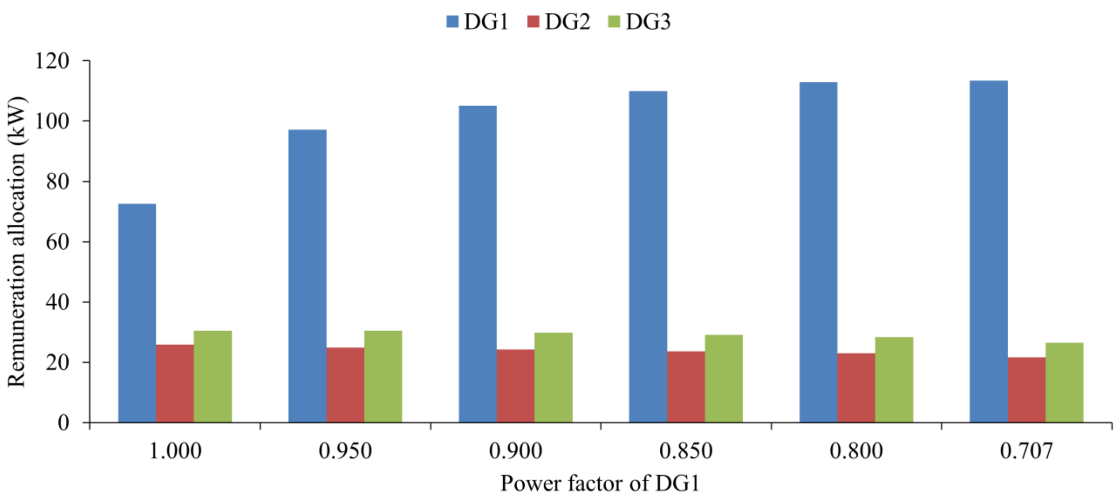


Fig. 3.13 Remuneration allocation to DGOs with variation in power factor of DG1

The performance of proposed BCDM is found to be satisfactory with established methods while considering standard test distribution system. However, practical distribution systems are large and complex and may have large number of DGs. Therefore, the LA method developed needs a thorough investigation on a practical distribution system, as presented in the forthcoming section.

3.2.2 CASE STUDY 2

The proposed method is investigated on well-known 83-bus Tai Power Corporation distribution system taken from [57]. This is an 11.40 kV distribution system with 83 normally closed sectionalizing switches and 13 normally open tie switches. The single line diagram of the system is shown in Fig. A.2. The nominal active and reactive power demand are 28.350 MW and 20.700 MVAr, respectively and the detailed line and bus data of the system may be referred from Appendix. The base configuration of this distribution network is obtained by opening the tie-lines 84-96. For this configuration the power loss at the nominal loading is 531.99 kW.

A. Loss Allocation to Load

Assuming no DGs in the system, the loss allocation to load points is first determined using proposed BCDM and other existing methods. The comparison of loss allocation is presented in Fig. 3.14. It can be observed from the figure that BCDM and other existing methods produce comparable loss allocation for this larger and real system.

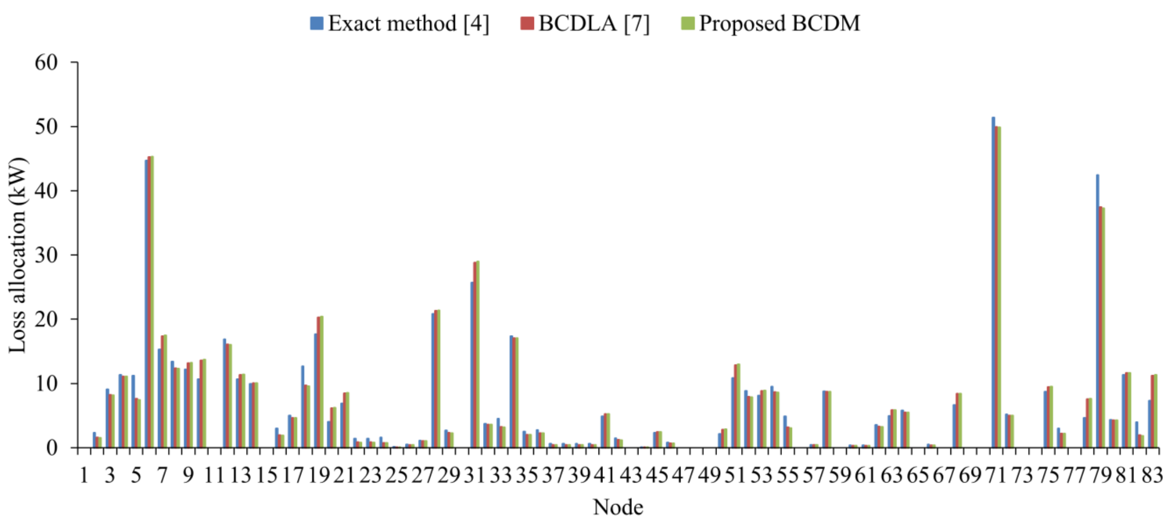


Fig. 3.14 Comparison of LA using BCDM with established methods

B. Remuneration to DGOs

The system is assumed with five DG units. The sizing and sitting of DGs have been taken from [64] as shown in Table 3.17. With this DG placement, the losses are reduced from 531.99 kW to 297.67 kW at nominal loading. Therefore, a loss reduction of 234.32

kW is observed using DGs. The proposed method is applied to this system and the results obtained are presented in Table 3.18. It can be observed from the table that total remuneration obtained using proposed method is 234.24 kW which is very close to the actual loss reduction of 234.32 kW by DGs. This shows that the application of Superposition in proposed BCDM produces insignificant error for large and complex system. The loss allocation to loads and remuneration to DGOs obtained using proposed method is shown in Fig. 3.15. The figure also shows net loss allocation to system nodes. It can be observed from the figure that the allocation is negative, i.e. remuneration is higher than the losses allocated, for all DG sites except at node 71. This is quite obvious as this is the node having highest loading.

Table 3.17 Power generation and siting of DGs

Particular	DG1	DG2	DG3	DG4	DG5
Node	6	19	52	71	79
Active power (kW)	2984	3099	2668	2449	3500

Table 3.18 Remuneration allocated to DGOs using proposed BCDM

Remuneration to DGOs (kW)	DG1	DG2	DG3	DG4	DG5	Total remuneration (kW)
Before adjustment	85.60	32.14	29.63	40.51	46.35	234.24
After adjustment	85.64	32.15	29.64	40.53	46.37	234.32

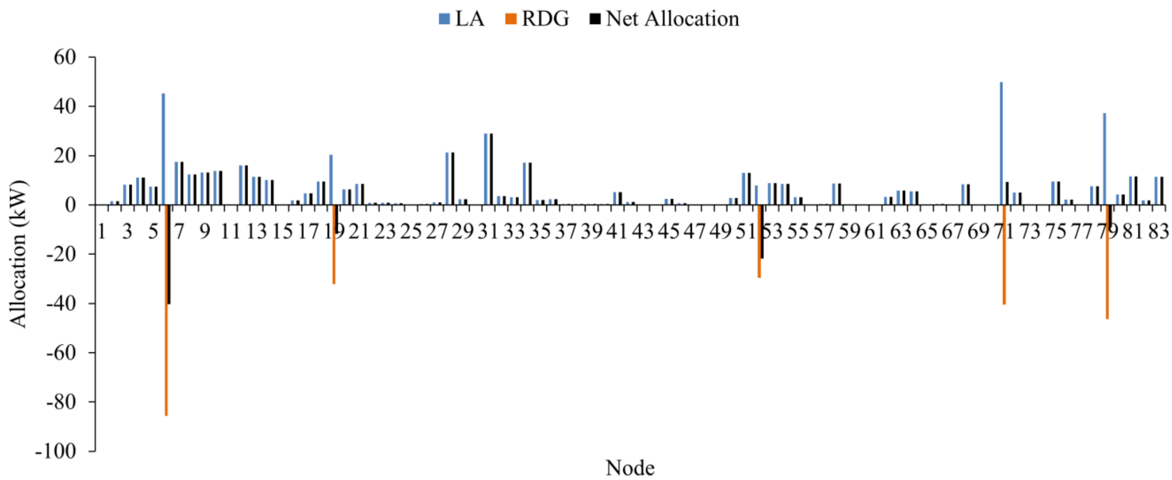


Fig. 3.15 Allocation to various entities

C. Loss incentives to DNO

The proposed strategy to incentivize DNO is now applied to this system while the distribution network is operating at BMLC, i.e. by opening switch at 7, 13, 34, 39, 41, 55, 62, 72, 83, 86, 89, 90, and 92. The classification of distribution nodes for diverse customers is taken as: residential (15-24, 30-42, 47-55, 56-64), commercial (1-10, 65-72, 77-83) and industrial (11-14, 25-29, 43-46, 73-76). The Load factors and load duration for this system to constitute daily load profile, however, are taken same as shown in Table 3.9. The feeder power losses for each of the concerned nine states are determined by conducting load flow while first ignoring DGs and then by considering DGs, assuming topology of distribution network in the BMLC. The results obtained are presented in Table 3.19. The distribution network is then optimally reconfigured to minimize feeder power losses using the method of [62] and the results of loss reduction by NR and corresponding optimal configurations are also presented in the table. Based upon the strategy proposed, the energy loss reduction caused by DGs alone or NR alone is evaluated for each system state and is presented in the Table 3.20. The table shows that the energy losses are reduced by DGs for all states, except for the first three states which is due to the over generation by DG units during light load conditions. The table shows a negative remuneration allocated to DGOs during these states. This shows that the proposed method can penalize DGOs if DGs causes any increase in feeder power losses. The table also shows that the economic equation thus obtained for the sample day states that an amount against the energy loss of 5665.27 kWh is allocated to load points for feeder power losses, out of which the actual losses incurred are 4020.87 kWh and 661.32 kWh are remunerated to DGOs, and the balance of 983.07 kWh is kept with DNO itself as a loss incentive for optimally reconfiguring distribution network.

Table 3.19 An Illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	112.12	168.02	123.11	14,29,34,54,57,61,69,86,88,90,91,92,95
2	142.51	198.41	143.27	14,29,34,54,57,61,69,86,88,90,91,92,95
3	179.83	206.92	152.08	14,29,34,54,57,61,69,86,88,90,91,92,95
4	219.09	199.99	156.57	14,29,34,42,55,60,63,71,86,88,90,91,92
5	327.92	230.06	195.93	14,34,42,55,60,61,86,87,88,90,91,92,93
6	296.01	198.14	169.78	14,34,39,42,63,84,85,86,87,88,90,91,92
7	399.48	251.50	226.54	14,34,42,62,83,84,85,86,87,88,90,92,93
8	471.05	290.30	269.21	14,34,42,62,83,84,85,86,87,88,90,92,93
9	263.89	228.21	175.55	14,20,33,35,42,54,60,63,70,86,88,90,92

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

Table 3.20 Economic Equation for RADN

State	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	784.87	1176.11	861.74	784.87	-391.25	314.37
2	142.51	198.41	143.27	142.51	-55.89	55.14
3	539.50	620.76	456.23	539.50	-81.25	164.53
4	657.28	599.96	469.71	657.28	57.32	130.25
5	1639.62	1150.28	979.64	1639.62	489.35	170.63
6	296.01	198.14	169.78	296.01	97.87	28.36
7	399.48	251.50	226.54	399.48	147.98	24.96
8	942.11	580.59	538.42	942.11	361.51	42.17
9	263.89	228.21	175.55	263.89	35.68	52.66
Total	5665.27	5003.94	4020.87	5665.27	661.32	983.07

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

For scaling the applicability of proposed application of Superposition to this system, an accuracy analysis is performed against the variation in system loading, load power factor and reactive power injection form DG units is presented in the following section.

D. Accuracy of Proposed BCDM

Practical distribution systems are large and complex with multiple DG units and other energy storage devices. Different variety of customers and DERs poses diverse load/generation profile and power factors which also varies dynamically. This causes complex power flow among distribution feeders. The LA method developed thus needs a thorough investigation about the accuracy against such variations that mostly occurs in practical distribution systems.

Variation in Load Demand

The system loading is varied from 0.2 p.u. to 2.0 p.u. in the step size of 0.2 p.u. by varying both active and reactive power demands of loads so that load power factor remained unchanged. For each load condition, the loss reduction by DGs is determined by conducting load flows without and with DGs. This loss reduction is regarded as the true value of remuneration. The total remuneration (before adjustment) for DGOs is then evaluated using proposed method and is regarded as the calculated value of remuneration. The true and calculated value of remunerations obtained are presented in Table 3.21. The table also shows the insignificant error incurred while determining remuneration using proposed method. This validates high accuracy of Superposition that employed in proposed BCDM to remunerate DGOs under varying load conditions. It is interesting to note that the accuracy of BCDM is better for this case study than the other considered.

Table 3.21 Accuracy of Superposition for Remuneration allocation to DGOs

Loading	Without DG	With DG	TRUE	Calculated	Error (%)	DV_max(%)
0.2	19.86	137.76	-117.90	-117.90	0.002	5.62
0.4	80.74	117.11	-36.37	-36.37	0.002	5.67
0.6	184.76	135.59	49.17	49.16	-0.021	5.73
0.8	334.29	195.08	139.21	139.16	-0.037	5.79
1	531.99	297.67	234.32	234.24	-0.037	5.87
1.2	780.88	445.66	335.21	334.94	-0.081	5.95
1.4	1084.38	641.65	442.73	442.73	0.000	6.05
1.6	1446.50	888.54	557.96	557.96	0.000	6.16
1.8	1871.90	1189.66	682.24	682.23	-0.001	6.30
2.0	2366.16	1548.82	817.34	817.33	-0.002	6.46

Variation in Load Power Factor

In order to investigate the accuracy of proposed method against variation in load power factor, the system is assumed passive and system nodes are arbitrarily divided into three nodal groups and two scenarios of power factor variations are considered, as in previous case study. The details of nodal groups and the scenarios considered are presented in Table 3.22. The power factor considered for these nodal groups may be referred from Table 3.23. The comparison of loss allocation obtained using proposed BCDM with Exact method [4] and BCDLA [7] while varying load power factor is presented Table 3.24, as per-cent change.

Table 3.22 Grouping of system nodes and scenarios considered for case study 2

Group	Nodes	Variation in power factor	
		Scenario 1	Scenario 2
A	22,23,24,55,82	-10%	-20%
B	20,31,45,68,78	+10%	+20%
C	2,3,4,5,6,7,8,9,10,12,13,14,16,17,18,19,21,25,26,27,28,29,32,33,34,35, 36,37,38,39,40,41,42,44,46,50,51,52,53,54,57,58,60,61,62,63,64,66,71, 72,75,76,79, 80,81, 83	No change	No change

Table 3.23 Load power factors for base case and scenarios considered for case study 2

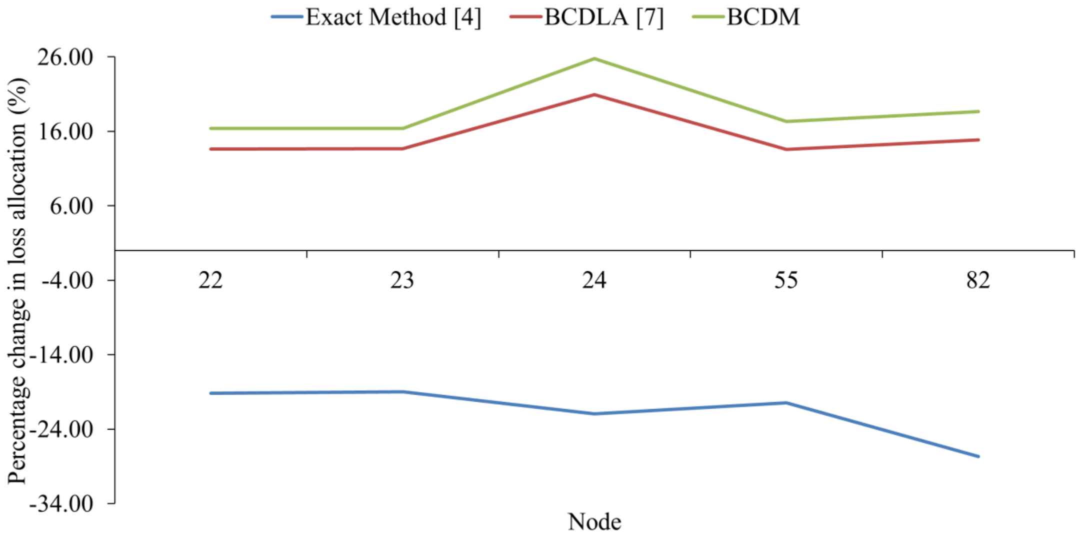
Node	Group-A			Node	Group-B		
	X	Y	Z		X	Y	Z
24	0.9844	0.8954	0.8001	20	0.7203	0.8038	0.8738
22	0.9359	0.8531	0.7621	31	0.7549	0.8371	0.9113
23	0.9359	0.8533	0.7622	45	0.7543	0.8313	0.9065
55	0.9372	0.8561	0.7652	68	0.7604	0.8507	0.9232
82	0.9677	0.8885	0.7970	78	0.7628	0.8549	0.9270
Node	**Group-C**			**Node**	**Group-C**		
	X	Y	Z		X	Y	Z
2	0.9039	0.9039	0.9039	38	0.9031	0.9035	0.9039
3	0.8485	0.8485	0.8485	39	0.9031	0.9035	0.9039
4	0.8327	0.8327	0.8327	40	0.9031	0.9035	0.9039
5	0.9261	0.9261	0.9261	41	0.7934	0.7940	0.7945
6	0.8321	0.8321	0.8321	42	0.8678	0.8683	0.8687
7	0.8064	0.8064	0.8064	44	0.8328	0.8329	0.8329
8	0.8548	0.8548	0.8548	46	0.8018	0.8020	0.8022
9	0.8190	0.8190	0.8190	50	0.7928	0.7927	0.7926
10	0.7828	0.7828	0.7828	51	0.8127	0.8126	0.8125
12	0.8386	0.8386	0.8386	52	0.8688	0.8687	0.8686
13	0.8072	0.8072	0.8072	53	0.8325	0.8323	0.8322
14	0.8209	0.8209	0.8209	54	0.8695	0.8694	0.8693
16	0.8990	0.8990	0.8990	57	0.8406	0.8406	0.8406
17	0.8261	0.8262	0.8262	58	0.8285	0.8285	0.8285
18	0.8764	0.8764	0.8764	60	0.9021	0.9021	0.9021
19	0.7793	0.7793	0.7794	61	0.9022	0.9022	0.9022
21	0.7658	0.7658	0.7658	62	0.8485	0.8485	0.8485
25	0.8589	0.8589	0.8589	63	0.7933	0.7933	0.7933
26	0.8601	0.8601	0.8601	64	0.8432	0.8432	0.8432
27	0.8253	0.8253	0.8253	66	0.8611	0.8612	0.8613
28	0.8181	0.8181	0.8181	71	0.8204	0.8206	0.8208
29	0.8641	0.8641	0.8641	72	0.8204	0.8206	0.8208
32	0.8082	0.8088	0.8093	75	0.7920	0.7920	0.7920
33	0.9007	0.9011	0.9015	76	0.8642	0.8642	0.8642
34	0.8099	0.8105	0.8110	79	0.8561	0.8561	0.8562
35	0.8661	0.8666	0.8671	80	0.8387	0.8388	0.8389
36	0.8674	0.8678	0.8683	81	0.8322	0.8322	0.8323
37	0.9030	0.9034	0.9038	83	0.7682	0.7682	0.7683

X: Base case, Y: Scenario 1, Z: Scenario 2

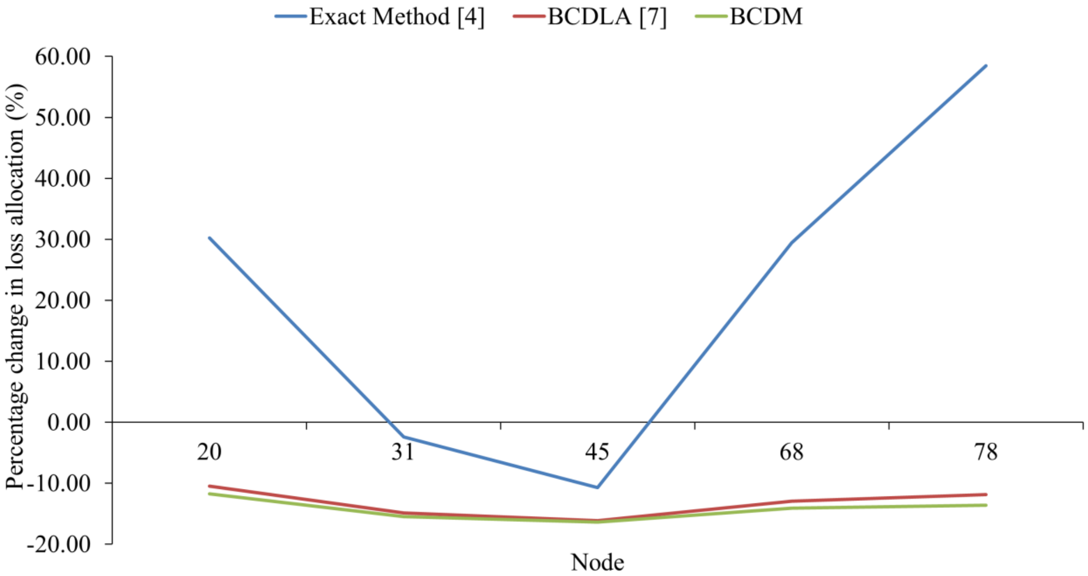
Table 3.24 Comparison of loss allocation methods for case study 2

Group-A						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
22	-19.17	13.64	16.40	-38.30	27.71	33.41
23	-18.96	13.69	16.39	-37.91	27.89	33.50
24	-21.95	20.92	25.77	-39.19	37.91	46.74
55	-20.47	13.55	17.35	-41.12	28.63	35.89
82	-27.69	14.86	18.64	-53.90	28.94	36.59
Group-B						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
20	30.19	-10.49	-11.77	55.72	-18.75	-21.23
31	-2.43	-14.88	-15.49	-1.83	-26.13	-28.19
45	-10.74	-16.13	-16.39	-17.63	-28.55	-29.65
68	29.45	-12.93	-14.12	55.25	-22.97	-25.61
78	58.44	-11.89	-13.64	107.89	-21.21	-24.69
Group-C						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
16	-1.39	-0.33	-0.34	-2.29	-0.54	-0.57
17	-1.78	-0.42	-0.36	-2.95	-0.69	-0.59
18	-1.53	-0.41	-0.40	-2.52	-0.67	-0.66
19	-2.21	-0.53	-0.42	-3.66	-0.87	-0.69
21	-1.26	-0.29	-0.24	-1.71	-0.38	-0.28
25	0	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
29	0	0	0	0	0	0
32	-16.03	-4.80	-3.97	-30.87	-9.25	-6.81
33	-12.05	-3.67	-3.85	-23.21	-7.07	-6.61
34	-13.79	-4.13	-3.41	-26.57	-7.95	-5.86
35	-11.57	-3.58	-3.35	-22.29	-6.89	-5.77
36	-10.48	-3.24	-3.03	-20.19	-6.25	-5.22
37	-9.38	-2.88	-3.02	-18.07	-5.58	-5.18
38	-9.34	-2.89	-3.00	-17.98	-5.54	-5.15
39	-9.31	-2.88	-2.97	-17.96	-5.56	-5.14
40	-9.32	-2.88	-2.99	-17.93	-5.55	-5.15
41	-12.65	-3.69	-2.95	-24.36	-7.11	-5.08
42	-10.07	-3.13	-2.92	-19.40	-6.03	-5.04
44	-26.44	-6.69	-6.13	-52.87	-13.68	-10.12
46	-22.68	-6.22	-5.26	-45.39	-12.43	-8.62
50	5.66	1.02	0.71	11.55	2.08	1.49
51	5.02	1.00	0.72	10.25	2.05	1.51
52	3.96	0.90	0.74	8.09	1.84	1.54

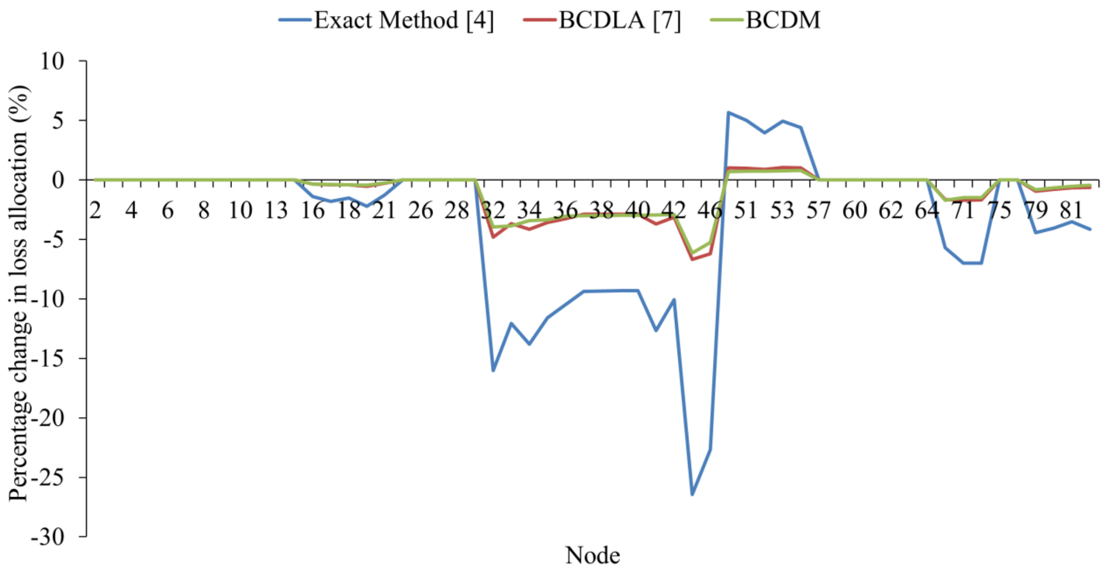
53	4.96	1.07	0.78	10.12	2.18	1.64
54	4.42	1.03	0.81	9.02	2.09	1.70
57	0	0	0	0	0	0
58	0	0	0	0	0	0
60	0	0	0	0	0	0
61	0	0	0	0	0	0
62	0	0	0	0	0	0
63	0	0	0	0	0	0
64	0	0	0	0	0	0
66	-5.71	-1.65	-1.70	-10.53	-3.03	-3.04
71	-6.99	-1.69	-1.50	-12.87	-3.11	-2.68
72	-6.98	-1.69	-1.49	-12.84	-3.10	-2.68
75	0	0	0	0	0	0
76	0	0	0	0	0	0
79	-4.43	-0.94	-0.81	-7.85	-1.66	-1.42
80	-4.04	-0.80	-0.66	-7.08	-1.40	-1.12
81	-3.52	-0.67	-0.53	-6.09	-1.14	-0.88
83	-4.16	-0.62	-0.44	-7.11	-1.04	-0.70



Group-A

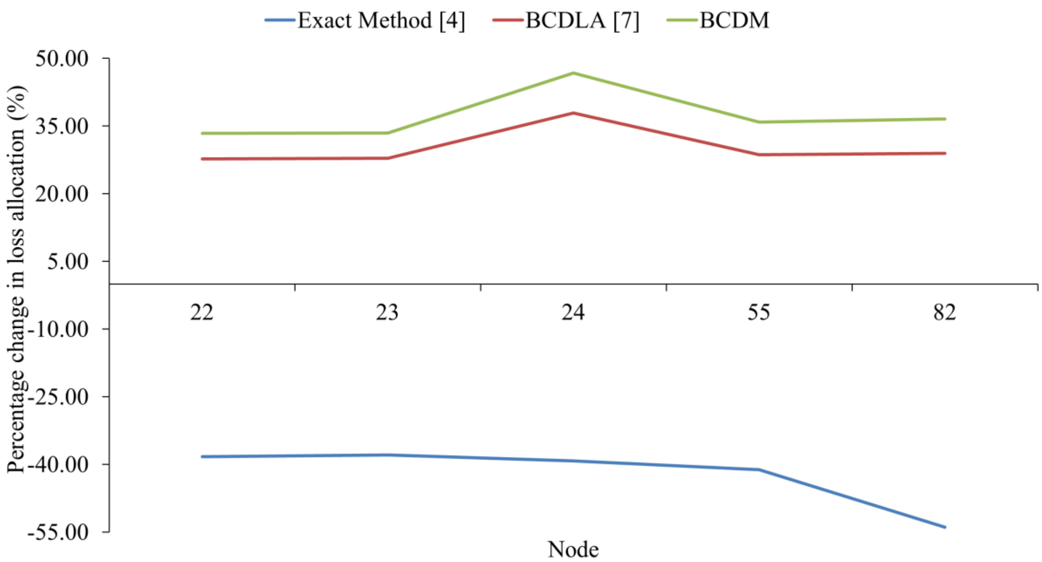


Group-B

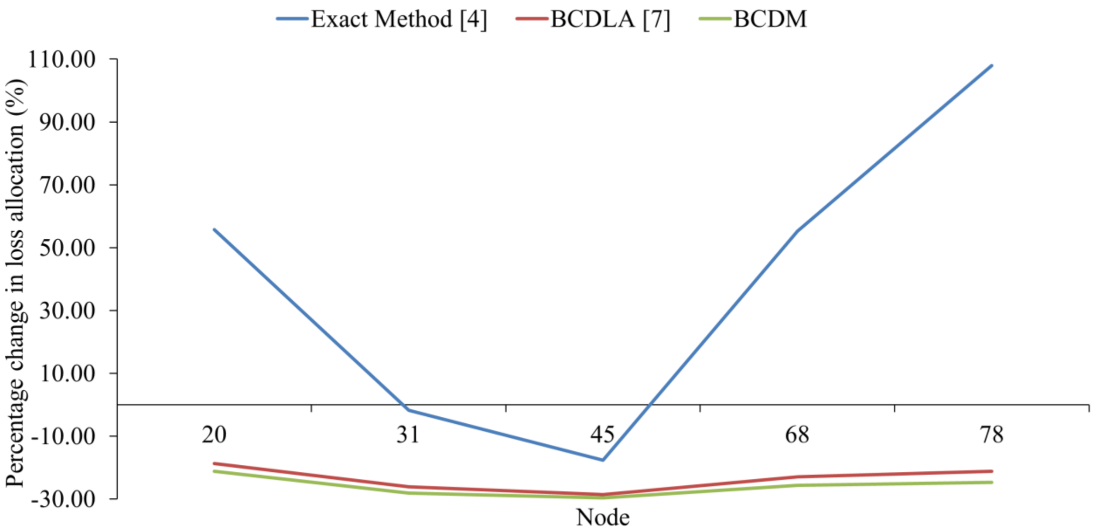


Group-C

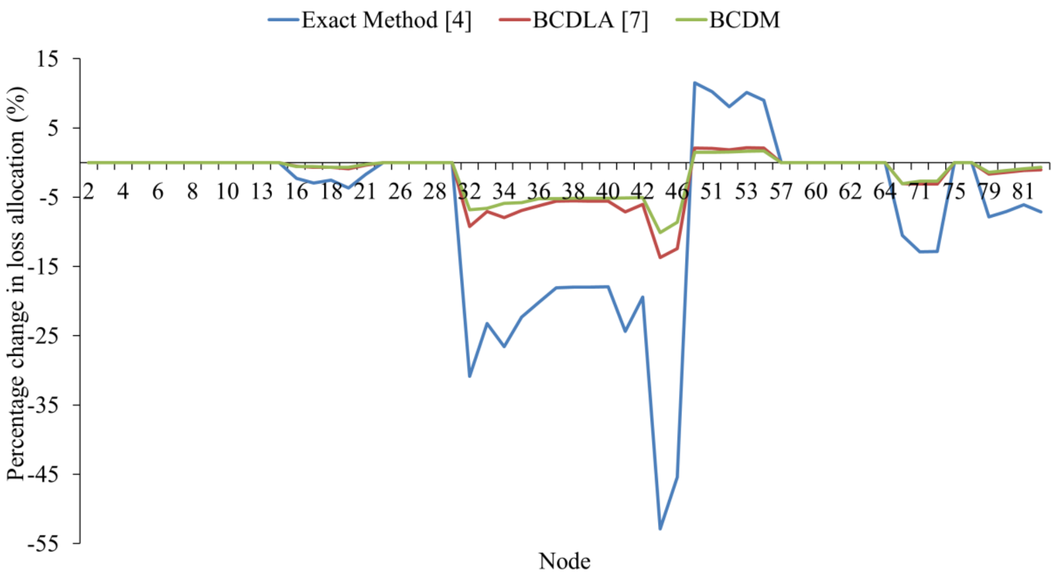
Fig. 3.16 Comparison of proposed methods with established methods for scenario 1



Group-A



Group-B



Group-C

Fig. 3.17 Comparison of proposed methods with established methods for scenario 2

The per-cent change in loss allocation with the variation in load power factor for all nodal groups is compared in Fig. 3.16. It can be observed from the figure that loss allocation is reduced for Group-A, increased for Group-B and remains almost unchanged for Group-C nodes while considering scenario 1. Similar results obtained for scenario 2 as shown in Fig. 3.17. There is a close resemblance while comparing the results obtained using BCDM and BCDLA [7] methods and are found to be consistent, however, the results obtained using Exact method [4] shows inconsistency while varying load power factor. The statistical error analysis carried to check the per-cent change in loss allocation to Group-C nodes while comparing these methods and is presented in Table 3.25. The table shows maximum, minimum, mean and SD of the per-cent change in loss allocation to Group-C nodes where load power factor was not varied. The table reveals that in general the loss allocation to Group-C nodes is least affected using proposed BCDM and BCDLA [7] methods, but the same is not true using Exact Method [4], however, BCDM performs slightly better for both scenarios considered.

Table 3.25 Statistical Error Analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	BCDM	Exact Method [4]	BCDLA [7]	BCDM
Max.	26.44	6.69	6.13	52.87	13.68	10.12
Min.	0	0	0	0	0	0
Mean	4.31	1.17	1.06	8.28	2.26	1.84
SD	5.95	1.69	1.54	11.72	3.33	2.60

Variation in DG power factor

The system is assumed with five DG units as shown in Table 3.17. DG5 is selected as having the highest rating. The power factor of this DG is varied from unity to 0.707

(leading) by varying reactive power injection while keeping active power generation constant. The remunerations allocated to DGOs are obtained by considering nominal load condition and the results are presented in Fig. 3.18. It can be observed from figure that more the reactive power being injected into the system by DG unit, more will be the remuneration allocated and vice-versa without affecting remuneration to other DG units. This shows high accuracy of proposed BCDM while varying DG power factor.

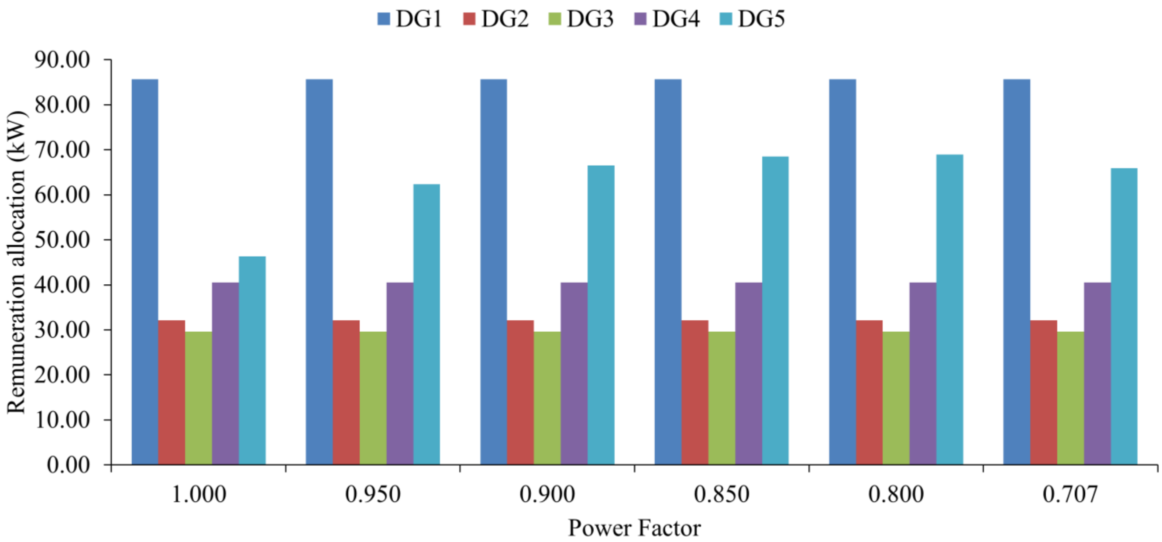


Fig. 3.18 Remuneration allocation to DGOs with variation in power factor of DG5

3.3 DISCUSSION

The main contributions in proposed BCDM are the concept of constrained virtual branch voltage drop while allocating losses to loads, and the application of Superposition while remunerating DGOs. The concept of constrained virtual branch voltage drop is based upon the fact that feeder power losses in a distribution system are independent of the branch reactance. The difference in BCDLA [7] and proposed BCDM is that the line reactances are neglected in the former method, whereas it has been made dynamic in the latter method so that losses can be judiciously allocated. Since both active and reactive components of line current are equally responsible for Joule's heating in distribution feeders, the proposed approach produces more convincing results. This can be analytically explained as below.

Consider Fig. 3.19, showing phasors pertaining to the branch ij of the distribution system. Let, $\Re\{\boldsymbol{I}(ij,k)\}$ and $Im\{\boldsymbol{I}(ij,k)\}$ are the active and reactive components of the nodal current $\boldsymbol{I}(ij,k)$. If $P\alpha(ij,k)$and $P\beta(ij,k)$ denotes the respective projections of $\Re\{\boldsymbol{I}(ij,k)\}$ and $Im\{\boldsymbol{I}(ij,k)\}$ about the virtual voltage drop $\Delta\boldsymbol{V}(ij)$ as in [7]. Then

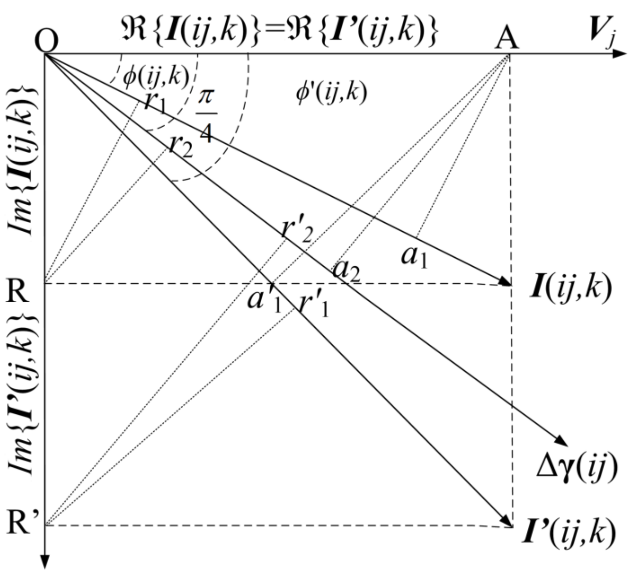


Fig. 3.19 Projections of current components about constrained virtual voltage drop

$$P\alpha(ij,k) = \Re\{\boldsymbol{I}(ij,k)\}cos\phi(ij,k) = \frac{P(ij,k)}{Vj}cos\phi(ij,k) \tag{3.27}$$

$$P\beta(ij,k) = Im\{\boldsymbol{I}(ij,k)\}sin\phi(ij,k) = \frac{P(ij,k)\ tan\phi(ij,k)}{Vj}sin\phi(ij,k) \tag{3.28}$$

However, using proposed BCDM, these projections are taken about CVBVD $\Delta\boldsymbol{\gamma}(ij)$ as

$$P\alpha'(ij,k) = \Re\{\boldsymbol{I}(ij,k)\}cos\left(\frac{\pi}{4}\right) = \frac{P(ij,k)}{Vj}cos\left(\frac{\pi}{4}\right) \tag{3.29}$$

$$P\beta'(ij,k) = Im\{\boldsymbol{I}(ij,k)\}sin\left(\frac{\pi}{4}\right) = \frac{P(ij,k)\ tan\phi(ij,k)}{Vj}sin\left(\frac{\pi}{4}\right) \tag{3.30}$$

A comparison of (3.27) with (3.29) shows that $P\alpha(ij,k)$ varies with power factor, but $P\alpha'(ij,k)$ does not. Nevertheless, the projection should remain constant for the given active power demand. On the other hand, the comparison of (3.28) with (3.30) reveals that $P\beta(ij,k)$ is proportional to $P(ij,k)$ $tan\phi(ij,k)$ $sin\phi(ij,k)$, i.e. $Q(ij,k)$ $sin\phi(ij,k)$, whereas $P\beta'(ij,k)$ is proportional to $P(ij,k)$ $tan\phi(ij,k)$, i.e. $Q(ij,k)$. However, when the reactive power demand increases keeping active power demand constant, $\phi(ij,k)$ and hence $sin\phi(ij,k)$ also increases. This causes undue increase in $P\beta'(ij,k)$ as compared with $P\beta(ij,k)$. This fact can be observed from the figure while comparing Or_1 with Or_1'. Thus the method of [7] not provide true signals for loss allocation while considering load power factor. Conversely, the proposed BCDM provides true projections of the contributing nodal currents while comparing Or_2 with Or_2' in the figure. In fact, both these methods provide comparable results whenever power factor is around 0.707, which mostly occurred in practice. However, if the power factor deviate much from this central value, the loss allocation provided by proposed BCDM will be more judicious. With similar lines it can be shown that proposed BCDM can judiciously allocates remuneration to DGOs.

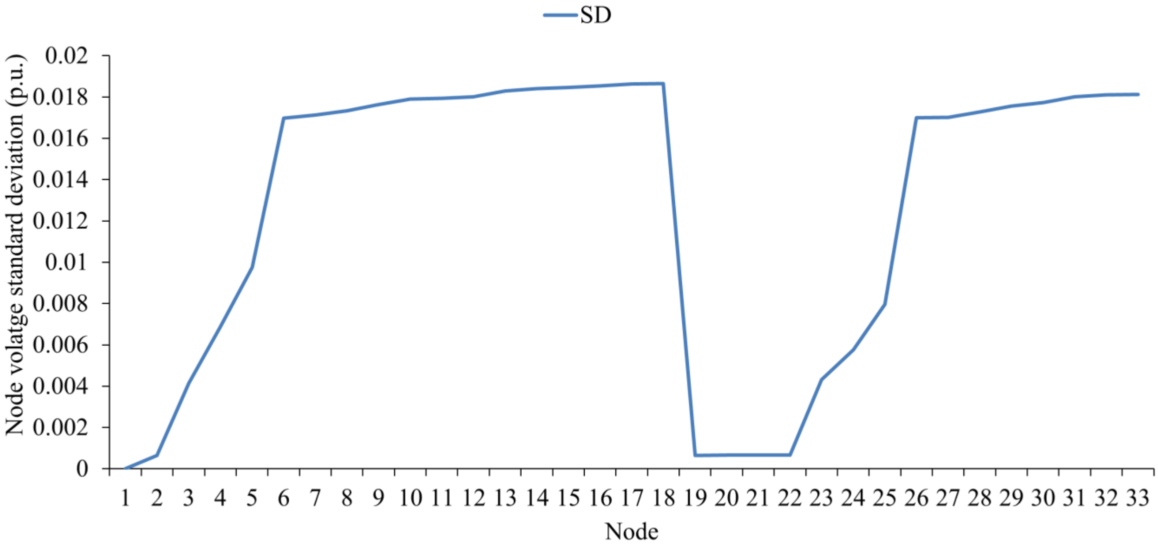


Fig. 3.20 Standard deviation of the nodal voltage load factor 2 for case study 1

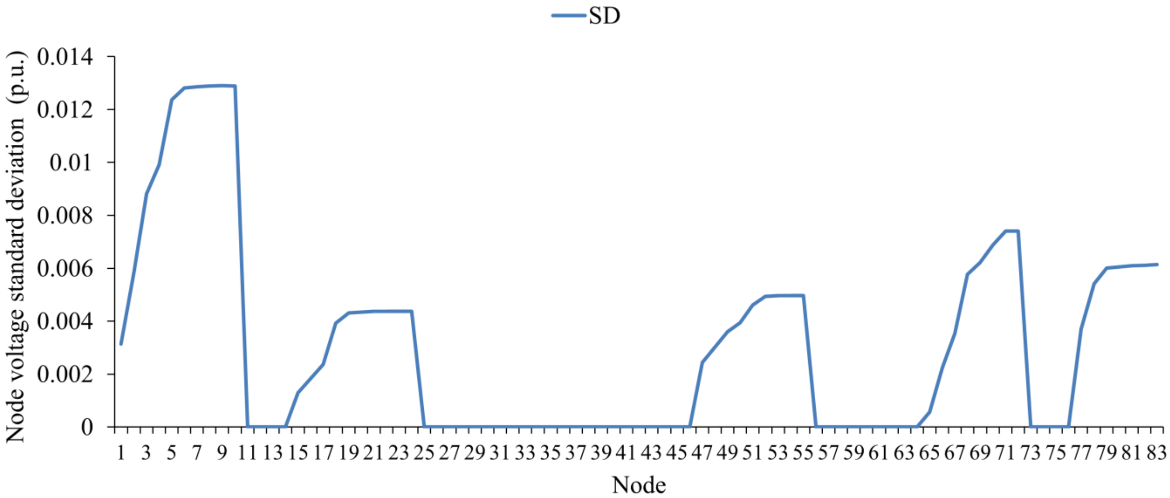


Fig. 3.21 Standard deviation of the nodal voltage at load factor 2 for case study 2

The Superposition is suggested to determine contributing currents of each DG unit, however, the manner in which it is employed is different than as mentioned in text. Here, the contributing current of a DG unit is determined by analysing two different situations, i.e. with all DGs and with all DGs except the DG under consideration. This tactic is adopted so that almost similar voltage profiles can be maintained in these two situations, otherwise the error will be high as Superposition, in general, cannot be applied to a non-linear system. However, small variations can be expected while employing Superposition and therefore a small error too in remuneration allocation to DGOs.

In this study, the error produced using Superposition is found to be much less for case study 2 than case study 1. The expected root cause behind this error is the variation in nodal voltages while employing Superposition. In order to investigate it, keeping load factor as 2.0, the voltage deviations produced at each distribution node is measured when every time applying Superposition. The SD of the node voltage deviation as each node is then determined. The set of SD obtained for system nodes is obtained for each case study as presented in Fig. 3.20 and Fig. 3.21. The comparison of figures shows that the value of SD is higher, in general, for case study 1 than case study 2. This shows that node voltage profiles are affected much more in case study 1 than case study 2 while employing Superposition. In order to quantify the comparison of variation in node voltage profiles, the mean of the set of SDs is obtained. It is found that the value is 0.0126 p.u. for case study 1 which is found to be only 0.0031 p.u. of case study 2. This shows why the error produced using Superposition is much less in case study 2.

Contemporary distribution systems are well equipped with diverse DERs so better node voltage profiles may be expected. Moreover, the distribution systems may be seen with a large number of DGs. With these concerns it is not difficult to say that the error produced will be vanishingly small, therefore, proposed method seems to be promising for contemporary distribution systems.

3.4 Summary

A new loss allocation method and allocation strategy among different entities is proposed for active distribution systems. Proposed branch current decomposition method (BCDM) employs branch-oriented approach while allocating feeder power losses to loads or remunerate DGOs. The method is especially designed to take care of power factor of loads and DG units so encourage prosumers to maintain better power factor. BCDM employs a novel concept of constrained virtual branch voltage drop that overcomes the limitations of other existing methods. Another novel approach in the proposed method is to employ Superposition while remunerating DGOs. This is certainly a significant step as distribution systems are, in general, not considered linear. However, the application results on standard test as well as practical distribution systems reveals that insignificant error will be produced if Superposition is employed in a different manner. The method also suggested strategy to avoid conflicts between customers, DGOs and DNO while allocating losses/remuneration or a penalty as it is based upon the philosophy, “you have to pay for what you do.” With this approach, the actual losses that may occurred in the absence of DGs is allocated to load points, the actual loss reduction that is caused by DGs is awarded to respective DGOs and any loss reduction caused by topological changes in distribution network is kept in the account of DNO. The accuracy and effectiveness of BCDM is thoroughly investigated under varying loading, power factor of load and DG units. The results study are presented and discussed. The application results highlight the importance of proposed method in the context of contemporary distribution systems.

CHAPTER 4
CROSSED-TERM DECOMPOSITION METHOD

In this chapter, another LA method is proposed for RADNs using a different branch-oriented approach. The LA method employs power loss formula I^2R for branch power loss thus needs allocation of crossed-terms. The crossed-term decomposition method (CTDM) that basically proposed for passive distribution systems is extended for active distribution systems by suggesting LAFs to individual DG units. LAFs suggested to both customers and DG units are derived analytically thus rationally allocates losses among various network users. The method is also investigated for reconfigured distribution networks using the LAS proposed in chapter 3. The proposed methodology is applied on 33-bus test distribution system and 83-bus practical distribution systems. The robustness and accuracy of proposed CTDM is thoroughly investigated under varying load, power factor and reactive power transactions of DG units. The application results obtained are presented and compared with other established methods.

4.1. PROPOSED CROSSED-TERM DECOMPOSITION METHOD

The loss allocation in distribution system has been under consideration since last two decades using different branch-oriented approaches. Among them one approach represents branch losses as I^2R where I denote contributing nodal current. This approach is quite straightforward, but the loss term involve squared and crossed-term. Squared-term provide loss allocation to contributing nodes, however, decomposition of crossed-terms among the contributing nodes is a difficult task. In past many approaches have been suggested, to decompose crossed-terms among contributing nodes such as *pro-rata* [9], [10] *quadratic* [1], [14], *proportional* sharing [11] [12] [13], geometric, [14]-[16] and shapley-value based method [8], [38]. The shapley-value based method is not suitable for distribution system, which usually contain constant power type of loads. Most of the methods of *pro-rata*, *proportional* sharing families ignore reactive power flow in the process of allocation [1] though is very important in distribution systems and are intuitively derived. Therefore, crossed-term decomposition method (CTDM) is proposed that considers reactive power transactions.

4.1.1. LOSS ALLOCATION TO CUSTOMERS

The proposed CTDM employs another branch-oriented approach where the branch power loss is given by the multiplication of branch resistance and the square of the sum of contributing nodal currents in the branch. Consider branch *ij* of a distribution feeder as shown in Fig. 4.1. The current flowing through the branch *ij* is

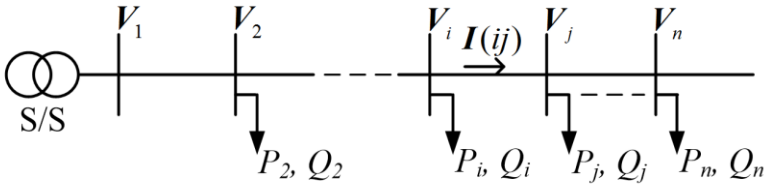


Fig. 4.1 Single line diagram of a distribution feeder

$$\boldsymbol{I}(ij) = \sum_{k \in CN(ij)} \boldsymbol{I}(ij,k) \tag{4.1}$$

The power loss through the branch *ij* is

$$ploss(ij) = \sum_{k \in CN(ij)} ploss(ij,k) = R(ij)\left[\Re(\boldsymbol{I}(ij))^2 + \mathrm{Im}(\boldsymbol{I}(ij))^2\right] \tag{4.2}$$

$$= R(ij)\left[\left(\sum_{k \in CN(ij)} I(ij,k)\cos\phi(ij,k)\right)^2 + \left(\sum_{k \in CN(ij)} I(ij,k)\sin\phi(ij,k)\right)^2\right] \tag{4.3}$$

$$= R(ij)\sum_{k \in CN(ij)} (I(ij,k))^2 + R(ij)\sum_{k \in CN(ij)} \sum_{\substack{q \in CN(ij) \\ q \neq k}} I(ij,k)I(ij,q)\cos\left\{\phi(ij,k) - \phi(ij,q)\right\} \tag{4.4}$$

$$=ST(ij)+CT(ij) \tag{4.5}$$

As discussed above, the first term of (4.5) clearly provides partial contribution of each contributing node for the power loss in the branch *ij*, however the second term needs a bifurcation to allocate power losses among the contributing nodes. It is noteworthy that the later term may contribute majority of the power losses in distribution systems with long distribution feeders. Therefore, it is important to investigate the dependency of crossed-terms on contributing node currents. Let us consider,

$$\frac{\partial CT(ij)}{\partial I(ij,k)} = R(ij)\sum_{\substack{q \in CN(ij) \\ q \neq k}} \left(I(ij,q)\cos\left\{\phi(ij,k) - \phi(ij,q)\right\}\right) \tag{4.6}$$

Using (4.4)-(4.6)

$$CT(ij) = \frac{1}{2}\sum_{k \in CN(ij)} I(ij,k)\frac{\partial CT(ij)}{\partial I(ij,k)} = \frac{1}{2}\sum_{k \in CN(ij)} CT(ij,k) \tag{4.7}$$

where,

$$CT(ij,k) = 2R\left(ij\right)\sum_{\substack{q \in CN(ij) \\ q \neq k}} I(ij,k)I(ij,q)\cos\left\{\phi(ij,k) - \phi(ij,q)\right\} \tag{4.8}$$

$$CT(ij,k) = I(ij,k)\frac{\partial CT(ij)}{\partial I(ij,k)} \tag{4.9}$$

CT(*ij*) denotes the loss contribution of the current *I*(*ij*,*k*) in the branch *ij* and its derivative term is independent of this current as shown in (4.6). Differentiating (4.9) with respect to $I(ij,k)$ yields

$$\frac{\partial CT(ij,k)}{\partial I(ij,k)} = \frac{\partial CT(ij)}{\partial I(ij,k)} \tag{4.10}$$

From Eqns. (4.9) and (4.10)

$$\frac{\partial CT(ij,k)}{CT(ij,k)} = \frac{\partial I(ij,k)}{I(ij,k)} \tag{4.11}$$

Equation (4.11) reveals that there exist a linear relationship between $CT(ij,k)$ and $I(ij,k)$. Therefore, to allocate crossed-terms of branch power loss, the loss allocation factor (LAF) assigned to the kth node in branch ij is proposed as

$$Lf(ij,k) = \frac{I(ij,k)}{\sum_{k \in CN(ij)} I(ij,k)} \tag{4.12}$$

The crossed-terms of power loss to each contributing node current $I(ij,k)$ in branch ij thus can be allocated as

$$CT(ij,k) = Lf(ij,k)CT(ij) \tag{4.13}$$

The loss contributed by kth node in branch ij may be evaluated as

$$ploss(ij,k) = R(ij)(I(ij,k))^2 + Lf(ij,k)CT(ij) \tag{4.14}$$

The loss allocated to kth node and the system losses are therefore given by

$$ploss(k) = \sum_{ij=1}^{NB} ploss(ij,k) \tag{4.15}$$

$$Ploss = \sum_{k=1}^{N} ploss(k) \tag{4.16}$$

The proposed CTDM on a small distribution system is illustrated as below.

Illustration

The 5-bus system considered in chapter 3 is taken to demonstrate proposed CTDM. The line and bus data of this system may be referred from Table 3.1. The CTDM is applied to this system and the step-wise calculations are presented in Table 4.1 and Table 4.2. The nodal voltages, nodal current injections and contributing currents in each branch obtained after load flow is presented in Table 4.1. With this information, $ST(ij, k)$ and $CT(ij, k)$ are evaluated using (4.4) and (4.13) respectively, as shown in Table 4.2. The table also shows loss allocation *ploss*(*k*) to various system nodes which can be evaluated using (4.14) and (4.15).

Table 4.1 Calculation for the components of contributing nodal currents

k	$\boldsymbol{V}_k$	$\boldsymbol{I}(k)$	$I\ (ij, k)$ 1-2	2-4	4-3	4-5
1	1.0000∠0	0∠0.00	0∠0.00	0∠0.00	0∠0.00	0∠0.00
2	0.9976∠-0.0586	0.0070∠-22.32	0.0070∠-22.32	0∠0.00	0∠0.00	0∠0.00
3	0.9959∠-0.1001	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0∠0.00
4	0.9962∠-0.0935	0.0137∠-21.86	0.0137∠-21.86	0.0137∠-21.86	0∠0.00	0∠0.00
5	0.9959∠-0.1001	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0∠0.00	0.0204∠-21.70

Table 4.2 Calculation for loss allocation to distribution nodes

ij / k	$ST(ij, k)$ 1-2	2-4	4-3	4-5	$CT(ij, k)$ 1-2	2-4	4-3	4-5	*ploss*(*k*)
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	0.77	0.00	0.00	0.00	4.88	0.00	0.00	0.00	5.65
3	6.63	4.42	2.21	0.00	14.32	7.75	0.00	0.00	35.34
4	2.98	1.99	0.00	0.00	9.60	5.20	0.00	0.00	19.77
5	6.63	4.42	0.00	2.21	14.32	7.75	0.00	0.00	35.34
ploss(*ij*)	17.02	10.83	2.21	2.21	43.13	20.70	0.00	0.00	96.10

4.1.2. REMUNERATION TO DGOS

The deployment of DGs in distribution system alters power flows through the network, which consequently alters feeder power losses. The DGOs, therefore, should be remunerated or penalized according to their contribution towards feeder power losses. DGs may be considered as constant power nature. When DG is in this mode, the power injection is considered as a negative load [65]. While adopting branch-oriented approach for loss allocation, it becomes essential to identify the contributing currents of individual DG units. However, it becomes a tedious task because the current flow in distribution branch is the phasor sum of the currents contributed by several contributing customers and DG units of that branch. As in (3.17), the current flow through branch *ij* while assuming no DGs in the system, may be considered as the phasor sum of contributing nodal currents in the presence of DGs and the current contributions from DG units as given below

$$\boldsymbol{I}(ij) = \boldsymbol{I}'(ij) - \boldsymbol{I}_{DG}(ij) \tag{4.17}$$

The following dot product holds good

$$\boldsymbol{I}(ij).\boldsymbol{I}(ij) = (\boldsymbol{I}'(ij) - \boldsymbol{I}_{DG}(ij)).(\boldsymbol{I}'(ij) - \boldsymbol{I}_{DG}(ij)) \tag{4.18}$$

$$I^2(ij) = I'^2(ij) + \boldsymbol{I}_{DG}(ij).\boldsymbol{I}_{DG}(ij) - 2\boldsymbol{I}'(ij).\boldsymbol{I}_{DG}(ij) \tag{4.19}$$

$$(I^2(ij) - I'^2(ij))R(ij) = \left(\boldsymbol{I}_{DG}(ij).\boldsymbol{I}_{DG}(ij) - 2\boldsymbol{I}'(ij).\boldsymbol{I}_{DG}(ij)\right)R(ij) \tag{4.20}$$

Let, $\boldsymbol{I}_{DG}(ij) = \sum_{p \in CDG(ij)} \boldsymbol{I}_{DG}(ij, p)$ (4.21)

The remuneration to concerned DGs for branch *ij* will be given by

$$R_{DG}(ij) = \left[\sum_{p\in CDG(ij)} \boldsymbol{I}_{DG}(ij,p). \sum_{p\in CDG(ij)} \boldsymbol{I}_{DG}(ij,p) - 2\boldsymbol{I}'(ij). \sum_{p\in CDG(ij)} \boldsymbol{I}_{DG}(ij,p) \right] R(ij) \tag{4.22}$$

$$= \left[\begin{array}{l} \displaystyle\sum_{p\in CDG(ij)} I_{DG}{}^{2}(ij,p) + \sum_{p\in CDG(ij)} \sum_{\substack{r\in CDG(ij) \\ r\neq p}} \boldsymbol{I}_{DG}(ij,p).\boldsymbol{I}_{DG}(ij,r) \\ \displaystyle -2\boldsymbol{I}'(ij). \sum_{p\in CDG(ij)} \boldsymbol{I}_{DG}(ij,p) \end{array} \right] R(ij) = \sum_{p\in CDG(ij)} R_{DG}(ij,p) \tag{4.23}$$

where, $R_{DG}(ij, p)$ denotes remuneration allocated to the *p*th DG for loss reduction in branch *ij* and may be written as

$$R_{DG}(ij,p) = \left[I_{DG}{}^{2}(ij,p) + 2Ru(ij,p) \sum_{\substack{r\in CDG(ij) \\ r\neq p}} \boldsymbol{I}_{DG}(ij,p).\boldsymbol{I}_{DG}(ij,r) - 2\boldsymbol{I}'(ij).\boldsymbol{I}_{DG}(ij,p) \right] R(ij) \tag{4.24}$$

where, $\upsilon(ij,p)$ is the remuneration allocation factor for the *p*th DG while bifurcating crossed-terms pertaining to the contributing currents from the *p*th DG in branch *ij*. Eq. (4.24) can be expressed as

$$=ST^{DG}(ij,p) + CT^{DG}(ij,p) + MT^{DG}(ij,p) \tag{4.25}$$

where,

$$ST^{DG}(ij,p) = I_{DG}{}^{2}(ij,p) R\left(ij\right) \tag{4.26}$$

$$CT^{DG}(ij,p) = 2Ru(ij,p) R\left(ij\right) \sum_{\substack{r\in CDG(ij) \\ r\neq p}} \boldsymbol{I}_{DG}(ij,p).\boldsymbol{I}_{DG}(ij,r) \tag{4.27}$$

$$MT^{DG}(ij,p) = -2\boldsymbol{I}'(ij).\boldsymbol{I}_{DG}(ij,p) R(ij) \tag{4.28}$$

Therefore, remuneration allocated to the *p*th DG is given by

$$\sum_{ij=1}^{NB} R_{DG}(ij,p) = \sum_{ij=1}^{NB} \left(ST^{DG}(ij,p) + CT^{DG}(ij,p) + MT^{DG}(ij,p) \right) \tag{4.29}$$

In (4.29), the determination of the first and the third term is straight forward, however, the second term involves crossed-terms related to the contributing DG currents which can be handled in the same way as defined by (4.13) while dealing with the allocation of crossed-terms contributed by the load currents.

Assuming almost flat voltage profile as expected in contemporary distribution systems, Superposition is applied to evaluate contributing branch current from each DG unit as in chapter 3. However, small error ε may arise while employing Superposition, as mentioned in chapter 3, while remunerating DG units using proposed CTDM. Due to the reasons explained, the error is small enough thus can be proportionally adjusted among all DGs.

There may be several approaches for this adjustment, but in proposed work the error is adjusted on the basis of respective contribution of DG unit towards loss reduction as suggested by (4.30). This approach is suggested because it is not necessary that largest DG unit would contribute towards maximum loss reduction rather it may cause loss enhancement some times. After this adjustment, the error in proposed remuneration will be zero from the utility point of view. The adjusted value of remuneration to each DG owner can be evaluated using (4.31).

$$\varepsilon_p = \varepsilon \left(\frac{\sum_{ij=1}^{NB} \left[ST^{DG}(ij,p) + CT^{DG}(ij,p) + MT^{DG}(ij,p) \right]}{\sum_{p=1}^{N_{DG}} \left(\sum_{ij=1}^{NB} \left[ST^{DG}(ij,p) + CT^{DG}(ij,p) + MT^{DG}(ij,p) \right] \right)} \right) \tag{4.30}$$

$$R_{DG}(p) = \sum_{ij=1}^{NB} R_{DG}(ij,p) = \sum_{ij=1}^{NB} \left(ST^{DG}(ij,p) + CT^{DG}(ij,p) + MT^{DG}(ij,p) \right) + \varepsilon_p \tag{4.31}$$

The CTDM can be applied to reconfigured distribution networks for allocating losses/loss incentives among load points, DGOs and DNO using the strategy suggested in chapter 3. The method is applied and investigated to two different systems as presented in the following section.

4.2. SIMULATION RESULTS

Proposed CTDM is applied to two different standard and practical distribution systems. The application results obtained are presented and compared with established methods available in literature. The robustness and accuracy of the method is thoroughly investigated under varying conditions of system loading, load power factor and reactive power injections from the DG units. The distribution network is then reconfigured for several system states. The application results obtained to allocate loss or loss incentives among customers, DGOs and DNO are presented and discussed.

4.2.1 CASE STUDY 1

The proposed CTDM is applied to well-known 33-bus test distribution system and detailed line and bus data may be referred from [50]. The system has 32 sectionalizing and 5 tie-lines. The nominal active and reactive power loading of the system are 3.715 MW and 2.3 MVAr, respectively. The power loss for this system with network topology in base configuration at nominal loading is 202.67 kW.

A. Loss allocation to loads

At nominal loading, the results obtained using proposed CTDM are compared with other established methods, i.e. Exact method [4], BCDLA [7], PSMLA [5], Method [15] and Method [16]. It has been observed that the total losses allocated by these methods are 202.59 kW, 202.67 kW, 202.68 kW, 202.68 kW, and 202.68 kW respectively. The comparison of LA using these methods is presented in Fig. 4.2 showing comparable results of proposed CTDM with other existing methods, except at node 30 owing to exceptionally poor factor of 0.32 (lag). This shows that proposed method is comparable to other established methods and all methods produce different results with diverse power factor. A detailed analysis will be presented later on.

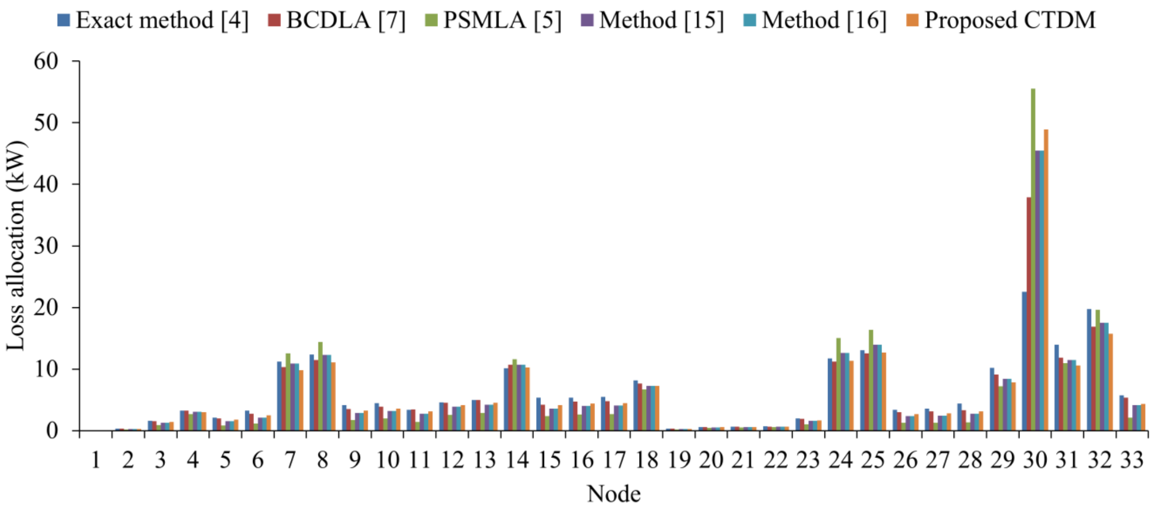


Fig. 4.2 Comparison of LA using CTDM with established methods

B. Remuneration to DGOs

In order to examine the applicability of proposed method for active distribution systems, the given system is modified by assuming three DGs as shown in Table 3.5 of chapter 3. With this DG penetration, the load flow shows that the feeder power losses are reduced from 202.67 kW to 43.44 kW. Thus a true loss reduction of 159.23 kW is contributed by DGs which should be remunerated among DGOs. Table 4.3 shows that the method basically calculates total remuneration as 153.09 kW which is then adjusted to 159.23 kW using (4.31). Therefore, the utility has to remunerate against loss reduction of 118.09 kW, 21.14 kW and 20.01 kW among DGOs as presented in the table.

Table 4.3 Remuneration allocated to DGOs using proposed CTDM

Remuneration	DG1	DG2	DG3	Total remuneration
Calculated	113.53	20.32	19.24	153.09
Adjusted	118.09	21.14	20.01	159.23

The allocation of losses and LIs in kW to all network users using various established methods is available in Ref. [16] and is compared with proposed CTDM in Table 4.4. It can be observed from the table that both LAL and RDG varies widely using all these methods, but NRU remains unchanged against 43.44 kW. This shows high inconsistency while using other methods because there is no doubt that the loss reduction caused by DGs is 153.23 kW, thus LA and LIs allocated using proposed method seems to be judicious.

Table 4.4 Comparison results of proposed CTDM with existing methods (in kW)

Node	BCDLA [7]	PSMLA [5]	Method [15]	Method [16]	Proposed CTDM
1	0.00	0.00	0.00	0.00	0.00
2	0.06	0.21	0.16	0.17	0.29
3	0.13	0.82	0.68	0.73	1.39
4	0.27	2.51	1.53	1.68	2.98
5	0.08	0.78	0.89	0.98	1.77
6	-0.07	1.06	1.20	1.34	2.50
7	0.35	11.02	4.82	5.52	9.79
8	1.35	12.68	6.00	6.84	11.06
9	0.62	1.57	1.85	2.06	3.27
10	0.91	1.81	2.14	2.39	3.60
11	0.95	1.27	1.90	2.11	3.11
12	1.29	2.32	2.59	2.90	4.14
13	1.63	2.60	2.93	3.27	4.52
14	3.66	10.40	6.87	7.74	10.26
15	1.35	2.12	2.50	2.79	4.12
16	1.61	2.36	2.81	3.14	4.37
17	1.70	2.43	2.90	3.24	4.46
18	2.80	6.00	4.90	5.50	7.28
19	0.08	0.19	0.17	0.18	0.28
20	0.36	0.47	0.45	0.46	0.56
21	0.41	0.52	0.50	0.51	0.61
22	0.45	0.56	0.54	0.55	0.65
23	0.20	0.94	0.80	0.86	1.68
24	1.02	11.17	4.34	4.85	11.35
25	-0.02	11.35	3.59	4.14	12.68
26	0.03	1.16	1.32	1.48	2.66
27	0.11	1.20	1.39	1.56	2.78
28	0.30	1.25	1.52	1.72	3.12
29	1.59	6.37	4.23	4.89	7.86
30	14.78	43.13	25.31	29.52	48.91
31	1.86	9.40	5.28	6.19	10.55
32	2.58	16.18	7.62	9.01	15.71
33	1.05	1.88	2.29	2.64	4.35
LAL	**43.49**	**167.73**	**106.02**	**120.96**	**202.67**
DG1	0.04	71.90	45.19	56.28	118.09
DG2	0.05	20.05	6.77	8.37	21.14
DG3	-0.04	32.34	10.62	12.87	20.01
RDG	**0.05**	**124.29**	**62.58**	**77.52**	**159.23**
NRU	**43.44**	**43.44**	**43.44**	**43.44**	**43.44**

NRU: Net revenue to utility; RDG: Remuneration to DGOs; LAL: LA to load points

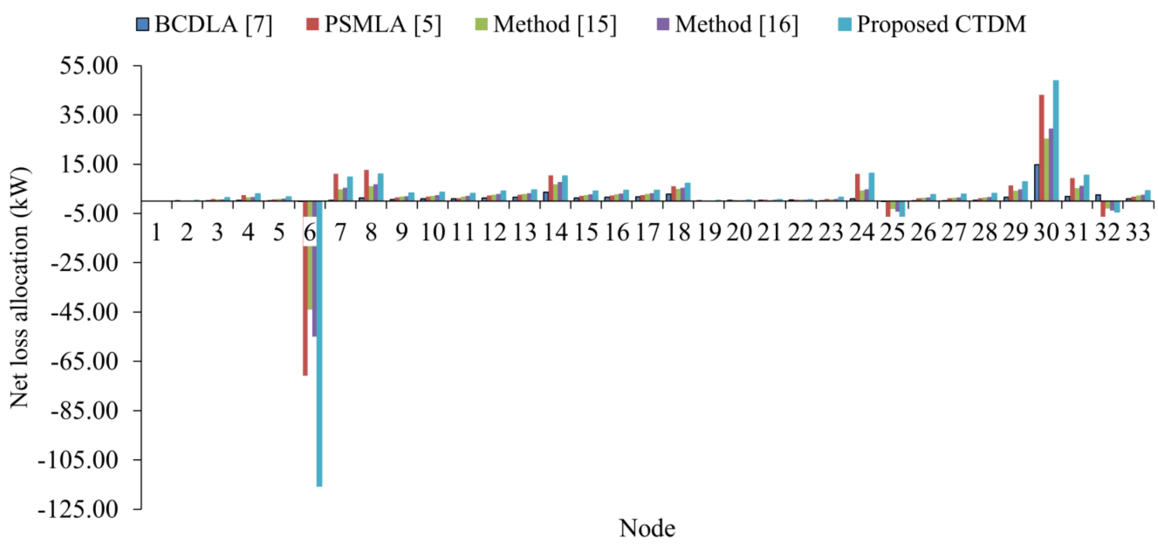


Fig. 4.3 Comparison of NLA to network users for different methods

The comparison of net LA (NLA) to network users is presented in Fig. 4.3. It can be observed from the figure that all the methods allocate different NLA at each node, specifically at node 6 and 30. The load power factor at node 6 is 0.95 (lag) whereas it is 0.32 (lag) at node 30. Therefore, the results obtained using proposed method seems to be more convincing than other methods. This shows that the proposed method considers power factor more effectively than other methods. This is an additive advantage of using the proposed method. A thorough investigation is presented in the following section.

C. Loss incentives to DNO

The proposed method is applied to RADNs with a realistic load profile as given in Table 3.9 of chapter 3. Assuming nominal topology of distribution network by opening the lines 7, 9, 14, 32 and 37. For this topology, the power losses are determined for each system state by conducting load flow with or without DGs. For simplicity, the power generation from DGs is taken same for all system states. The power loss occurred in each system state are presented in Table 4.5. The distribution network is then optimally reconfigured using GA to minimize power loss and the results obtained are also presented in the table. The energy loss reduction caused independently by DGs or NR are evaluated and are presented in the Table 4.6. The table shows the economic equation for each state of the reconfigured active distribution network using proposed LAS. The table shows that before NR, the energy losses are reduced by DGs except in few system states, i.e. state 1, 2, 3 and 9. It can be observed from the table that proposed method not only remunerate DGs for loss reduction but also penalize them if causes increased losses. It can also be observed that for the sample day, DNO would receive an amount for system losses of

1718.71 kWh against the losses contributed by the load points assuming no DGs in the system. The losses are reduced to 1485.12 kWh in the presence of DGs. Therefore, the total loss reduction by DG units is 233.59 kWh which is remunerated to DGOs. The losses are reduced from 1485.12 kWh to 628.29 kWh, i.e. 856.82 kWh, which is loss incentive (LI) of DNO. This economic equation equally holds good for each system state of RADN as can be verified from the table.

Table 4.5 An Illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	35.69	61.79	32.13	13,18,22,34,35
2	45.35	56.38	25.86	13,15,18,22,35
3	53.26	56.77	21.80	13,15,18,22,35
4	69.19	56.01	21.21	13,18,23,30,35
5	100.46	61.97	24.10	13,19,24,31,35
6	87.59	64.87	22.64	13,20,23,31,35
7	125.14	68.27	27.54	13,20,24,31,35
8	139.55	74.58	29.18	13,24,31,33,35
9	62.07	65.68	19.44	12,18,22,30,35

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

Table 4.6 Economic Equation for RADN

S	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	249.8	432.6	224.9	249.8	-182.7	207.7
2	45.4	56.4	25.9	45.4	-11.0	30.5
3	159.8	170.3	65.4	159.8	-10.5	104.9
4	207.6	168.0	63.6	207.6	39.5	104.4
5	502.3	309.9	120.5	502.3	192.4	189.3
6	87.6	64.9	22.6	87.6	22.7	42.2
7	125.1	68.3	27.5	125.1	56.9	40.7
8	279.1	149.2	58.4	279.1	129.9	90.8
9	62.1	65.7	19.4	62.1	-3.6	46.2
Sum	1718.7	1485.1	628.3	1718.7	233.6	856.8

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

It has been seen that the remuneration to DGOs is found to be less than the loss incentive (LI) to DNO. It happened because the power generation from all DGs is assumed to be constant. In practice, DGOs can vary their power generation to enhance remuneration, on the cost of reduction of LI to DNO. This is how DGOs and DNO can act to enhance their respective benefits which in turn enhances energy efficiency of the system. Whatsoever be the situation, the proposed strategy always avoid conflicts among them while distributing loss reduction benefits.

D. Accuracy of Proposed CTDM

The results obtained after the application of proposed CTDM to this system are found promising when compared with other existing methods. Since distribution system faces dynamically varying system states, it will be exciting to investigate the accuracy of developed LA method against the variation in system loading, load power factor and reactive power injection from DG units.

Variation in Load Demand

In order to examine the accuracy of Superposition while remunerating DGOs, the system loading is widely varied from 0.2 to 2.0. The remuneration/penalties allocated to DGOs at each loading are determined by considering and ignoring DGs, and is presented in Table 4.7. Table shows the maximum deviation in nodal voltages while employing superposition for different load factor. It can be observed from the table that in general the percentage error in remuneration allocation is ranging from 3%-4% while the maximum node voltage deviation varies around 4%. However, the error in remuneration is found to be more only when its magnitude is small. Moreover, the error is disbursed among DGOs, proposed LA method may be practically accepted under widely varying loading conditions.

Table 4.7 Accuracy of Superposition for Remuneration allocation to DGOs

Load Factor	Without DG	With DG	TRUE	Calculated	Error (%)	DVmax (%)
0.2	7.23	84.31	-77.08	-77.90	1.06	3.55
0.4	29.72	53.99	-24.28	-26.08	7.41	3.64
0.6	68.74	36.42	32.32	29.35	-9.19	3.73
0.8	125.81	32.53	93.27	88.88	-4.71	3.83
1	202.67	43.44	159.23	153.09	-3.86	3.94
1.2	301.42	70.40	231.02	222.65	-3.62	4.06
1.4	424.53	114.86	309.67	298.37	-3.65	4.20
1.6	575.40	178.55	396.84	381.22	-3.94	4.34
1.8	757.46	263.50	493.97	477.30	-3.37	4.55
2	975.78	372.30	603.48	580.01	-3.89	4.73

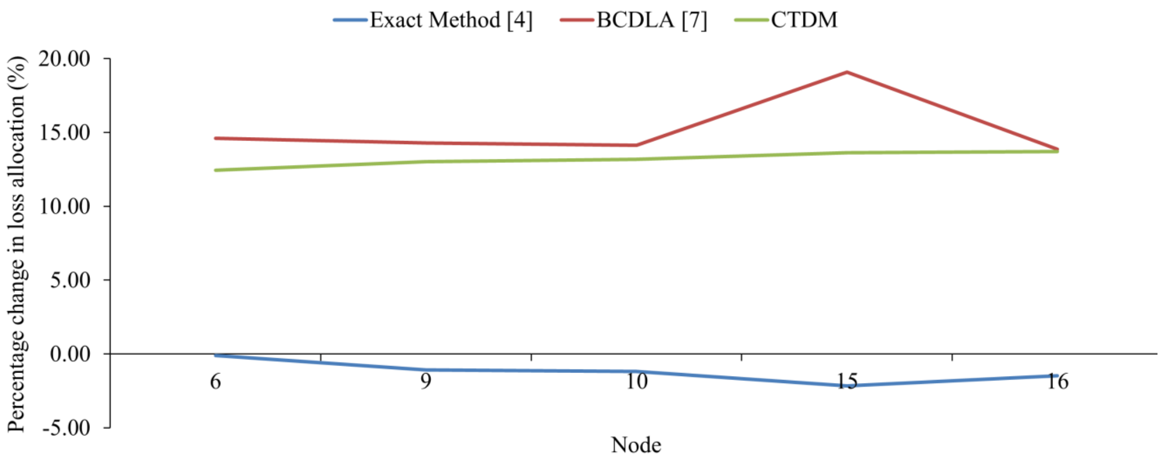
Variation in load power factor

The system nodes are arbitrarily divided into three groups and two scenarios are considered, as in chapter 3, by varying load power factors as presented in Table 3.14. Exact method [4], BCDLA [7] and proposed CTDM method are applied to this system for each of these scenarios. The percentage change in LA with the variation in power factor is evaluated and compared as shown in Table 4.8. The LA should increase for Group-A nodes and decrease for Group-B nodes whereas it should not alters for the nodes belong to Group-C. For better understanding, taking the help from Fig. 4.4 and Fig. 4.5 and Table 4.9. It can be observed from the figures that after varying power factor, only BCDLA [7] and CTDM produces comparable and promising results for Group-A and Group-B nodes and it is found to be true for both scenarios. The statistical error analysis carried about the absolute value of percent change in LA to Group-C nodes and the results so obtained are presented in Table 4.9. The table shows that LA using CTDM is not much affected as by using BCDLA [7] for both the scenarios considered. This validates accuracy and robustness of CTDM with the variation in load power factor.

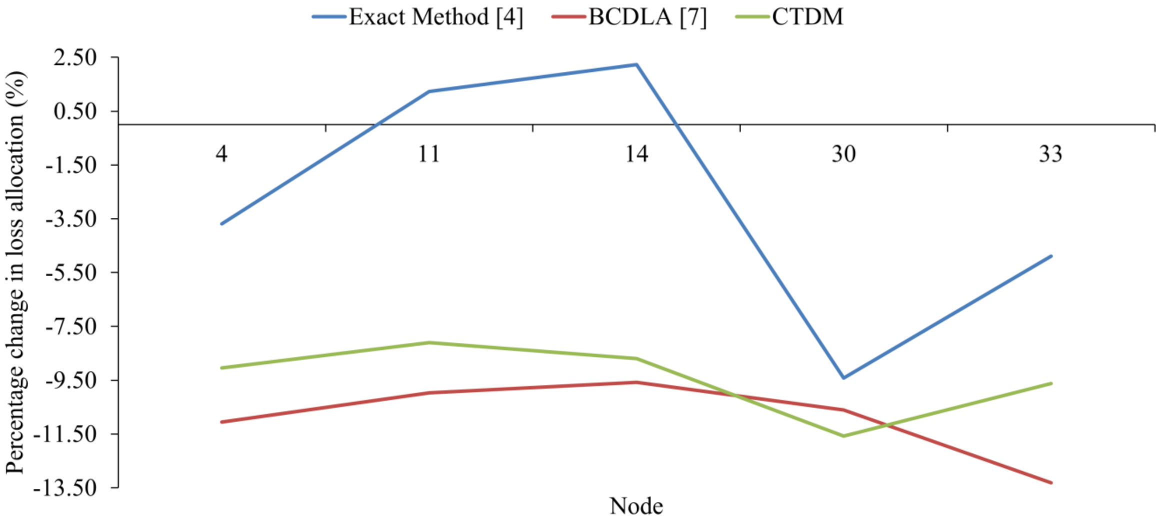
Table 4.8 Comparison of loss allocation methods for case study 1

Group-A						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
6	-0.11	14.60	12.44	-2.88	25.53	24.45
9	-1.08	14.28	13.03	-5.07	25.01	25.04
10	-1.19	14.14	13.19	-5.53	24.63	25.09
15	-2.16	19.10	13.63	-7.08	30.97	25.62
16	-1.48	13.87	13.72	-6.39	24.09	25.92
Group-B						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
4	-3.68	-11.06	-9.05	-8.95	-28.56	-18.76
11	1.23	-9.96	-8.10	1.39	-27.11	-18.00
14	2.23	-9.57	-8.70	3.31	-26.36	-19.10
30	-9.41	-10.61	-11.58	-19.41	-20.45	-22.42
33	-4.89	-13.31	-9.61	-9.79	-32.92	-19.69
Group-C						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
2	-1.18	-0.68	0.35	-3.61	-2.10	-1.36
3	-1.15	-0.63	0.37	-3.53	-1.94	-1.60
5	-1.27	-0.74	0.68	-3.95	-2.27	-1.43
7	-0.91	-0.63	0.92	-3.68	-2.11	-0.95
8	-0.59	-0.42	1.04	-3.15	-1.79	-0.88
12	0.20	-0.02	1.43	-2.47	-1.48	-1.00
13	0.40	0.07	1.53	-2.42	-1.43	-1.03
17	0.75	0.17	1.63	-1.20	-0.77	-0.80
18	0.83	0.23	1.56	-1.33	-0.88	-0.77
19	-0.91	-0.50	0.28	-2.77	-1.50	-1.21
20	-0.49	-0.26	0.14	-1.49	-0.80	-0.61
21	-0.46	-0.24	0.13	-1.39	-0.73	-0.56
22	-0.43	-0.24	0.14	-1.30	-0.68	-0.52
23	-1.07	-0.62	0.32	-3.28	-1.88	-1.40
24	-0.79	-0.44	0.21	-2.42	-1.34	-0.96
25	-0.72	-0.40	0.19	-2.19	-1.21	-0.87
26	-1.33	-0.72	0.86	-4.03	-2.12	-1.13
27	-1.51	-0.82	0.77	-4.34	-2.29	-1.26
28	-2.21	-1.01	0.44	-5.44	-2.52	-1.78
29	-3.18	-1.68	0.20	-7.46	-4.01	-2.08
31	-3.19	-1.60	-0.03	-7.41	-3.77	-2.45
32	-3.25	-1.63	-0.07	-7.57	-3.85	-2.44

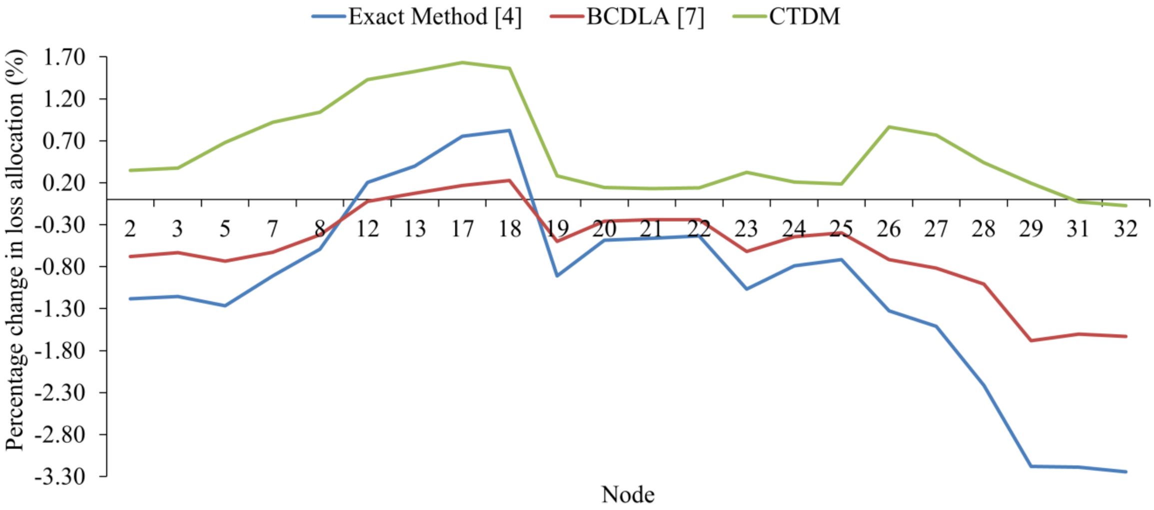
X: Base case, Y: Scenario 1, Z: Scenario 2



(a) Group-A

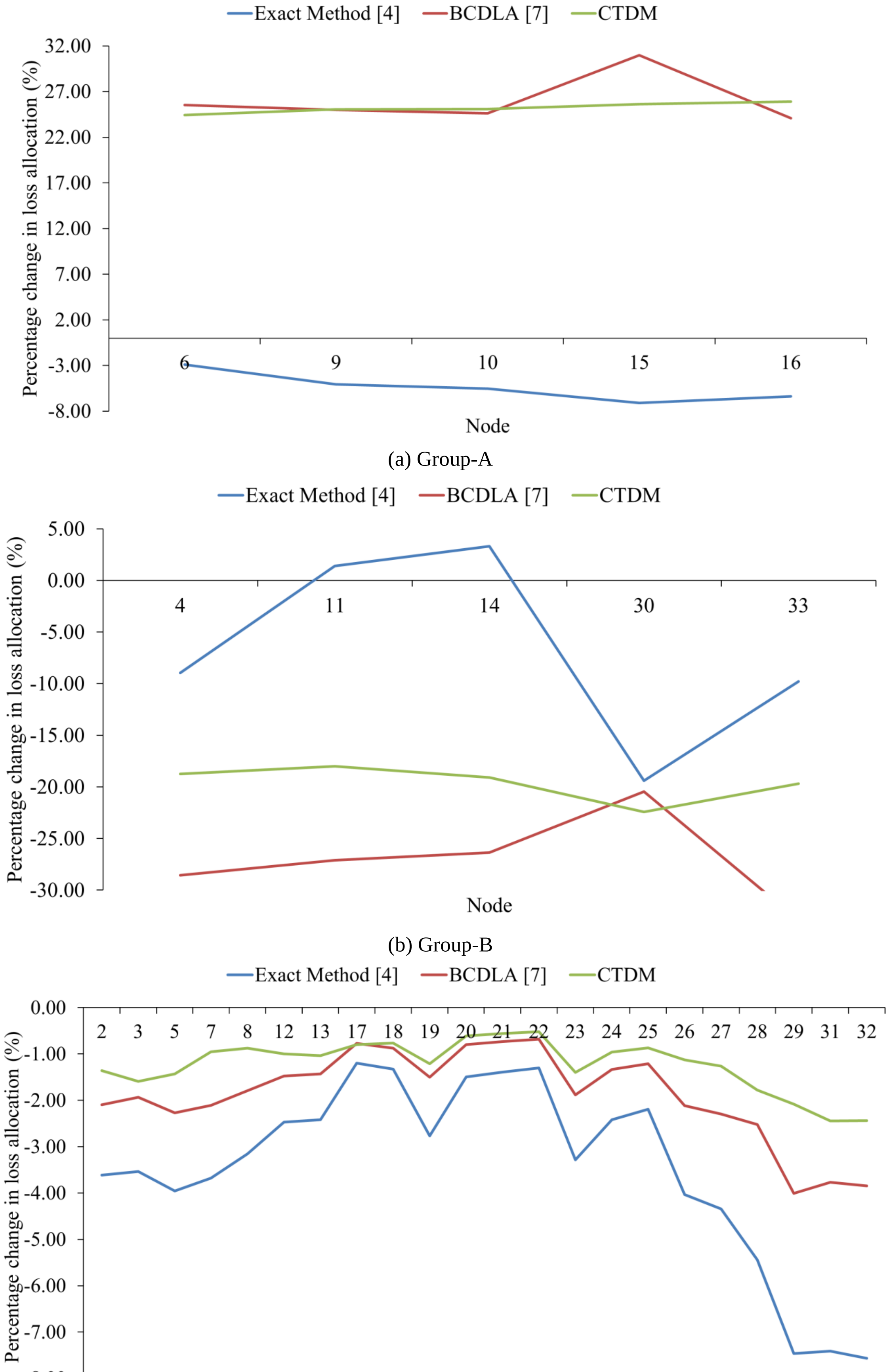


(b) Group-B



(c) Group-C

Fig. 4.4 Comparison of proposed methods with established methods for scenario 1



(c) Group-C

Fig. 4.5 Comparison of proposed methods with established methods for scenario 2

Table 4.9 Statistical Error Analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
Max.	3.245	1.683	1.631	7.565	4.009	2.445
Min.	0.204	0.022	0.026	1.196	0.684	0.519
Mean	1.219	0.625	0.604	3.475	1.884	1.230
SD	0.899	0.472	0.522	1.926	0.960	0.541

Variation in DG power factor

Among all DG units, the power factor of DG having highest MVA rating is varied from unity to 0.707 (leading) while maintaining its active power constant. The results obtained for remuneration allocation using proposed LA method are presented in Fig. 4.6 showing remuneration to all three DG units while varying power factor of DG1 at unity, 0.95, 0.90, 0.85, 0.80 and 0.707. It can be observed that with increasing its reactive power injection the remuneration to DG1 increases consistently without much affecting remuneration to other DG units. This shows that remuneration allocated to DGOs using proposed method is not only sensitive to reactive power transactions made by particular DG unit but also not affects remuneration allocated to other DG units. This shows fairness of CTDM while considering power transactions from DG units thus encourages DGOs for injecting appropriate reactive power into the system.

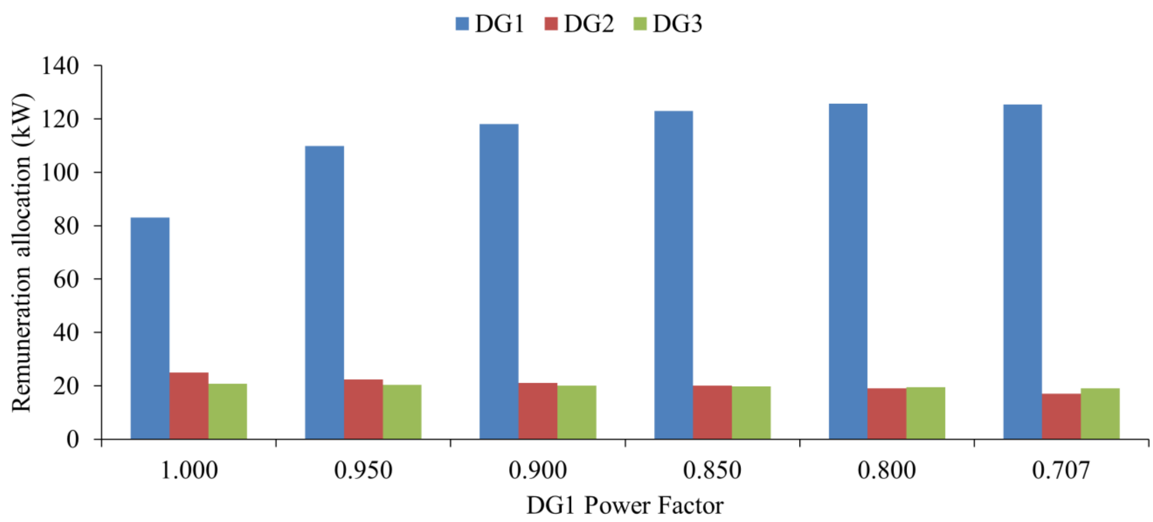


Fig. 4.6 Remuneration allocation to DGOs with variation in power factor of DG1

The investigation results of proposed CTDM are found to be fair, consistent and promising than other established methods while a standard test distribution system was taken for study. However, practical distribution systems are large and complex, and may have large number of DGs. Therefore, a thorough investigation is much needed for the application of LA method to practical distribution system. This is presented in the forthcoming section.

4.2.2 CASE STUDY 2

The proposed CTDM is now applied to 11.40 kV, 83-bus Tai Power Corporation distribution system [57] as in chapter 3. The system is having 83 normally closed sectionalizing switches and 13 normally open tie switches. The nominal active and reactive power demand are 28.350 MW and 20.700 MVAr, respectively. The power loss under base configuration, i.e. by opening the tie-lines 84-96, for nominal loading is obtained as 531.99 kW.

A. Loss allocation to load points

Considering no DGs in the system, the comparison results for LA obtained using proposed and other established methods is presented in Fig. 4.7. It can be observed that proposed method is showing comparable results for this larger and practical distribution system. This validates applicability of proposed CTDM for passive distribution systems.

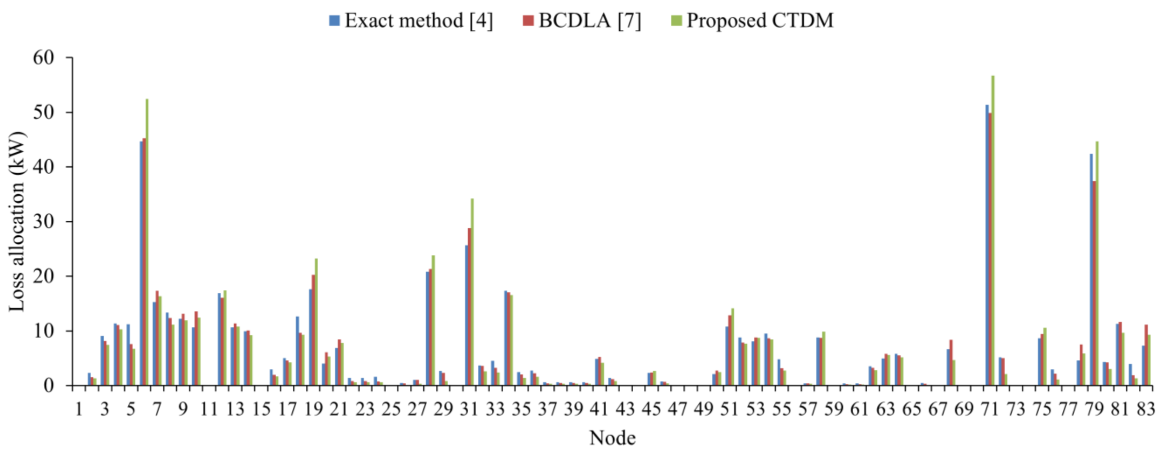


Fig. 4.7 Comparison of LA using CTDM with established methods

B. Remuneration to DGOs

In order to investigate the applicability of proposed method for active distribution systems, the system is modified by assuming five DG units with sizing and siting as considered in Table 3.17 of Chapter 3. The load flow shows that with this DG placement, the losses are reduced from 531.99 kW to 297.67 kW at nominal loading. Thus a loss reduction of 234.32 kW is observed using DGs which is to be remunerated using LA method. This remuneration is evaluated using proposed CTDM and the results obtained are presented in Table 4.10. It is interesting to note that the total remuneration allocated is found to be very close to the true value. This shows that proposed LA method is highly accurate for larger and complex distribution systems. Next, the LA to loads and remuneration to DGOs using proposed method is presented in Fig. 4.8. The figure also shows net LA (NLA) to system nodes. It can be observed from the figure that NLA is negative, i.e. LA is more than the remuneration being allocated, for all DG sites, except at node 71. This is because of the highest loading at this node.

Table 4.10 Remuneration allocated to DGOs using proposed CTDM

Remuneration to DGOs (kW)	DG1	DG2	DG3	DG4	DG5	Total remuneration (kW)
Before adjustment	85.54	32.14	29.63	40.51	46.35	234.17
After adjustment	85.59	32.16	29.65	40.54	46.38	234.32

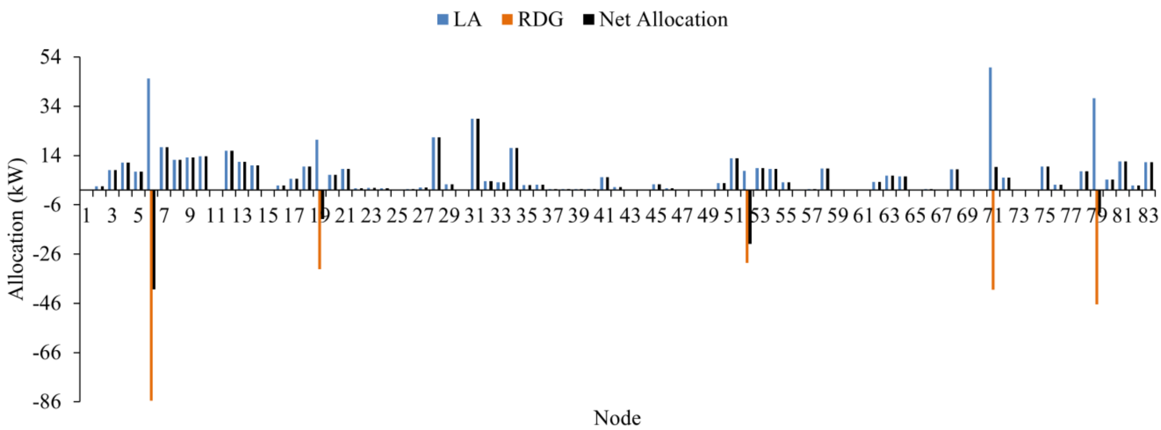


Fig. 4.8 Allocation to various entities

C. Loss incentives to DNO

The proposed strategy is now applied to this system while operating at BMLC, i.e. by opening switch at 7, 13, 34, 39, 41, 55, 62, 72, 83, 86, 89, 90, and 92. The classification of distribution nodes for diverse customers, the system states considered and corresponding load factors and load durations are taken same as given in Table 3.9 of chapter 3. The loss reduction by DGs for each state are determined as shown in Table 4.11. The given active distribution network is then optimally reconfigured to minimize feeder power losses.

Table 4.11 An Illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	112.12	168.02	123.11	14,29,34,54,57,61,69,86,88,90,91,92,95
2	142.51	198.41	143.27	14,29,34,54,57,61,69,86,88,90,91,92,95
3	179.83	206.92	152.08	14,29,34,54,57,61,69,86,88,90,91,92,95
4	219.09	199.99	156.57	14,29,34,42,55,60,63,71,86,88,90,91,92
5	327.92	230.06	195.93	14,34,42,55,60,61,86,87,88,90,91,92,93
6	296.01	198.14	169.78	14,34,39,42,63,84,85,86,87,88,90,91,92
7	399.48	251.50	226.54	14,34,42,62,83,84,85,86,87,88,90,92,93
8	471.05	290.30	269.21	14,34,42,62,83,84,85,86,87,88,90,92,93
9	263.89	228.21	175.55	14,20,33,35,42,54,60,63,70,86,88,90,92

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

The table also shows state-wise optimal configuration, loss reduction by DGs and NR. The economic equation for a sample day is presented in Table 4.12. The table shows that an amount of 5665.27 kWh are allocated to load points against feeder power losses. Since

DGs cause a loss reduction from 5665.27 kWh to 5003.94 kWh, a reward corresponding to 661.32 kWh is allocated as total remuneration to DGOs and since NR further reduces this loss to 4020.87 kWh, an amount corresponding to 983.07 kWh is to be kept with DNO as LI for NR using proposed LA strategy.

Table 4.12 Economic Equation for RADN

State	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	784.87	1176.11	861.74	784.87	-391.25	314.37
2	142.51	198.41	143.27	142.51	-55.89	55.14
3	539.50	620.76	456.23	539.50	-81.25	164.53
4	657.28	599.96	469.71	657.28	57.32	130.25
5	1639.62	1150.28	979.64	1639.62	489.35	170.63
6	296.01	198.14	169.78	296.01	97.87	28.36
7	399.48	251.50	226.54	399.48	147.98	24.96
8	942.11	580.59	538.42	942.11	361.51	42.17
9	263.89	228.21	175.55	263.89	35.68	52.66
Total	5665.27	5003.94	4020.87	5665.27	661.32	983.07

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

The accuracy of CTDM for this system is now investigated in the following section.

D. Accuracy of Proposed CTDM

The practical distribution systems are large and complexity arises owing to diverse customers and DERs. The load demand, load power factor and generation profile vary dynamically, making complex line flow among distribution feeders. Therefore, the LA method developed needs a thorough investigation while considering abovementioned variations.

Variation in Load Demand

The accuracy for application of Superposition is investigated against variation in load demand. For that system loading is varied widely from 0.2 p.u. to 2.0 p.u. in the steps of 0.2 p.u. At these loading the true value of remuneration allocated to DGOs is evaluated by

Table 4.13 Accuracy of Superposition for Remuneration Allocation to DGOs

Loading	Without DG	With DG	TRUE	Calculated	Error	DV_max(%)
0.2	19.86	137.76	-117.90	-117.90	0.002	5.62
0.4	80.74	117.11	-36.37	-36.37	0.002	5.67
0.6	184.76	135.59	49.17	49.16	-0.021	5.73
0.8	334.29	195.08	139.21	139.16	-0.037	5.79
1	531.99	297.67	234.32	234.17	-0.065	5.87
1.2	780.88	445.66	335.21	334.79	-0.127	5.95
1.4	1084.38	641.65	442.73	442.73	0.000	6.05
1.6	1446.50	888.54	557.96	557.96	0.000	6.16
1.8	1871.90	1189.66	682.24	682.23	-0.001	6.30
2	2366.16	1548.82	817.34	817.33	-0.002	6.46

conducting two load flows, without and with DGs. The remuneration is also calculated using proposed method as shown in Table 4.13. The table shows that there is an insignificant error in proposed method. It probably occurs due to larger number of DG units in the system. Practical distribution systems may have several DG units. This shows promising nature of proposed method to remunerate DGOs under varying system loading condition.

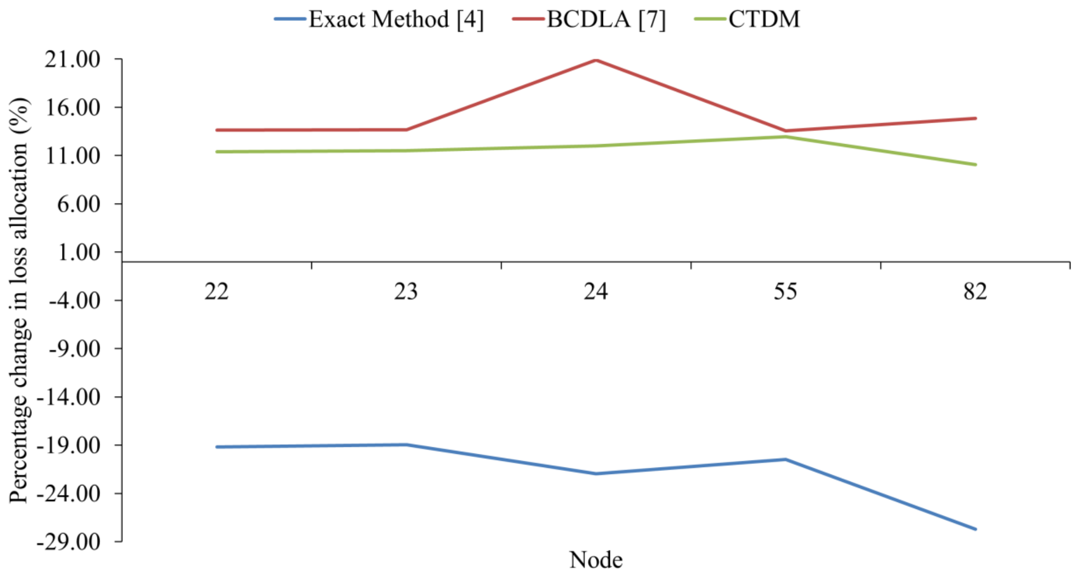
Variation in Load Power Factor

Next, the method is investigated against variation in load power factor. For that purpose, the system is assumed to be passive and system nodes are arbitrarily divided into three nodal groups with two scenarios, as shown in Table 3.23 of chapter 3. The power factor considered for these nodal groups are given in Table 3.24 of the same chapter. Proposed and other existing methods are applied and the percentage change in LA obtained by power factor variation is compared in Table 4.14. It has been observed from the table that proposed CTDM is producing consistent and comparable results with BCDLA for all groups of nodes and for both scenarios but once again the Exact method is not found suitable as it provides results with opposite signs for Group-A and Group-B nodes. The fact can also be better visualized from Fig. 4.9 and Fig. 4.10. It can also be observed that Exact method is also not doing well with Group-C nodes, where again proposed and BCDLA methods seem quite comparable and promising. This, however, can be further verified by conducting statistical error analysis for the results obtained for group-C nodes presented in Table 4.15 that clearly shows superiority of the proposed CTDM over other methods.

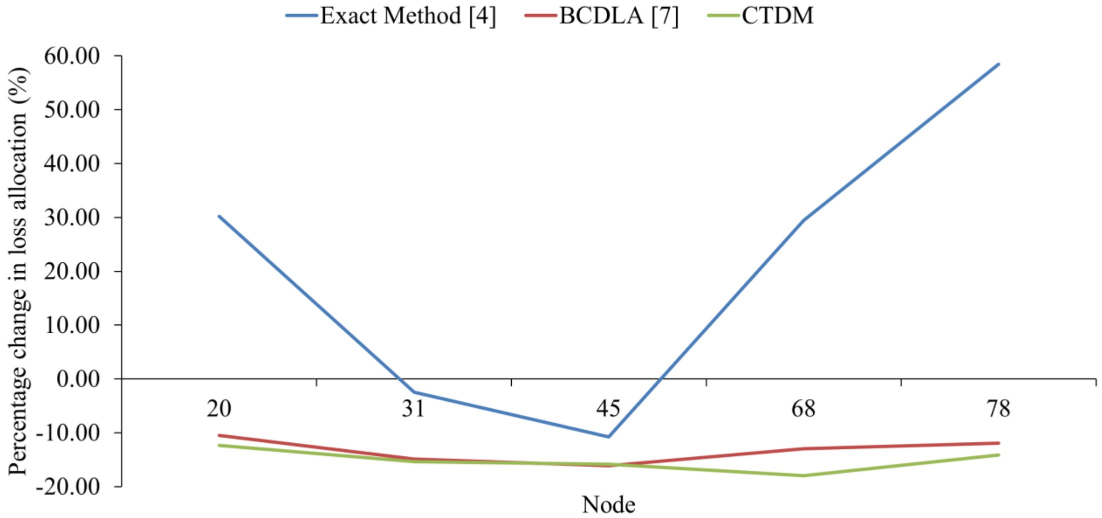
Table 4.14 Comparison of loss allocation methods for case study 2

Group-A						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
22	-19.17	13.64	11.41	-38.30	27.71	26.35
23	-18.96	13.69	11.51	-37.91	27.89	26.61
24	-21.95	20.92	12.02	-39.19	37.91	27.24
55	-20.47	13.55	12.94	-41.12	28.63	30.55
82	-27.69	14.86	10.07	-53.90	28.94	24.02
Group-B						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
20	30.19	-10.49	-12.32	55.72	-18.75	-20.85
31	-2.43	-14.88	-15.34	-1.83	-26.13	-26.82
45	-10.74	-16.13	-15.86	-17.63	-28.55	-28.30
68	29.45	-12.93	-17.94	55.25	-22.97	-29.82
78	58.44	-11.89	-14.12	107.89	-21.21	-23.29

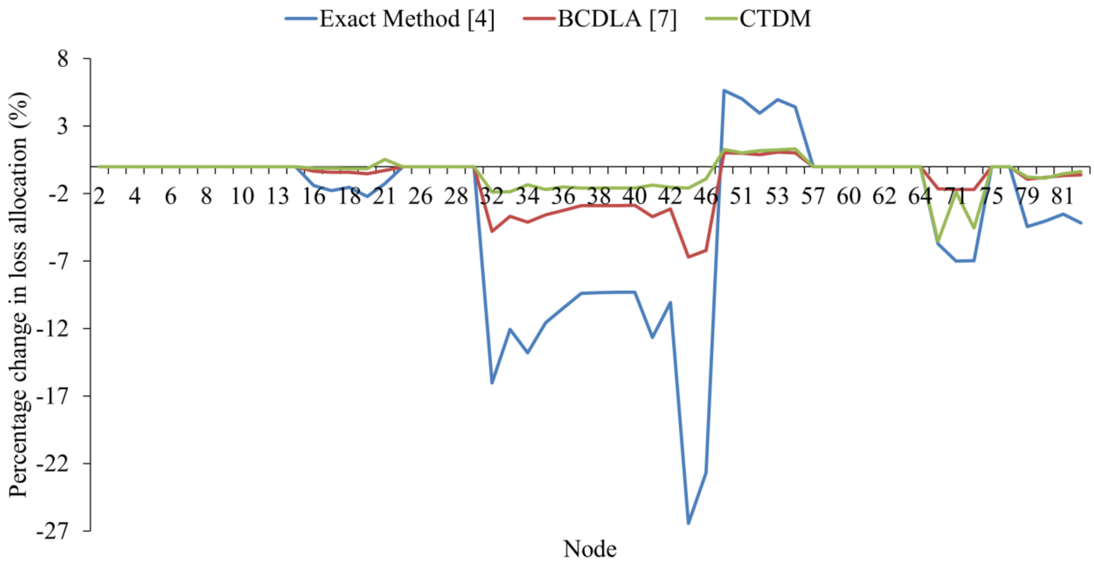
Group-C						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
16	-1.39	-0.33	-0.11	-2.29	-0.54	-0.39
17	-1.78	-0.42	-0.11	-2.95	-0.69	-0.39
18	-1.53	-0.41	-0.14	-2.52	-0.67	-0.43
19	-2.21	-0.53	-0.13	-3.66	-0.87	-0.39
21	-1.26	-0.29	0.52	-1.71	-0.38	0.75
25	0	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
29	0	0	0	0	0	0
32	-16.03	-4.80	-1.87	-30.87	-9.25	-4.53
33	-12.05	-3.67	-1.84	-23.21	-7.07	-4.45
34	-13.79	-4.13	-1.35	-26.57	-7.95	-3.18
35	-11.57	-3.58	-1.69	-22.29	-6.89	-4.05
36	-10.48	-3.24	-1.52	-20.19	-6.25	-3.61
37	-9.38	-2.88	-1.59	-18.07	-5.58	-3.79
38	-9.34	-2.89	-1.58	-17.98	-5.54	-3.78
39	-9.31	-2.88	-1.58	-17.96	-5.56	-3.77
40	-9.32	-2.88	-1.58	-17.93	-5.55	-3.76
41	-12.65	-3.69	-1.37	-24.36	-7.11	-3.23
42	-10.07	-3.13	-1.52	-19.40	-6.03	-3.62
44	-26.44	-6.69	-1.58	-52.87	-13.68	-4.87
46	-22.68	-6.22	-0.90	-45.39	-12.43	-2.64
50	5.66	1.02	1.26	11.55	2.08	2.35
51	5.02	1.00	1.03	10.25	2.05	1.94
52	3.96	0.90	1.18	8.09	1.84	2.21
53	4.96	1.07	1.25	10.12	2.18	2.33
54	4.42	1.03	1.31	9.02	2.09	2.45
57	0	0	0	0	0	0
58	0	0	0	0	0	0
60	0	0	0	0	0	0
61	0	0	0	0	0	0
62	0	0	0	0	0	0
63	0	0	0	0	0	0
64	0	0	0	0	0	0
66	-5.71	-1.65	-5.52	-10.53	-3.03	-10.61
71	-6.99	-1.69	-1.89	-12.87	-3.11	-3.61
72	-6.98	-1.69	-4.55	-12.84	-3.10	-8.70
75	0	0	0	0	0	0
76	0	0	0	0	0	0
79	-4.43	-0.94	-0.76	-7.85	-1.66	-1.54
80	-4.04	-0.80	-0.85	-7.08	-1.40	-1.79
81	-3.52	-0.67	-0.53	-6.09	-1.14	-1.15
83	-4.16	-0.62	-0.37	-7.11	-1.04	-0.83



(a) Group-A

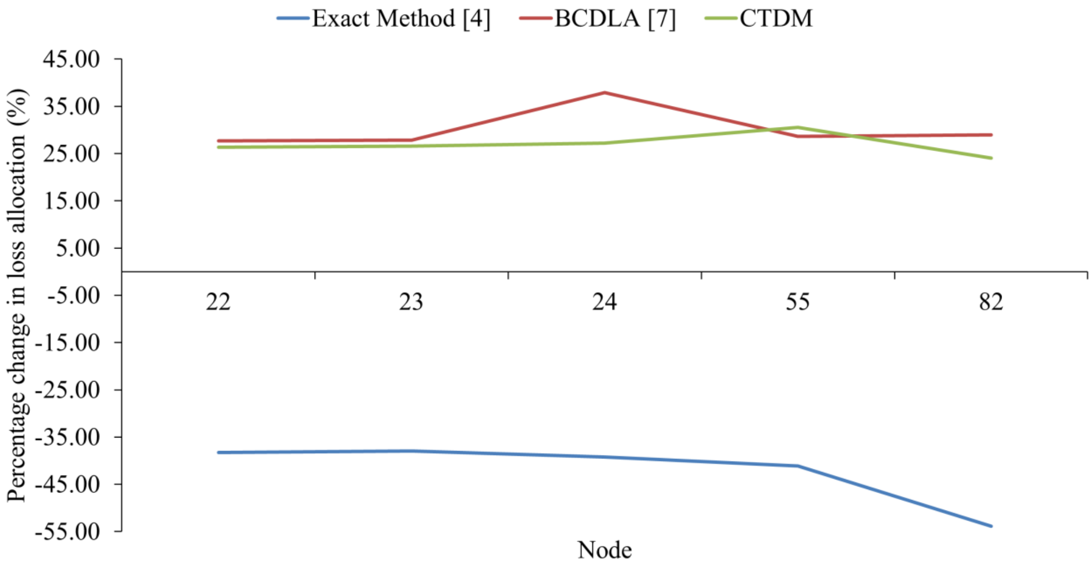


(b) Group-B

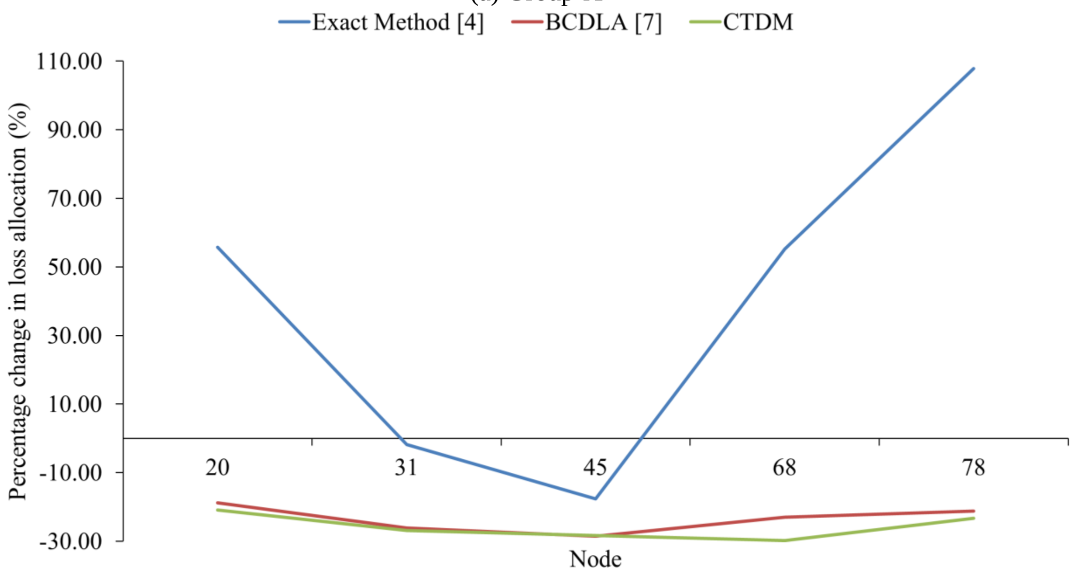


(c) Group-C

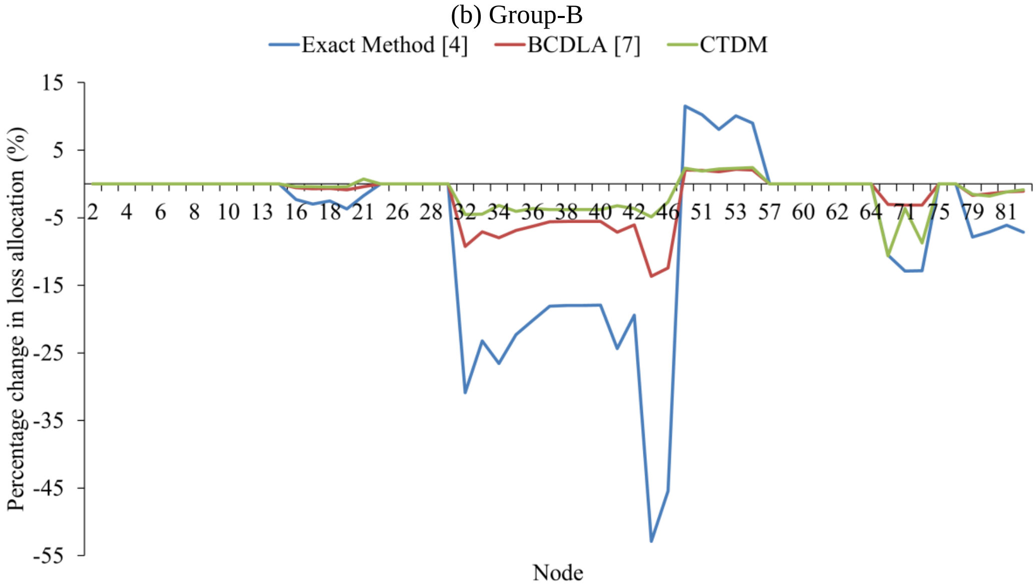
Fig. 4.9 Comparison of proposed methods with established methods for scenario 1



(a) Group-A



(b) Group-B



(c) Group-C

Fig. 4.10 Comparison of proposed methods with established methods for scenario 2

Table 4.15 Statistical Error Analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	CTDM	Exact Method [4]	BCDLA [7]	CTDM
Max.	26.44	6.69	5.52	52.87	13.68	10.61
Min.	0	0	0	0	0	0
Mean	4.31	1.17	0.74	8.28	2.26	1.63
SD	5.95	1.69	1.09	11.72	3.33	2.25

Variation in DG power factor

The reactive power injection from the DG unit having highest MVA rating, i.e. DG5 is varied. For this purpose, its power factor is varied from unity to 0.707 lead keeping active power generation constant. The remuneration allocated to all DG units is determined using proposed CTDM as shown in Fig. 4.11. It can be observed from the figure that the remuneration to DG5 increases with the increase in injection of reactive power and that of other DG units remain unaltered. This shows that CTDM work encourages DGOs to maintain appropriate power factor without affecting remuneration to other DG units in the system.

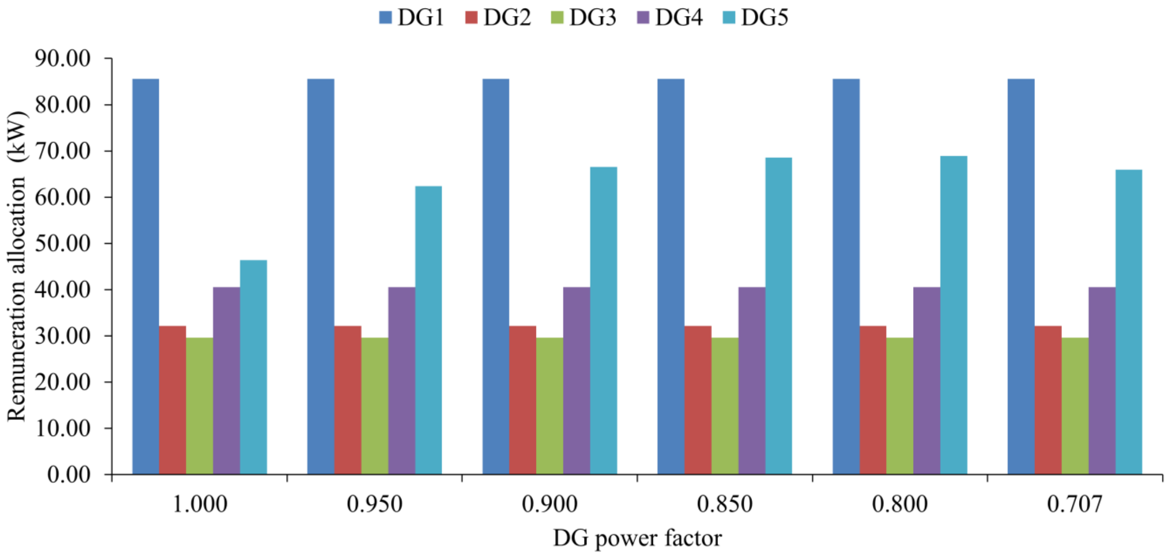


Fig. 4.11 Remuneration allocation to DGOs with variation in power factor of DG5

4.3. SUMMARY

Another circuit theory-based LA method is proposed for distribution systems. The method decomposes the crossed-terms of branch power loss using analytically derived loss allocation factor. Moreover, the decomposition of crossed-terms pertaining to remuneration allocated to DGOs is suggested using Superposition on injected currents from each individual DG unit. However, the LAS proposed in chapter 3 is employed to allocate losses or loss incentives among customers, DGOs and DNO. Proposed CTDM method is applied to standard test as well as practical distribution systems. The results obtained are compared with several established LA methods available in literature. The comparison results with other methods highlights suitability of proposed method to modern reconfigured active distribution systems. Proposed LA method is thoroughly investigated against variation in system loading, power factor of customers and reactive power injection from DG unit. The method is simple, accurate, robust and easy to implement thus may serve as promising tool for distribution utilities.

CHAPTER 5
EXACT CROSSED-TERM DECOMPOSITION METHOD

Crossed-Term Decomposition Method is presented in the previous chapter. In practice, utilities encourage customers to maintain better power factors to reduce system losses. Similarly, DGOs are also encouraged for proper reactive power injections from DG units in order to avoid deficit of reactive power in the system. With these concerns, a new LA method is proposed that can check power factor of end users while allocating losses and penalize or incentivize them accordingly. The proposed Exact Crossed-Term Decomposition Method (ECTDM) bifurcates crossed-terms associated with real and imaginary components of nodal injections and then allocates losses or loss incentives by suggesting separate LAFs for these components of nodal injections. LAFs are derived to allocate losses as well as remuneration. The proposed method is equally suitable to both passive and active distribution systems under varying topology. ECTDM is applied to 33-bus test distribution system and 83-bus practical distribution system. Thorough investigation results highlight the promising nature of proposed method.

5.1 PROPOSED EXACT CROSSED-TERM DECOMPOSITION METHOD

There are many methods available in literature for loss allocation. Among these methods the power loss in a branch can be treated as I^2R, where I is branch current having two components i.e. real and imaginary. The branch current is the phasor sum of current forms all downstream nodes. The branch power losses are having squared-terms and crossed-terms associated with these currents. Allocations to squared-terms is straightforward however crossed-terms not so. There are methods available in literature which can bifurcate crossed-terms, they are *pro-rata* [9], [10] *quadratic* [1], [14], *proportional* sharing [11]-[13], geometric, [14]-[16] and shapley-value based method [8], [38]. But these methods are found to be inconsistent from reactive power transactions and are based on heuristics. In the proposed method the LAF not only considers both active and reactive power transaction separately but also judiciously bifurcates crossed-terms. It considers reactive power transactions by decomposing currents into real and imaginary components. And for these components of currents different LAFs are proposed for crossed-terms associated with both real and imaginary part of the nodal current.

The proposed ECTDM employs branch-oriented approach to allocate losses among contributing nodes. The loss incentives to DGOs are evaluated independently using

Superposition. Thereafter, loss incentives are allocated among DGOs and DNO by adopting LAS as suggested in chapter 3.

5.1.1. LOSS ALLOCATION TO CUSTOMERS

The proposed ECTDM employs another branch-oriented approach where the branch power loss is given by the multiplication of branch resistance and the square of the sum of contributing nodal currents in the branch. Consider branch *ij* of a distribution feeder as shown in Fig. 5.1.

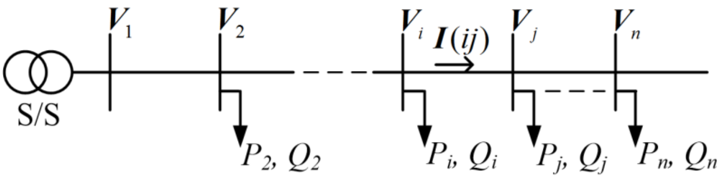


Fig. 5.1 Single line diagram of a distribution feeder

The power loss in branch *ij* bearing current $\boldsymbol{I}(ij)$ is

$$Ploss(ij) = R(ij)I^2(ij) = \sum_{k\in CN(ij)} ploss(ij,k) \tag{5.1}$$

where, $ploss(ij,k)$ is the LA to the kth contributing node of branch *ij*. Let the current $\boldsymbol{I}\,(ij)$ contributed by contributing nodal currents $\boldsymbol{I}(ij, k)$; $\forall\ k \in CN(ij)$, then

$$\boldsymbol{I}(ij) = \sum_{k\in CN(ij)} \boldsymbol{I}(ij,k) = \sum_{k\in CN(ij)} \left[\Re\{\boldsymbol{I}(ij,k)\} + \mathrm{j}Im\{\boldsymbol{I}(ij,k)\}\right] \tag{5.2}$$

$$\text{Thus, } Ploss(ij) = R(ij)\left[\sum_{k\in CN(ij)} \Re\{\boldsymbol{I}(ij,k)\}\right]^2 + R(ij)\left[\sum_{k\in CN(ij)} Im\{\boldsymbol{I}(ij,k)\}\right]^2 \tag{5.3}$$

$$Ploss(ij) = R(ij)\left[\begin{array}{l}\displaystyle\sum_{k\in CN(ij)} [\Re\{\boldsymbol{I}(ij,k)\}]^2 \\ \displaystyle+\sum_{k\in CN(ij)}\sum_{\substack{q\in CN(ij)\\ q\neq k}} \Re\{\boldsymbol{I}(ij,k)\}.\Re\{\boldsymbol{I}(ij,q)\}\end{array}\right] + R(ij)\left[\begin{array}{l}\displaystyle\sum_{k\in CN(ij)} [Im\{\boldsymbol{I}(ij,k)\}]^2 \\ \displaystyle+\sum_{k\in CN(ij)}\sum_{\substack{q\in CN(ij)\\ q\neq k}} Im\{\boldsymbol{I}(ij,k)\}.Im\{\boldsymbol{I}(ij,q)\}\end{array}\right] \tag{5.4}$$

$$\begin{aligned} Ploss(ij) = {} & R(ij)\left[\begin{array}{l}\displaystyle\sum_{k\in CN(ij)} [\Re\{\boldsymbol{I}(ij,k)\}]^2 \\ \displaystyle+\sum_{k\in CN(ij)} [Im\{\boldsymbol{I}(ij,k)\}]^2\end{array}\right] + R(ij)\sum_{k\in CN(ij)}\sum_{\substack{q\in CN(ij)\\ q\neq k}} \Re\{\boldsymbol{I}(ij,k)\}.\Re\{\boldsymbol{I}(ij,q)\} \\ & + R(ij)\sum_{k\in CN(ij)}\sum_{\substack{q\in CN(ij)\\ q\neq k}} Im\{\boldsymbol{I}(ij,k)\}.Im\{\boldsymbol{I}(ij,q)\} \end{aligned} \tag{5.5}$$

$$Ploss(ij) = ST\left(ij\right) + CT^a\left(ij\right) + CT^r\left(ij\right) \tag{5.6}$$

The first term of (5.5) provides partial contribution of each contributing node for the power loss in branch *ij*, but the second and third terms need bifurcation to allocate power losses among the contributing nodes. Therefore, it is important to investigate the dependency of contributing node currents on crossed-terms of the power loss. Let us consider,

$$\frac{\partial CT^{a}(ij)}{\partial \Re\{\boldsymbol{I}(ij,k)\}} = R(ij) \sum_{\substack{q \in CN(ij) \\ q \neq k}} \Re\{\boldsymbol{I}(ij,q)\} \tag{5.7}$$

Substituting (5.7) in (5.5), gives crossed-terms with a multiplication factor of two. Therefore, a correction factor of $\frac{1}{2}$ is introduced. The crossed-terms related to active component of currents can be expressed as:

$$CT^{a}(ij) = \frac{1}{2} \sum_{k \in CN(ij)} \Re\{\boldsymbol{I}(ij,k)\} \frac{\partial CT^{a}(ij)}{\partial \Re\{\boldsymbol{I}(ij,k)\}} = \frac{1}{2} \sum_{k \in CN(ij)} CT^{a}(ij,k) \tag{5.8}$$

where, $CT^{a}(ij,k) = 2R(ij) \sum_{\substack{q \in CN(ij) \\ q \neq k}} \Re\{\boldsymbol{I}(ij,k)\}.\Re\{\boldsymbol{I}(ij,q)\}$ (5.9)

$$CT^{a}(ij,k) = \Re\{\boldsymbol{I}(ij,k)\} \frac{\partial CT^{a}(ij)}{\partial \Re\{\boldsymbol{I}(ij,k))\}} \tag{5.10}$$

Refer to (5.5) and (5.6), the first term in $CT^{a}(ij)$ denotes the loss contribution in branch *ij* due to R{$\boldsymbol{I}(ij,k)$}whereas its derivative is independent of this current, therefore

$$\frac{\partial CT^{a}(ij,k)}{\partial \Re\{\boldsymbol{I}(ij,k)\}} = \frac{\partial CT^{a}(ij)}{\partial \Re\{\boldsymbol{I}(ij,k)\}} \tag{5.11}$$

From equations (5.10) and (5.11)

$$\frac{\partial CT^{a}(ij,k)}{CT^{a}(ij,k)} = \frac{\partial \Re\{\boldsymbol{I}(ij,k)\}}{\Re\{\boldsymbol{I}(ij,k)\}} \tag{5.12}$$

Equation (5.12) reveals that there exist a linear relationship between $CT^{a}(ij,k)$ and $\Re\{\boldsymbol{I}(ij,k)\}$. Therefore, to allocate crossed-terms of branch power loss, LA factors (LAFs) assigned to the *k*th node in branch *ij* are proposed as

$$Lf^{a}(ij,k(q)) \;=\; \frac{\Re\{\boldsymbol{I}(ij,k)\}}{\Re\{\boldsymbol{I}(ij,k)\} + \Re\{\boldsymbol{I}(ij,q)\}}; \forall q \in CN(ij); q \neq k \tag{5.13}$$

$$Lf^{r}(ij,k(q)) \;=\; \frac{Im\{\boldsymbol{I}(ij,k)\}}{Im\{\boldsymbol{I}(ij,k)\} + Im\{\boldsymbol{I}(ij,q)\}}; \forall q \in CN(ij); q \neq k \tag{5.14}$$

LAFs defined above are employed to bifurcate the respective crossed-terms $CT^{a}(ij, k)$ and $CT^{r}(ij, k)$ of the power loss in branch *ij* for its contributing node *k*.

Substituting LAFs defined by (5.13) and (5.14) in (5.5), the loss allocated to *k*th contributing node for branch *ij* is given by

$$ploss(ij,k) = R(ij)\begin{bmatrix}[\Re\{\boldsymbol{I}(ij,k)\}]^2 \\ +[Im\{\boldsymbol{I}(ij,k)\}]^2\end{bmatrix} + 2R(ij)\sum_{\substack{q\in CN(ij)\\ q\neq k}}\begin{bmatrix}Lf^a(ij,k(q))\Re\{\boldsymbol{I}(ij,k)\}.\Re\{\boldsymbol{I}(ij,q)\} \\ +Lf^r(ij,k(q))Im\{\boldsymbol{I}(ij,k)\}.Im\{\boldsymbol{I}(ij,q)\}\end{bmatrix} \tag{5.15}$$

The loss allocated to kth node and therefore system losses are given by

$$ploss(k) = \sum_{ij=1}^{NB} ploss(ij,k) \tag{5.16}$$

$$Ploss = \sum_{k=1}^{N} ploss(k) \tag{5.17}$$

For illustration proposed ECTDM applied to a small distribution system as below.

Illustration

For illustration purpose the 5-bus system considered in chapter 3 is taken. For detailed line and bus data of this system Table 3.1 may be referred. The step-wise calculations of ECTDM for this system are presented in Table 5.1, Table 5.2(a) and Table 5.2(b). The nodal voltages, nodal current injections and contributing currents in each branch obtained after load flow is presented in Table 5.1. With this information, *ST*(*ij*, *k*) and *CT*(*ij*, *k*) are evaluated using (5.5), and (5.13), (5.14), (5.15) respectively, as shown in Table 5.2(a) and Table 5.2(b). All the losses in Table represented in kW. The table also shows loss

Table 5.1 Calculation for the components of contributing nodal currents

k	$\boldsymbol{V}_k$	$\boldsymbol{I}(k)$	$I(ij,k)$ 1-2	2-4	4-3	4-5
1	1.0000∠0	0∠0.00	0∠0.00	0∠0.00	0∠0.00	0∠0.00
2	0.9976∠-0.0586	0.0070∠-22.32	0.0070∠-22.32	0∠0.00	0∠0.00	0∠0.00
3	0.9959∠-0.1001	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0∠0.00
4	0.9962∠-0.0935	0.0137∠-21.86	0.0137∠-21.86	0.0137∠-21.86	0∠0.00	0∠0.00
5	0.9959∠-0.1001	0.0204∠-21.70	0.0204∠-21.70	0.0204∠-21.70	0∠0.00	0.0204∠-21.70

Table 5.2 (a) Calculation for loss allocation to squared-term related to distribution nodes

ij / k	$ST(ij,k)$ 1-2	2-4	4-3	4-5	$ST(k)$
1	0.00	0.00	0.00	0.00	0.00
2	0.77	0.00	0.00	0.00	0.77
3	6.63	4.42	2.21	0.00	13.27
4	2.98	1.99	0.00	0.00	4.97
5	6.63	4.42	0.00	2.21	13.27
Total	17.02	10.83	2.21	2.21	32.27

Table 5.2 (b) Calculation for loss allocation to distribution nodes

ij / k	$CT^a(ij,k)$ 1-2	2-4	4-3	4-5	$CT^r(ij,k)$ 1-2	2-4	4-3	4-5	$ST(k)$	$ploss(k)$
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	2.84	0.00	0.00	0.00	0.48	0.00	0.00	0.00	0.77	4.09
3	13.19	6.86	0.00	0.00	2.14	1.11	0.00	0.00	13.27	36.57
4	7.86	4.09	0.00	0.00	1.29	0.67	0.00	0.00	4.97	18.88
5	13.19	6.86	0.00	0.00	2.14	1.11	0.00	0.00	13.27	36.57
ploss(*ij*)	37.07	17.81	0.00	0.00	6.06	2.89	0.00	0.00	32.27	96.10

allocation $Ploss(k)$ to various system nodes which can be evaluated using (5.15) and (5.16).

5.1.2. REMUNERATION TO DGOS

The integration of DG units in distribution systems causes bilateral power flows thus significantly affects feeder power flow and losses. Therefore, DGOs should be remunerated for any contribution of DGs in loss reduction or conversely may be penalized against increase in losses. However, the allocation is not straightforward because the amount of remuneration/penalty is non-linearly related with DG power generation and DG contributing currents are the function of node voltages. Therefore, proposed method employs Superposition principle to evaluate contributing branch currents of each DG unit. The current flow through branch ij may be considered as

$$\boldsymbol{I}(ij) = \boldsymbol{I}'(ij) - \sum_{p \in CDG(ij)} \boldsymbol{I}_{DG}(ij, p) \tag{5.18}$$

where, $\boldsymbol{I}(ij)$ and $\boldsymbol{I}'(ij)$ are the phasor currents through branch ij without and with DGs, respectively and $\boldsymbol{I}_{DG}(ij,p)$ is the contributing current by pth DG in branch ij, therefore

$$\boldsymbol{I}(ij) = \Re\{\boldsymbol{I}'(ij)\} - \sum_{p \in CDG(ij)} \Re\{\boldsymbol{I}_{DG}(ij, p)\} + \mathrm{j}\, Im\{\boldsymbol{I}'(ij)\} - \mathrm{j} \sum_{p \in CDG(ij)} Im\{\boldsymbol{I}_{DG}(ij, p)\} \tag{5.19}$$

The following dot product holds good

$$\begin{aligned}
&\boldsymbol{I}(ij).\boldsymbol{I}(ij) = \\
&I^2(ij) = \left[\Re\{\boldsymbol{I}'(ij)\}\right]^2 + \left[Im\{\boldsymbol{I}'(ij)\}\right]^2 + \left[\sum_{p \in CDG(ij)} \Re\{\boldsymbol{I}_{DG}(ij, p)\}\right]^2 \\
&+ \left[\sum_{p \in CDG(ij)} Im\{\boldsymbol{I}_{DG}(ij, p)\}\right]^2 - 2\Re\{\boldsymbol{I}'(ij)\}. \sum_{p \in CDG(ij)} \Re\{\boldsymbol{I}_{DG}(ij, p)\} - 2Im\{\boldsymbol{I}'(ij)\}. \sum_{p \in CDG(ij)} Im\{\boldsymbol{I}_{DG}(ij, p)\}
\end{aligned} \tag{5.20}$$

$$\begin{aligned}
&I^2(ij) - I'^2(ij) = \sum_{p \in CDG(ij)} \left[\Re\{\boldsymbol{I}_{DG}(ij, p)\}\right]^2 + \sum_{p \in CDG(ij)} \left[Im\{\boldsymbol{I}_{DG}(ij, p)\}\right]^2 \\
&+ \sum_{p \in CDG(ij)} \sum_{\substack{r \in CDG(ij) \\ r \neq p}} \Re\{\boldsymbol{I}_{DG}(ij, p)\}.\Re\{\boldsymbol{I}_{DG}(ij, r)\} + \sum_{p \in CDG(ij)} \sum_{\substack{r \in CDG(ij) \\ r \neq p}} Im\{\boldsymbol{I}_{DG}(ij, p)\}.Im\{\boldsymbol{I}_{DG}(ij, r)\} \\
&-2\Re\{\boldsymbol{I}'(ij)\}. \sum_{p \in CDG(ij)} \Re\{\boldsymbol{I}_{DG}(ij, p)\} - 2Im\{\boldsymbol{I}'(ij)\}. \sum_{p \in CDG(ij)} Im\{\boldsymbol{I}_{DG}(ij, p)\}
\end{aligned} \tag{5.21}$$

The remuneration allocated to DGOs corresponding to the branch ij is therefore given by

$$R_{DG}(ij) = R(ij)\left[I^2(ij) - I'^2(ij)\right]$$
$$= R(ij)\sum_{p\in CDG(ij)}\left(\begin{array}{l} I_{DG}^2(ij,p) + \sum\limits_{\substack{r\in CDG(ij)\\ r\neq p}}\begin{bmatrix}\Re\{\boldsymbol{I}_{DG}(ij,p)\}.\Re\{\boldsymbol{I}_{DG}(ij,r)\}\\ +Im\{\boldsymbol{I}_{DG}(ij,p)\}.Im\{\boldsymbol{I}_{DG}(ij,r)\}\end{bmatrix}\\ -2\Re\{\boldsymbol{I}'(ij)\}.\Re\{\boldsymbol{I}_{DG}(ij,p)\} - 2Im\{\boldsymbol{I}'(ij)\}.Im\{\boldsymbol{I}_{DG}(ij,p)\}\end{array}\right) \quad (5.22)$$

Let, $R_{DG}(ij) = \sum\limits_{p\in CDG(ij)} R_{DG}(ij,p)$, where $R_{DG}(ij, p)$ is the remuneration allocated to pth DG owner contributing loss reduction in the branch ij, and is given by

$$R_{DG}(ij,p) = R(ij)\left(\begin{array}{l} I_{DG}^2(ij,p)\\ +2\sum\limits_{\substack{r\in CDG(ij)\\ r\neq p}}\begin{bmatrix}Ru^a\left(ij,p(r)\right)\Re\{\boldsymbol{I}_{DG}(ij,p)\}.\Re\{\boldsymbol{I}_{DG}(ij,r)\}\\ +Ru^r\left(ij,p(r)\right)Im\{\boldsymbol{I}_{DG}(ij,p)\}.Im\{\boldsymbol{I}_{DG}(ij,r)\}\end{bmatrix}\\ -2\Re\{\boldsymbol{I}'(ij)\}\Re\{\boldsymbol{I}_{DG}(ij,p)\}\\ -2Im\{\boldsymbol{I}'(ij)\}Im\{\boldsymbol{I}_{DG}(ij,p)\}\end{array}\right) \quad (5.23)$$

$$R_{DG}(ij,p) = ST_{DG}\left(ij,p\right) + Ru^a\left(ij,p(r)\right)CT_{DG}^a\left(ij,p\right) + Ru^r\left(ij,p(r)\right)CT_{DG}^r\left(ij,p\right) + MT_{DG}\left(ij,p\right) \quad (5.24)$$

where, $$Ru^a\left(ij,p(r)\right) = \frac{\Re\{\boldsymbol{I}_{DG}(ij,p)\}}{\Re\{\boldsymbol{I}_{DG}(ij,p)\} + \Re\{\boldsymbol{I}_{DG}(ij,r)\}};\forall r\in CDG(ij); r\neq p \quad (5.25)$$

$$Ru^r\left(ij,p(r)\right) = \frac{Im\{\boldsymbol{I}_{DG}(ij,p)\}}{Im\{\boldsymbol{I}_{DG}(ij,p)\} + Im\{\boldsymbol{I}_{DG}(ij,r)\}};\forall r\in CDG(ij); r\neq p \quad (5.26)$$

are the remuneration allocation factors for the pth DG owner contributing loss reduction in the branch ij. The remuneration allocated to pth DG owner and the total remuneration allocated to DGOs are given by

$$R_{DG}(p) = \sum_{ij=1}^{NB} R_{DG}(ij,p) \quad (5.27)$$

$$R_{DG} = \sum_{p=1}^{NDG} R_{DG}(p) \quad (5.28)$$

An insignificant error may creep in RDG while employing Superposition on account of small node voltage variations. The error so produced is distributed among DGOs in proportional to the amount of loss reduction caused by individual DG. This result in net zero error in remuneration from utility point of view.

The proposed ECTDM is investigated on two different active distribution systems and investigation results are presented and discussed.

5.2 SIMULATION RESULTS

The Proposed ECTDM is applied to two different systems, namely 33-bus standard test system and 83-bus real distribution systems, and the application results obtained are compared with other established methods.

5.2.1 CASE STUDY 1

The proposed method is applied to 33-bus test distribution system as in previous chapters. The power loss for this system under nominal loading without DGs is 202.67 kW n the base topology of the distribution network.

A. Loss allocation to load points

The LA obtained using ECTDM is compared with other established methods, i.e. BCDLA [7], PSMLA [5], Method [15] and Method [16] and is presented in .Fig. 5.2. It can be observed from the figure that proposed method provides comparable results, except at node 30, where all methods produces different results. This is due to exceptionally poor power factor. The proposed method therefore seems to be promising for passive distribution systems.

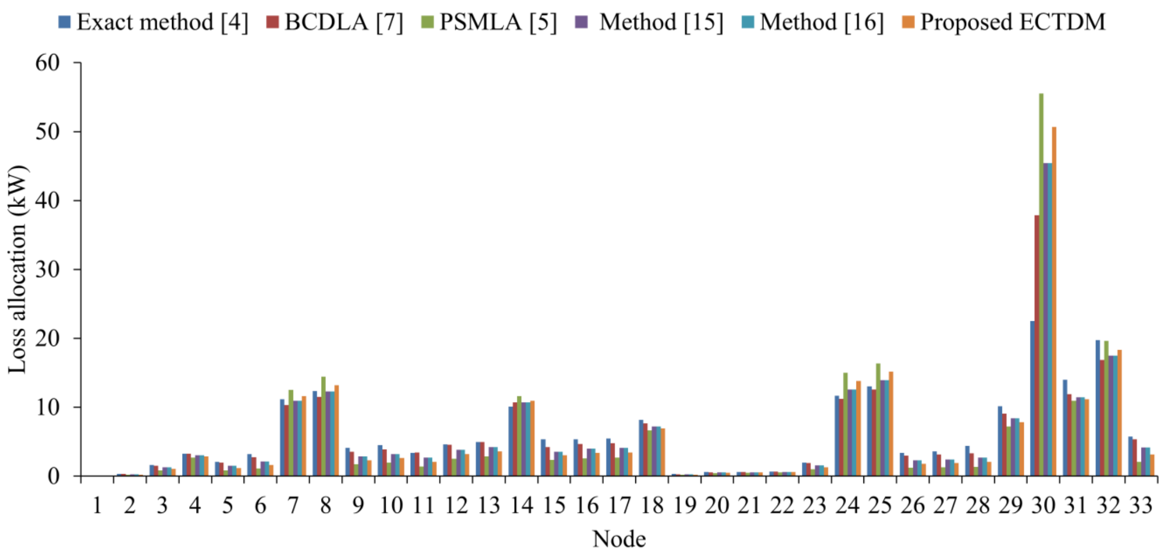


Fig. 5.2 Comparison of LA using ECTDM with established methods

B. Remuneration to DGOs

The applicability of proposed method for active distribution systems is investigated by placing three DGs as in [16]. The sizing and siting of DG units may be referred from Table 3.5 of chapter 3. With this modification, the load flow runs and it shows that feeder power losses are reduced from 202.67 kW to 43.44 kW. Therefore, the presence of DGs causes a true loss reduction of 159.23 kW. DGOs are then remunerated using proposed application of Superposition as shown in Table 5.3. The table also shows the calculated value of remuneration using ECTDM as. 153.27 kW, which is then adjusted to 159.23 kW. Therefore, the utility will remunerate DGOs with 118.84 kW, 20.89 kW and 19.49 kW, to DG1, DG2, and DG3 respectively, against their respective contribution in loss reduction.

Table 5.3 Remuneration allocated to DGOs using proposed ECTDM

Remuneration to DGOs (kW)	DG1	DG2	DG3	Total remuneration
Calculated	114.40	20.11	18.76	153.27
Adjusted	118.84	20.89	19.49	159.23

Table 5.4 Comparison results of proposed ECTDM with existing methods

Node	BCDLA [7]	PSMLA [5]	Method [15]	Method [16]	Proposed ECTDM
1	0.00	0.00	0.00	0.00	0.00
2	0.06	0.21	0.16	0.17	0.24
3	0.13	0.82	0.68	0.73	1.07
4	0.27	2.51	1.53	1.68	2.86
5	0.08	0.78	0.89	0.98	1.18
6	-0.07	1.06	1.20	1.34	1.66
7	0.35	11.02	4.82	5.52	11.61
8	1.35	12.68	6.00	6.84	13.19
9	0.62	1.57	1.85	2.06	2.33
10	0.91	1.81	2.14	2.39	2.64
11	0.95	1.27	1.90	2.11	2.08
12	1.29	2.32	2.59	2.90	3.23
13	1.63	2.60	2.93	3.27	3.59
14	3.66	10.40	6.87	7.74	10.95
15	1.35	2.12	2.50	2.79	3.04
16	1.61	2.36	2.81	3.14	3.36
17	1.70	2.43	2.90	3.24	3.46
18	2.80	6.00	4.90	5.50	6.92
19	0.08	0.19	0.17	0.18	0.23
20	0.36	0.47	0.45	0.46	0.51
21	0.41	0.52	0.50	0.51	0.56
22	0.45	0.56	0.54	0.55	0.60
23	0.20	0.94	0.80	0.86	1.28
24	1.02	11.17	4.34	4.85	13.85
25	-0.02	11.35	3.59	4.14	15.20
26	0.03	1.16	1.32	1.48	1.81
27	0.11	1.20	1.39	1.56	1.89
28	0.30	1.25	1.52	1.72	2.08
29	1.59	6.37	4.23	4.89	7.83
30	14.78	43.13	25.31	29.52	50.70
31	1.86	9.40	5.28	6.19	11.20
32	2.58	16.18	7.62	9.01	18.36
33	1.05	1.88	2.29	2.64	3.16
LAL	**43.49**	**167.73**	**106.02**	**120.96**	**202.67**
DG1	0.04	71.90	45.19	56.28	118.84
DG2	0.05	20.05	6.77	8.37	20.89
DG3	-0.04	32.34	10.62	12.87	19.49
RDG	**0.05**	**124.29**	**62.58**	**77.52**	**159.23**
NRU	**43.44**	**43.44**	**43.44**	**43.44**	**43.44**

NRU: Net revenue to utility; RDG: Remuneration to DGOs; LAL: LA to load points

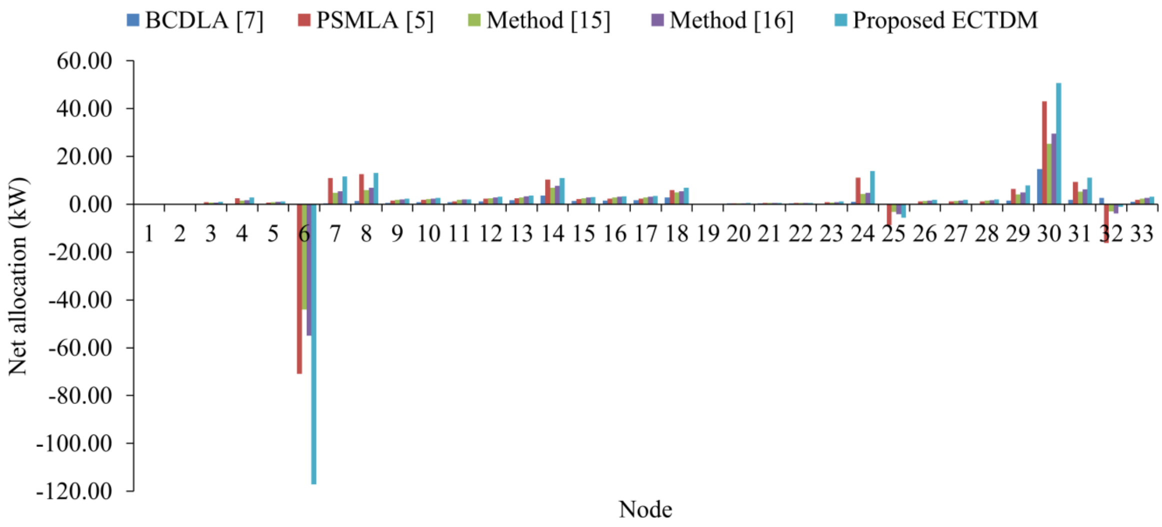


Fig. 5.3 Comparison of NLA to network users using different methods

The LA obtained for all nodes using proposed method is presented in Table 5.4 and are compared with existing methods as available in [16]. The comparison shows that LAL ranges from 43.49 kW to 202.67 kW and RDG from 0.05 kW to 159.23 kW using different methods. This shows that the application of different LA methods is producing dissimilar results while allocating losses to loads or remunerations to DGOs in active distribution systems. In fact, the losses incurred in supplying all system loads is 202.67kW in absence of DGs which is then reduced to 43.44 kW with DGs. The proposed ECTDM, therefore, seems to be fair and more accurate than other methods as it provides 202.67 kW for LAL and 159.23 kW (202.67 kW-43.44 kW) for RDG. However, an identical figure of 43.44 kW is suggested for NRU using proposed as well as all other methods, which is very interesting. This shows that the share of DG remuneration is being transferred to load points, in different proportions using different existing methods, to reduce their loss allocations. This is serious limitation of these methods. Consequently, all these methods allocates different NLAs to network users as shown in Fig. 5.3. More specifically, at node 30, having maximum loading and at node 6, having biggest DG unit. It can be observed that ECTDM provides maximum LA to node 30 and a maximum remuneration to node 6 than other methods, which is quite justified as per aforementioned discussion.

C. Loss incentives to DNO

To investigate the applicability of the proposed ECTDM to RADNs, a realistic load as shown in Table 3.9 of chapter 3 is taken. The Table shows loading for classified feeder containing connected group of nodes and duration for each loading state. The BMLC of the distribution network is obtained by opening the lines 7, 9, 14, 32 and 37. With this network configuration, separate load flow runs for each system state while neglecting/considering DGs. The power losses occurred for each system state, without and with DGs, are presented in Table 5.5. The distribution network is then optimally reconfigured for each system state to minimize power loss. The optimal network configuration and the corresponding losses obtained are also shown in the table. The energy loss reduction caused independently either by DGs or NR is evaluated as shown in Table 5.6. The table shows the economic equation for each state of RADN using LAS as proposed in chapter 3. It can be observed from the table that energy losses are reduced by DGs except in states 1, 2, 3 and 9. As a consequence, RDG is negative for these states. This shows that proposed method not only remunerates DGOs for loss reduction but also penalize them DG power injection increases losses. Assuming no DGs and NR, the losses are 1718.71 kWh which were reduced to 1485.12 kWh by virtue of DGs, the amount against the balance of 233.59 kWh is rewarded to DG owners. If distribution network is optimally reconfigured for each system state, the losses reduced from 1485.12 kWh to 628.29 kWh. The amount against this loss reduction of 856.82 kWh is awarded to DNO using proposed LAS.

Table 5.5 An Illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	35.69	61.79	32.13	13, 18, 22, 34 35
2	45.35	56.38	25.86	13, 15, 18, 22, 35
3	53.26	56.77	21.80	13, 15, 18, 22, 35
4	69.19	56.01	21.21	13, 18, 23, 30, 35
5	100.46	61.97	24.10	13, 19, 24, 31, 35
6	87.59	64.87	22.64	13, 20, 23, 31, 35
7	125.14	68.27	27.54	13, 20, 24, 31, 35
8	139.55	74.58	29.18	13, 24, 31, 33, 35
9	62.07	65.68	19.44	12, 18, 22, 30, 35

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

Table 5.6 Economic Equation for RADN

State	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	249.81	432.56	224.90	249.81	-182.75	207.65
2	45.35	56.38	25.86	45.35	-11.03	30.52
3	159.79	170.31	65.41	159.79	-10.52	104.90
4	207.58	168.03	63.62	207.58	39.55	104.41
5	502.28	309.86	120.52	502.28	192.42	189.35
6	87.59	64.87	22.64	87.59	22.72	42.23
7	125.14	68.27	27.54	125.14	56.87	40.73
8	279.10	149.16	58.37	279.10	129.94	90.80
9	62.07	65.68	19.44	62.07	-3.60	46.24
Total	1718.71	1485.12	628.29	1718.71	233.59	856.82

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

It can be observed from the table that the remuneration to DGOs is less than the loss incentives awarded to DNO. It occurs because the power generation from all DGs are assumed to be fixed for all system states, so remunerations become negative during light load conditions. Therefore, DGOs can optimize power generation from DG units in order to enhance remuneration, however, then the loss incentives to DNO would be reduced. This is how DGOs and DNO can act to enhance their respective benefit which in turn enhances energy efficiency of the system. Whatsoever may happens, the proposed LAS always avoids any conflict among load points, DGOs and DNO while allocating losses or loss incentives among these entities.

D. Accuracy of Proposed ECTDM

The application results obtained using proposed ECTDM have been found satisfactory with other established methods. Since distribution systems undergo dynamically varying states, therefore, it is interesting and important to check the accuracy of developed LA method against variation in system loading, load power factor and reactive power injection from DG units.

Variation in Load Demand

In order to check the accuracy of proposed Superposition to remunerate DGOs, the system loading is widely varied from 0.2-2.0 p.u. The results of loss allocation obtained using ECTDM without and with DGs are presented in Table 5.7.

Table 5.7 Accuracy of Superposition for Remuneration allocation to DGOs

Loading	Without DG	With DG	True	Calculated	Error (%)	DVmax (%)
0.2	7.23	84.31	-77.08	-76.81	-0.35	3.55
0.4	29.72	53.99	-24.28	-25.29	4.17	3.64
0.6	68.74	36.42	32.32	29.85	-7.66	3.73
0.8	125.81	32.53	93.27	89.17	-4.40	3.83
1	202.67	43.44	159.23	153.27	-3.74	3.94
1.2	301.42	70.40	231.02	222.76	-3.58	4.06
1.4	424.53	114.86	309.67	298.45	-3.62	4.20
1.6	575.40	178.55	396.84	381.27	-3.92	4.34
1.8	757.46	263.50	493.97	477.31	-3.37	4.55
2	975.78	372.30	603.48	580.01	-3.89	4.73

The table shows true value of the total remuneration allocated using load flow and compares it with that calculated using proposed method to determine the error produced. The table shows that the percentage error produced is of the same order as that of the percentage maximum node voltage deviation produced while applying Superposition. This depicts high suitability of ECTDM for contemporary distribution systems having large number of DG units. In present study, the error is found to be around 4% even for 2.0 p.u.

loading conditions which is not affecting remunerations actually allocated to DGOs as this small error is proportionately divided among all DG units in proposed method.

Variation in load power factor

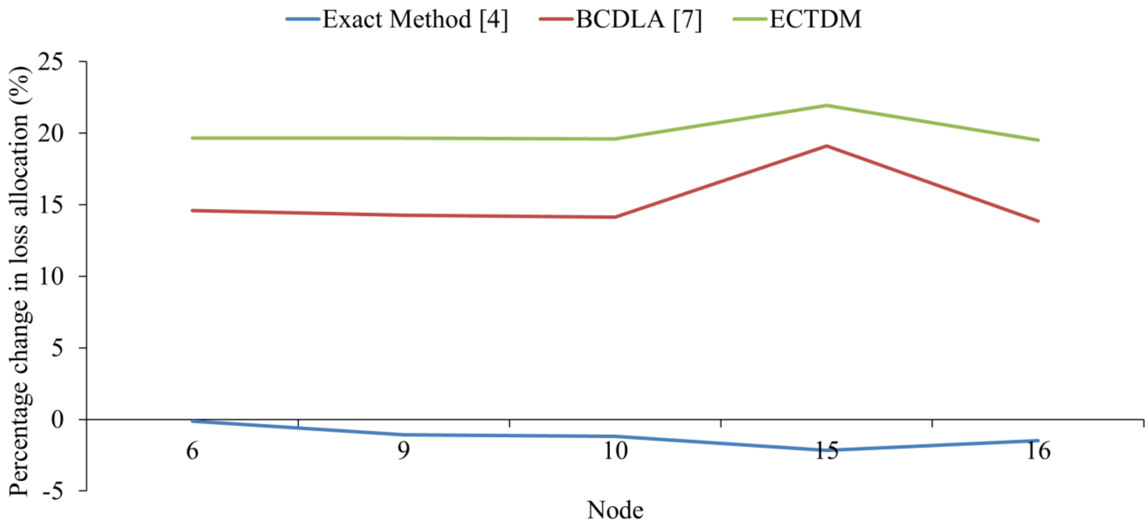
Proposed ECTDM is now investigated against the variation in load power factor. For the purpose, system nodes are arbitrarily divided into three nodal groups and two scenarios are considered as in chapter 3. Exact method [4], BCDLA [7] and proposed ECTDM are applied and the percentage change in loss allocation is determined for each of these scenarios as shown in Table 5.8. Ideally speaking, the LA should increase for Group-A nodes (where power factor has been deteriorated) and decrease for Group-B nodes (where power factor has been improved), and should remain same Group-C nodes (where power factor is not altered). For better comparison of methods, Fig. 5.4 and Fig. 5.5 are presented for scenario 1 and scenario 2, respectively. From the figures, the common observation depicts that Exact method [4] has shown inconsistency whereas both BCDLA [7] and ECTDM produce comparable results, however, more promising results are produced using ECTDM. It happened as the proposed method not only more severely penalizes to Group-A nodes and reduces LA to Group-B nodes but also not much practically affecting the LA to Group-C nodes.

Table 5.8 Comparison of loss allocation methods for case study 1

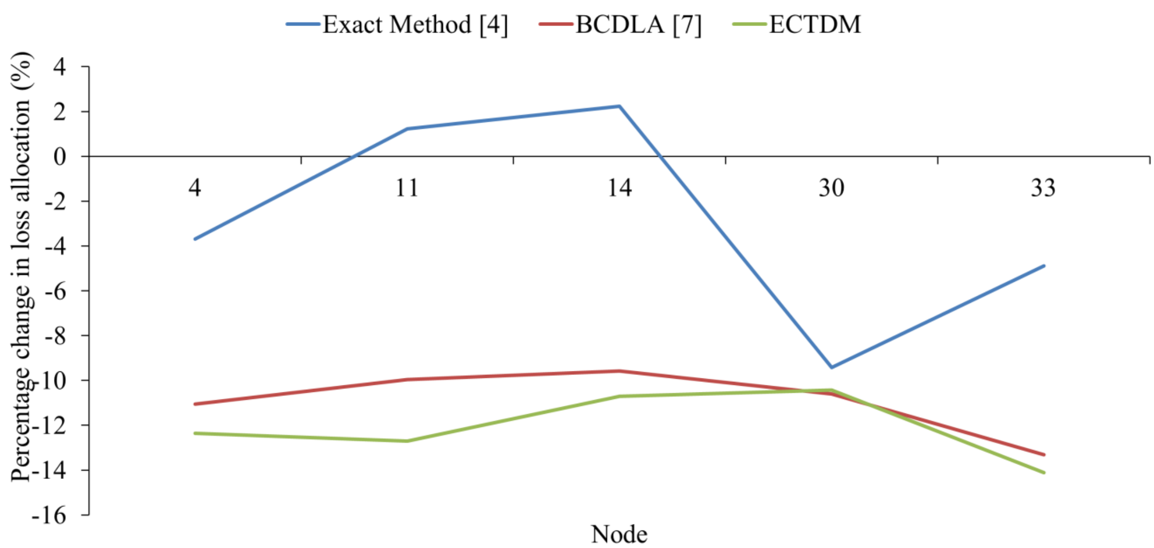
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
Group-A						
6	-0.11	14.60	19.65	-2.88	25.53	37.91
9	-1.08	14.28	19.65	-5.07	25.01	37.32
10	-1.19	14.14	19.59	-5.53	24.63	36.81
15	-2.16	19.10	21.94	-7.08	30.97	40.47
16	-1.48	13.87	19.51	-6.39	24.09	36.41
Group-B						
4	-3.68	-11.06	-12.36	-8.95	-28.56	-27.20
11	1.23	-9.96	-12.70	1.39	-27.11	-27.28
14	2.23	-9.57	-10.71	3.31	-26.36	-25.96
30	-9.41	-10.61	-10.42	-19.41	-20.45	-21.06
33	-4.89	-13.31	-14.12	-9.79	-32.92	-28.68
Group-C						
2	-1.18	-0.68	0.54	-3.61	-2.10	-0.89
3	-1.15	-0.63	0.42	-3.53	-1.94	-0.85
5	-1.27	-0.74	0.59	-3.95	-2.27	-0.96
7	-0.91	-0.63	0.64	-3.68	-2.11	-0.58
8	-0.59	-0.42	0.79	-3.15	-1.79	-0.41

12	0.20	-0.02	1.39	-2.47	-1.48	-0.60
13	0.40	0.07	1.51	-2.42	-1.43	-0.53
17	0.75	0.17	0.74	-1.20	-0.77	-0.34
18	0.83	0.23	1.21	-1.33	-0.88	-0.15
19	-0.91	-0.50	0.32	-2.77	-1.50	-0.58
20	-0.49	-0.26	0.14	-1.49	-0.80	-0.27
21	-0.46	-0.24	0.13	-1.39	-0.73	-0.25
22	-0.43	-0.24	0.12	-1.30	-0.68	-0.23
23	-1.07	-0.62	0.50	-3.28	-1.88	-0.92
24	-0.79	-0.44	0.13	-2.42	-1.34	-0.66
25	-0.72	-0.40	0.11	-2.19	-1.21	-0.61
26	-1.33	-0.72	0.43	-4.03	-2.12	-0.85
27	-1.51	-0.82	0.38	-4.34	-2.29	-0.93
28	-2.21	-1.01	0.06	-5.44	-2.52	-1.07
29	-3.18	-1.68	0.15	-7.46	-4.01	-1.71
31	-3.19	-1.60	-0.10	-7.41	-3.77	-1.80
32	-3.25	-1.63	-0.18	-7.57	-3.85	-1.86

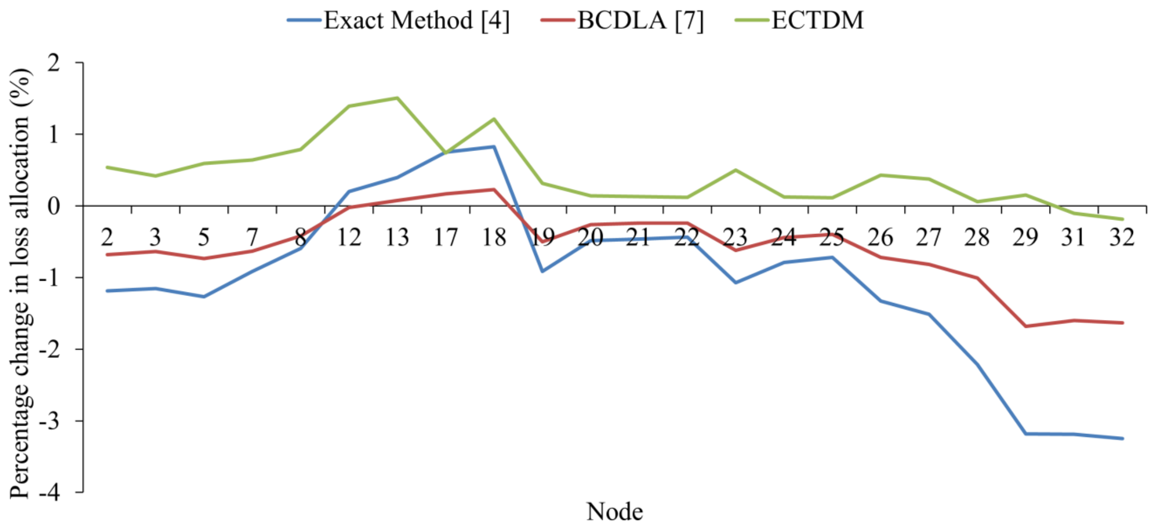
X: Base case, Y: Scenario 1, Z: Scenario 2



(a) Group-A

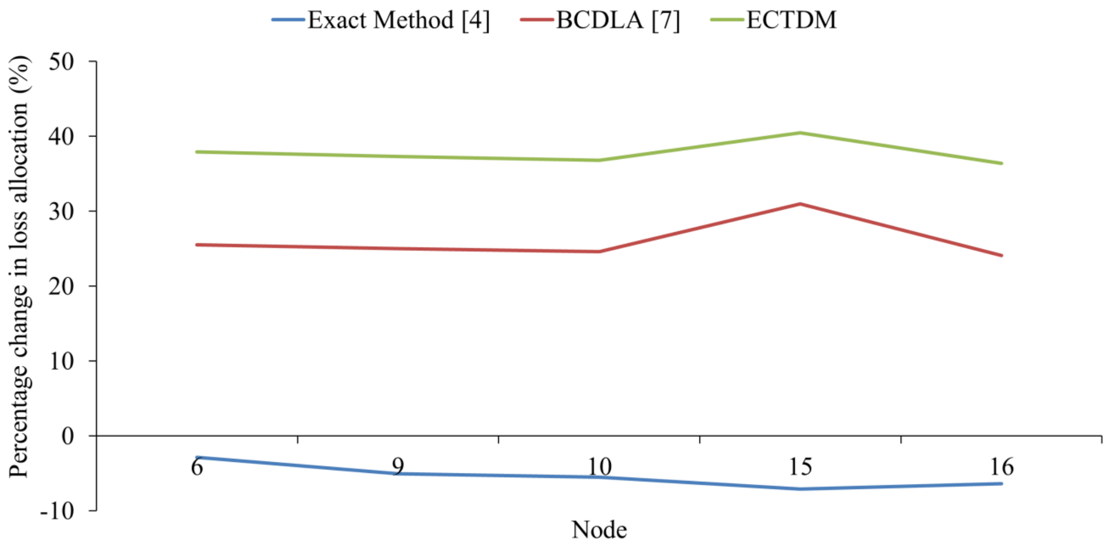


(b) Group-B

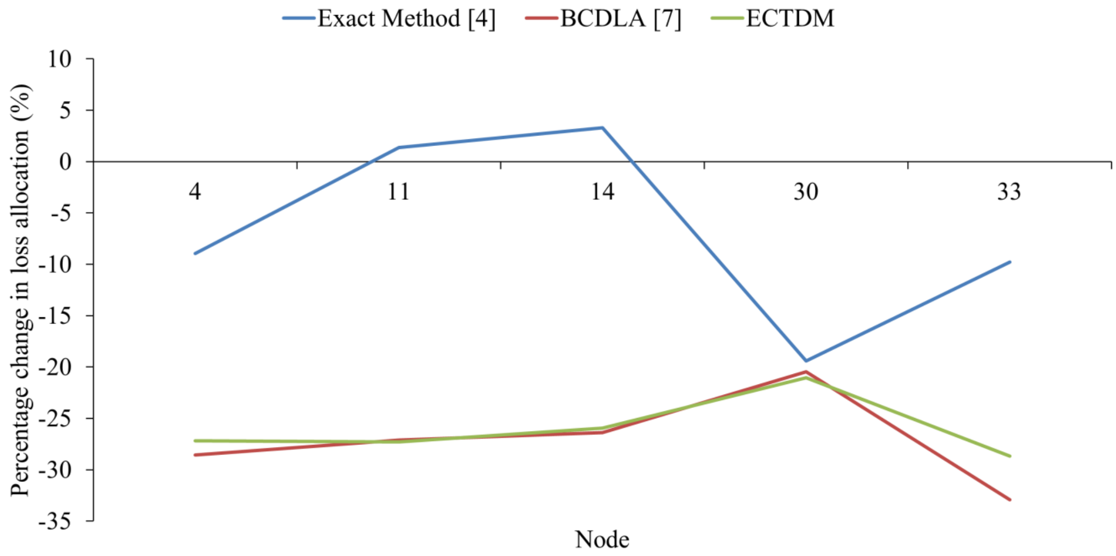


(c) Group-C

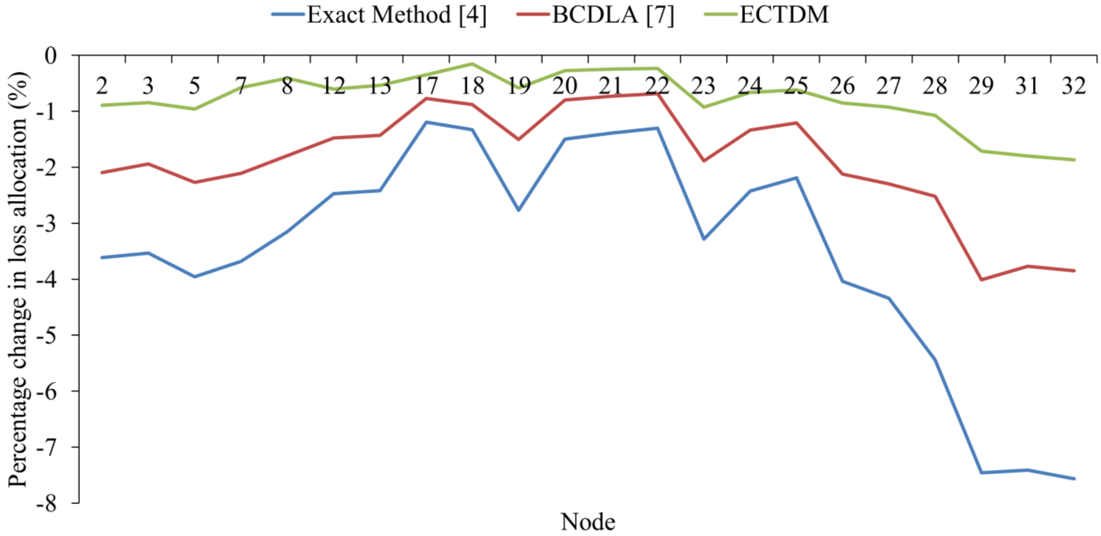
Fig. 5.4. Comparison of proposed methods with established methods for scenario 1



(a) Group-A



(b) Group-B



(c) Group-C

Fig. 5.5. Comparison of proposed methods with established methods for scenario 2

Furthermore, a statistical error analysis is carried out on the absolute value of percent change in the LA to Group-C nodes. The Maximum, minimum and mean values along with the standard deviation of the sampled data are presented in Table 5.9. The table clearly shows that all the statistic indices obtained are smallest using proposed method. Therefore, the allocations to Group-C nodes are least affected using proposed method. This clearly shows the superiority of ECTDM over other established methods while considering variation in load power factor at certain nodes in the distribution system.

Table 5.9 Statistical error analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
Max.	3.245	1.683	1.510	7.565	4.009	1.862
Min.	0.204	0.022	0.062	1.196	0.684	0.154
Mean	1.219	0.625	0.481	3.475	1.884	0.776
SD	0.899	0.472	0.417	1.926	0.960	0.478

Variation in DG power factor

The investigation is carried by varying the power factor of highest rating DG unit. i.e. DG 1, keeping power factors of all other DG units remain unaltered. The power factor is varied from unity to 0.707 (leading) keeping active power generation constant. ECTDM is applied and the remunerations of all DGs against each variation are evaluated. The results obtained are presented in Fig. 5.6. It can be observed that the remuneration to DG1 increases consistently with the increase in reactive power injection without much affecting the remunerations to other DG units. This shows fairness and robustness of ECTDM while considering reactive power transactions from DG units. Moreover, proposed method encourages DGOs to inject appropriate reactive power from the DG units.

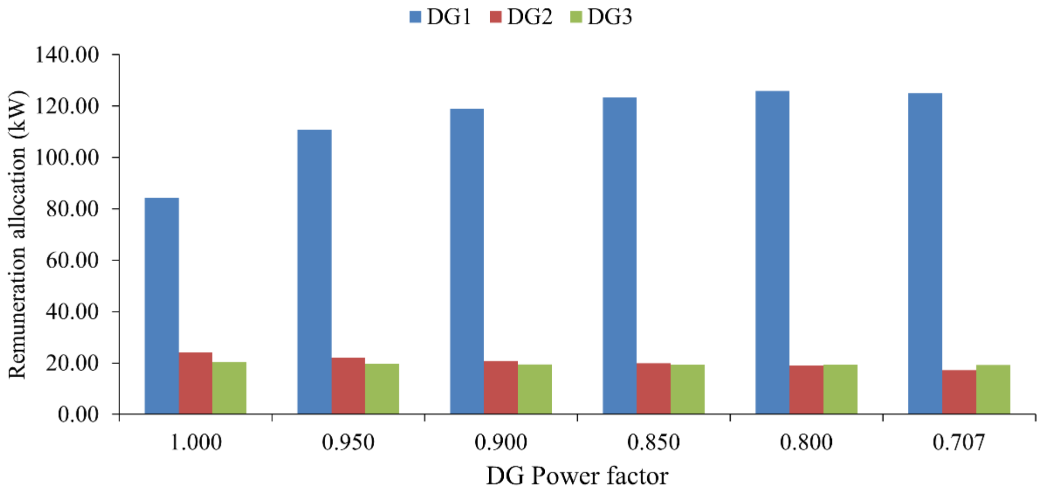


Fig. 5.6 Remuneration allocation to DGOs with variation in power factor of DG1

The ECTDM method has shown good performance on a standard test distribution system. The method is now applied and investigated to a real distribution system in the forthcoming section.

5.2.2 CASE STUDY 2

The proposed ECTDM is applied to 11.40 kV, 83-bus Tai Power Corporation distribution system as in chapter 3. The power losses of the system in base configuration under nominal loading are 531.99 kW.

A. Loss allocation to load points

Considering no DGs in the system, proposed ECTDM, Exact method [4] and BCDLA [7] are applied to this system to determine loss allocation. The comparison results obtained are presented in Fig. 5.7. It can be observed from the figure that the loss allocations suggested by ECTDM are comparable to other methods. This validates the applicability of proposed method for large passive distribution systems.

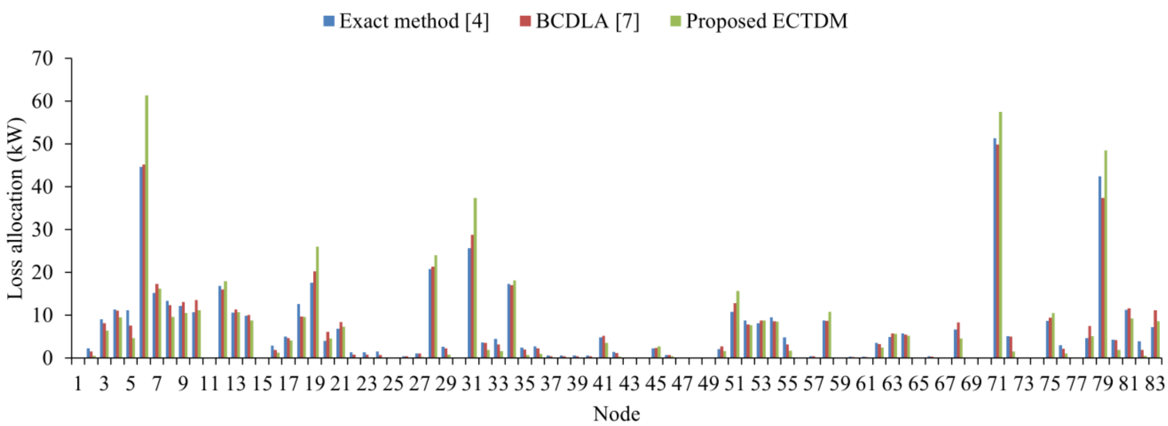


Fig. 5.7. Comparison of LA using ECTDM with established methods

B. Remuneration to DGOs

In order to examine the applicability of proposed method to active distribution systems, the system is modified by placing five DGs as in Table 3.17 of chapter 3. With this placement, losses are reduced from 531.99 kW to 297.67 kW. Thus, DGs causes a loss reduction of 234.32 kW. This loss reduction is allocated as remuneration among DG units using proposed ECTDM as shown Table 5.10. This is interesting to note that the total remuneration allocated is very close to the actual loss reduction caused by DG units, so error produced using Superposition is insignificant. This shows that proposed remuneration allocation is highly accurate for this larger system. The LA to loads, remuneration to DGOs and the net allocation are presented in Fig. 5.8.

Table 5.10 Remuneration allocated to DGOs using proposed ECTDM

Remuneration to DGOs (kW)	DG1	DG2	DG3	DG4	DG5	Total remuneration (kW)
Calculated	85.54	32.14	29.63	40.51	46.35	234.17
Adjusted	85.59	32.16	29.65	40.54	46.38	234.32

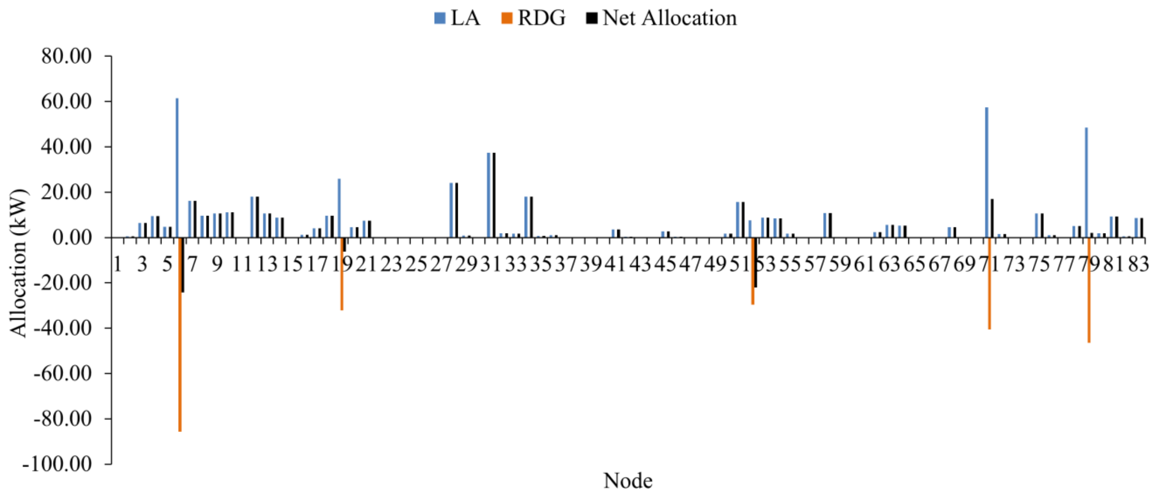


Fig. 5.8 Allocation to various entities

C. Loss incentives to DNO

The proposed strategy is applied to the system with BMLC, i.e. by opening switch at 7, 13, 34, 39, 41, 55, 62, 72, 83, 86, 89, 90, and 92. The operating states, loads and duration of loads are taken from Table 3.9 of chapter 3. The feeder power losses for each state is determined by conducting separate load flow without and with DGs and are presented in Table 5.11. The distribution network is then optimally reconfigured to minimize feeder power losses using the method of [62] for each state and the results obtained are also presented in the table. The proposed LAS is applied to determine the energy loss reduction caused independently either by DGs or by NR. The application results are summarized in Table 5.12. Table shows that the energy losses are reduced by DGs for all states, except for state 1, 2 and 3. For states 1,2 and 3, there is increase in loss and therefore DGO should be penalize under these states. This highlights that DGO can also be penalized if they are contributing in increase of net power loss. The NR causes further loss reduction as shown in the table. This reduction in loss is the LI of the DNO which may be called as reconfiguration benefit to DNO (RBD).

Table 5.11 An illustration for loss incentives to DNO

State	Power loss (kW)			OC
	BMLC w/o DGs	BMLC with DGs	RN with DGs	
1	112.12	168.02	123.11	14,29,34,54,57,61,69,86,88,90,91,92,95
2	142.51	198.41	143.27	14,29,34,54,57,61,69,86,88,90,91,92,95
3	179.83	206.92	152.08	14,29,34,54,57,61,69,86,88,90,91,92,95
4	219.09	199.99	156.57	14,29,34,42,55,60,63,71,86,88,90,91,92
5	327.92	230.06	195.93	14,34,42,55,60,61,86,87,88,90,91,92,93
6	296.01	198.14	169.78	14,34,39,42,63,84,85,86,87,88,90,91,92
7	399.48	251.50	226.54	14,34,42,62,83,84,85,86,87,88,90,92,93
8	471.05	290.30	269.21	14,34,42,62,83,84,85,86,87,88,90,92,93
9	263.89	228.21	175.55	14,20,33,35,42,54,60,63,70,86,88,90,92

BMLC: Base Case Minimum Loss Configuration, RN: Reconfigured Network, OC: Optimal configuration

Table 5.12 Economic Equation for RADN

State	Energy loss (kWh)			LAL	RDG	RBD
	BMLC w/o DGs	BMLC with DGs	OC with DGs			
	(a)	(b)	(c)	(a)	(a)-(b)	(b)-(c)
1	784.87	1176.11	861.74	784.87	-391.25	314.37
2	142.51	198.41	143.27	142.51	-55.89	55.14
3	539.50	620.76	456.23	539.50	-81.25	164.53
4	657.28	599.96	469.71	657.28	57.32	130.25
5	1639.62	1150.28	979.64	1639.62	489.35	170.63
6	296.01	198.14	169.78	296.01	97.87	28.36
7	399.48	251.50	226.54	399.48	147.98	24.96
8	942.11	580.59	538.42	942.11	361.51	42.17
9	263.89	228.21	175.55	263.89	35.68	52.66
Total	5665.27	5003.94	4020.87	5665.27	661.32	983.07

BMLC: Base Case Minimum Loss Configuration, OC: Optimal configuration, RBD: Reconfiguration benefit to DNO

The accuracy of ECTDM is investigated in the following section.

D. Accuracy of Proposed ECTDM

The accuracy of the method is investigated by considering variation in load demand, load power factor and reactive power injections from DG units.

Variation in Load Demand

The system loading is varied from 0.2 to 2.0 p.u. in the step size of 0.2 p.u. The power losses are evaluated for each loading conditions by conducting separate load flow. Losses are evaluated without and with DGs. ECTDM are applied to determine remunerations to DG units using Superposition. The results obtained are presented in Table 5.13. The table shows true loss reduction obtained using load flow which is very close to that calculated using proposed method. Thus accuracy of the method is very good for this large system while allocating remunerations using Superposition.

Table 5.13 Accuracy of Superposition for Remuneration allocation to DGOs

Loading	Without DG	With DG	TRUE	Calculated	Error	DV_max(%)
0.2	19.86	137.76	-117.90	-117.90	0.002	5.62
0.4	80.74	117.11	-36.37	-36.37	0.002	5.67
0.6	184.76	135.59	49.17	49.16	-0.021	5.73
0.8	334.29	195.08	139.21	139.16	-0.037	5.79
1	531.99	297.67	234.32	234.17	-0.064	5.87
1.2	780.88	445.66	335.21	334.80	-0.124	5.95
1.4	1084.38	641.65	442.73	442.73	0.000	6.05
1.6	1446.50	888.54	557.96	557.96	0.000	6.16
1.8	1871.90	1189.66	682.24	682.23	-0.001	6.30
2	2366.16	1548.82	817.34	817.33	-0.002	6.46

Variation in Load Power Factor

Proposed method is thoroughly investigated against variation in load power factor. For the purpose, system nodes are arbitrarily dived into three groups and two different scenarios of power factor variations are considered as shown in Table 3.23 of chapter 3. For each of these scenarios, the LA is determined using Exact method [4], BCDLA [7] and proposed ECTDM. The percentage change in LA is determined and the comparison results of these methods are presented in Table 5.14. It can be observed from the table that Exact method [4] is not showing consistency in loss allocations, but the same is not true for BCDLA [7] and proposed method while considering allocations for all nodal groups for both scenarios. A close look on the table reveals that proposed method performs better than BCDLA [7] as it imposes higher penalties to Group-A nodes, as they have deteriorated power factors, and reduced loss allocations to Group-B nodes, where power factors have been improved. Moreover, the change in LA to Group-C nodes is least using proposed method. These facts can be clearly observed from Fig. 5.9 and Fig. 5.10. This fact can be further verified from Table 5.15 showing statistical error analysis carried on the results obtained for Group-C nodes. This shows the superiority of proposed ECTDM over other established methods even for a larger practical distribution system while considering variation in load power factor at certain nodes.

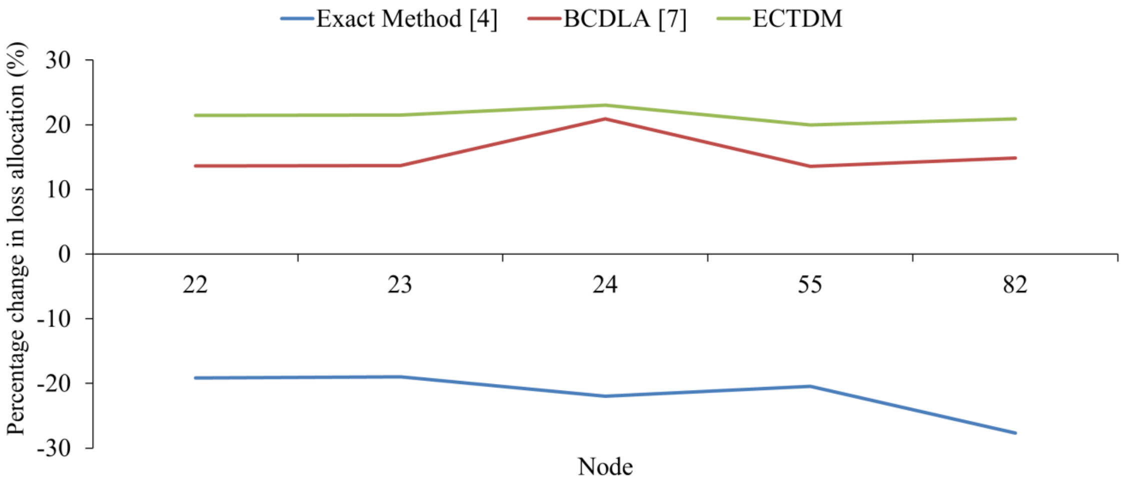
Table 5.14 Comparison of loss allocation methods for case study 2

Group-A						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
22	-19.17	13.64	21.46	-38.30	27.71	52.07
23	-18.96	13.69	21.51	-37.91	27.89	52.21
24	-21.95	20.92	23.03	-39.19	37.91	54.63
55	-20.47	13.55	19.96	-41.12	28.63	46.92
82	-27.69	14.86	20.90	-53.90	28.94	49.79
Group-B						
	Scenario 1			Scenario 2		
Node	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
20	30.19	-10.49	-14.45	55.72	-18.75	-25.08

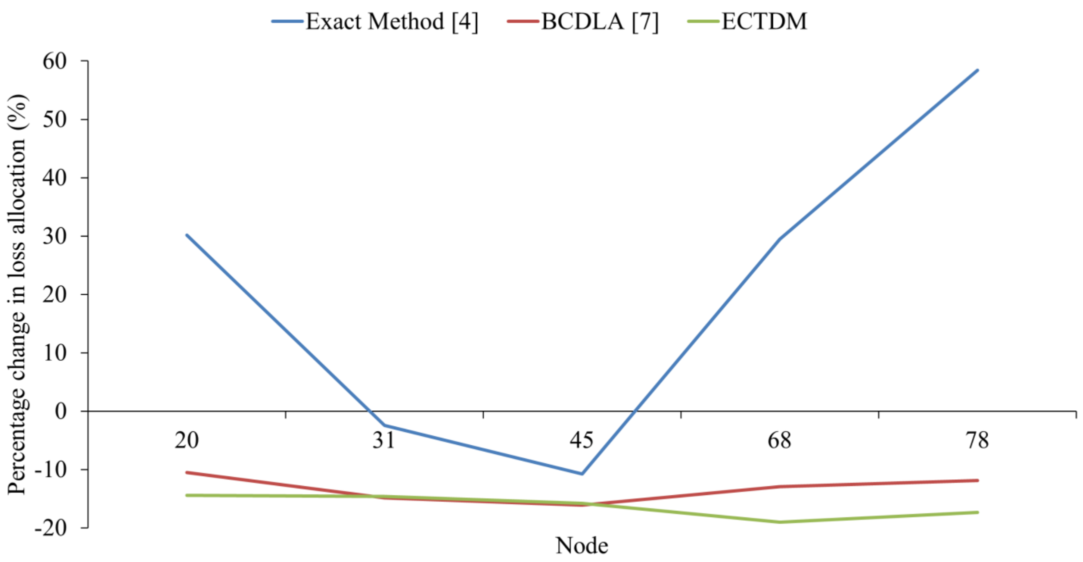
31	-2.43	-14.88	-14.58	-1.83	-26.13	-25.98
45	-10.74	-16.13	-15.82	-17.63	-28.55	-28.29
68	29.45	-12.93	-19.00	55.25	-22.97	-31.40
78	58.44	-11.89	-17.33	107.89	-21.21	-29.26
Group-C						
Node	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
2	0	0	0	0	0	0
3	0	0	0	0	0	0
4	0	0	0	0	0	0
5	0	0	0	0	0	0
6	0	0	0	0	0	0
7	0	0	0	0	0	0
8	0	0	0	0	0	0
9	0	0	0	0	0	0
10	0	0	0	0	0	0
12	0	0	0	0	0	0
13	0	0	0	0	0	0
14	0	0	0	0	0	0
16	-1.39	-0.33	0.65	-2.29	-0.54	1.09
17	-1.78	-0.42	0.37	-2.95	-0.69	0.60
18	-1.53	-0.41	0.24	-2.52	-0.67	0.38
19	-2.21	-0.53	-0.17	-3.66	-0.87	-0.30
21	-1.26	-0.29	1.22	-1.71	-0.38	2.14
25	0	0	0	0	0	0
26	0	0	0	0	0	0
27	0	0	0	0	0	0
28	0	0	0	0	0	0
29	0	0	0	0	0	0
32	-16.03	-4.80	-0.59	-30.87	-9.25	-1.25
33	-12.05	-3.67	-0.49	-23.21	-7.07	-0.99
34	-13.79	-4.13	-1.08	-26.57	-7.95	-2.39
35	-11.57	-3.58	-0.47	-22.29	-6.89	-0.92
36	-10.48	-3.24	-0.46	-20.19	-6.25	-0.91
37	-9.38	-2.88	-0.44	-18.07	-5.58	-0.85
38	-9.34	-2.89	-0.44	-17.98	-5.54	-0.85
39	-9.31	-2.88	-0.44	-17.96	-5.56	-0.85
40	-9.32	-2.88	-0.44	-17.93	-5.55	-0.85
41	-12.65	-3.69	-0.55	-24.36	-7.11	-1.13
42	-10.07	-3.13	-0.45	-19.40	-6.03	-0.87
44	-26.44	-6.69	-0.17	-52.87	-13.68	-0.42
46	-22.68	-6.22	-0.92	-45.39	-12.43	-2.32
50	5.66	1.02	1.21	11.55	2.08	2.13
51	5.02	1.00	1.17	10.25	2.05	2.25
52	3.96	0.90	1.01	8.09	1.84	1.86
53	4.96	1.07	1.25	10.12	2.18	2.33
54	4.42	1.03	1.14	9.02	2.09	2.12
57	0	0	0	0	0	0
58	0	0	0	0	0	0
60	0	0	0	0	0	0
61	0	0	0	0	0	0
62	0	0	0	0	0	0
63	0	0	0	0	0	0
64	0	0	0	0	0	0
66	-5.71	-1.65	-0.28	-10.53	-3.03	-0.66
71	-6.99	-1.69	-1.97	-12.87	-3.11	-3.78
72	-6.98	-1.69	-1.27	-12.84	-3.10	-2.78
75	0	0	0	0	0	0
76	0	0	0	0	0	0
79	-4.43	-0.94	-0.81	-7.85	-1.66	-1.53

80	-4.04	-0.80	0.46	-7.08	-1.40	0.52
81	-3.52	-0.67	0.08	-6.09	-1.14	-0.04
83	-4.16	-0.62	0.24	-7.11	-1.04	0.25

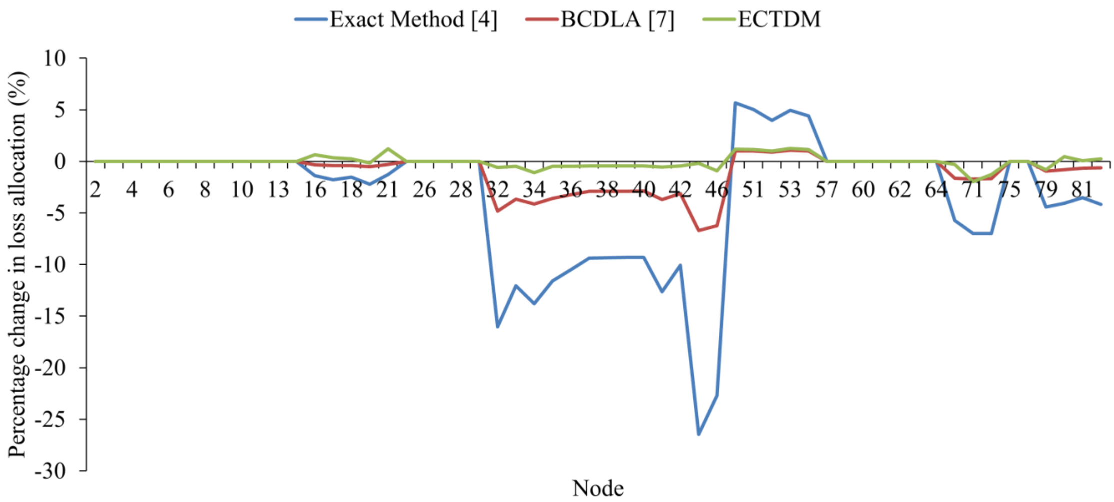
X: Base case, Y: Scenario 1, Z: Scenario 2



(a) Group-A

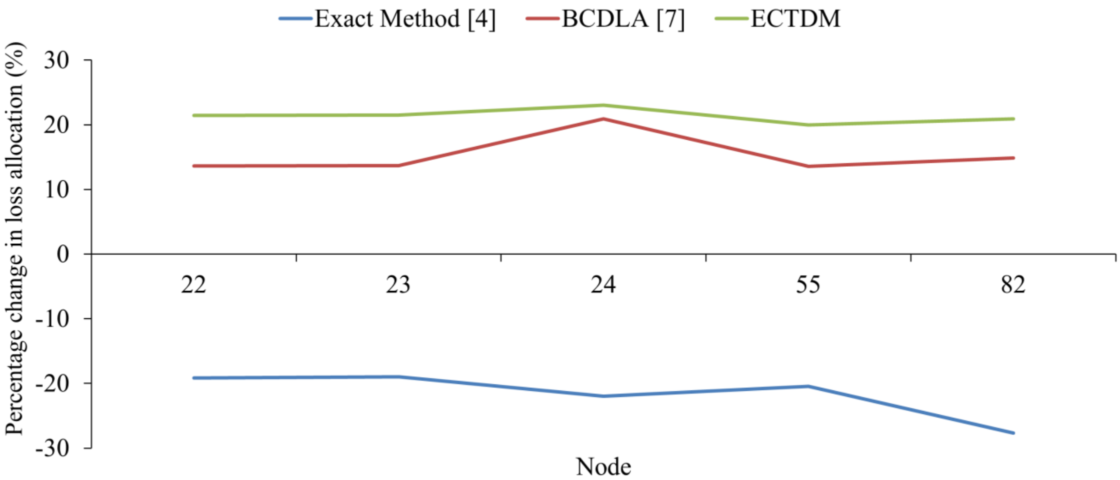


(b) Group-B

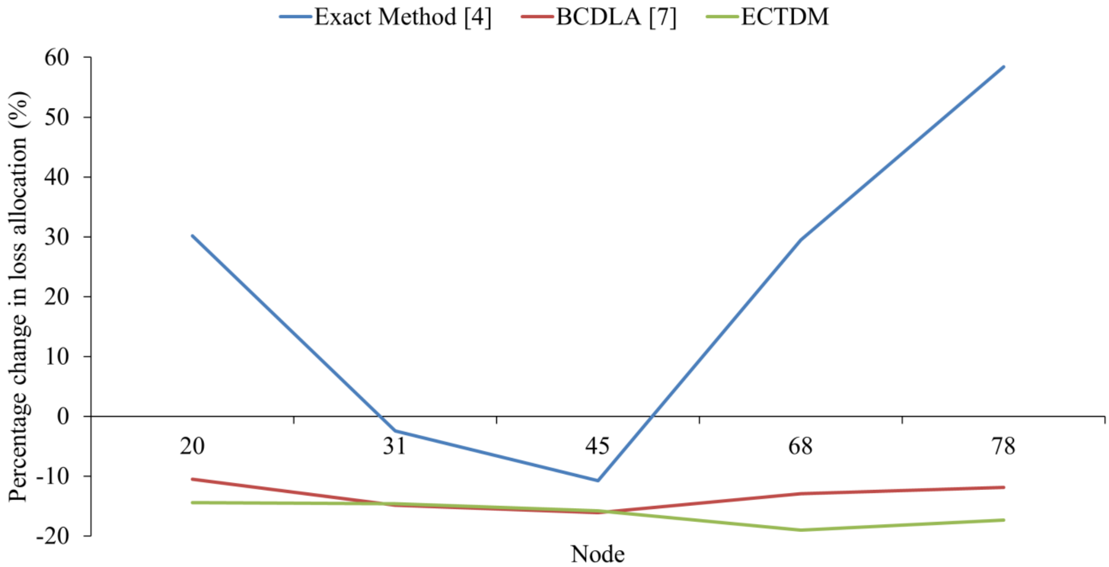


(c) Group-C

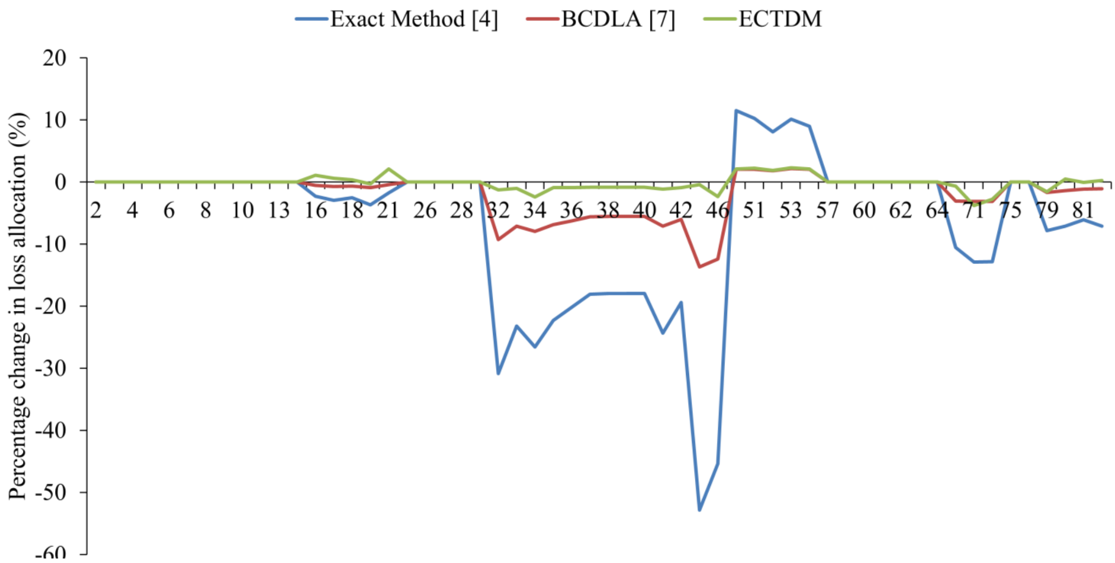
Fig. 5.9. Comparison of proposed methods with established methods for scenario 1



(a) Group-A



(b) Group-B



(c) Group-C

Fig. 5.10. Comparison of proposed methods with established methods for scenario 2

Table 5.15 Statistical Error Analysis for the results obtained for Group-C nodes (absolute value)

Index	Scenario 1			Scenario 2		
	Exact Method [4]	BCDLA [7]	ECTDM	Exact Method [4]	BCDLA [7]	ECTDM
Max.	26.44	6.69	1.97	52.87	13.68	3.78
Min.	0	0	0	0	0	0
Mean	4.31	1.17	0.37	8.28	2.26	0.70
SD	5.95	1.69	0.47	11.72	3.33	0.93

Variation in DG power factor

The power factor of DG 5 having highest MVA rating is varied from 1.0 to 0.707 (lead) by increasing reactive power injection keeping active power generation constant. For each of this condition, ECTDM is applied to evaluate remuneration of all five DG units. The results obtained are presented in Fig. 5.11. It can be observed from the figure that the remuneration to DG5 increases with increased reactive power injections whereas remunerations allocated to other DG units remain almost unaltered. This shows robustness of proposed ECTDM that encourages DGOs to maintain appropriate power factor of DG units without affecting remunerations of other DG units.

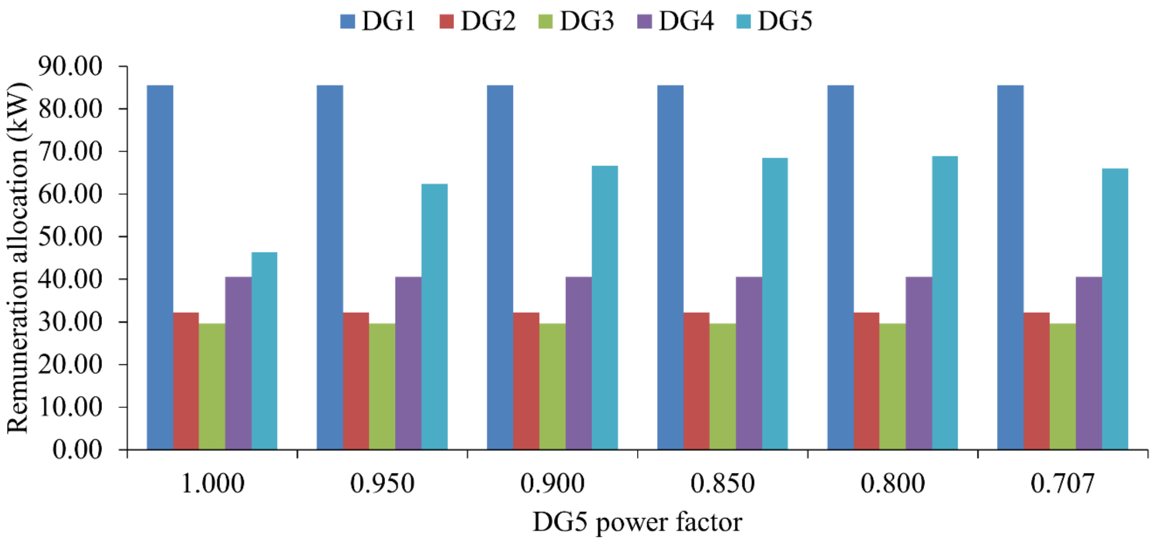


Fig. 5.11. Remuneration allocation to DGOs with variation in power factor of DG5

5.3 SUMMARY

Another circuit theory-based loss allocation method is proposed for distribution systems. Proposed ECTDM is different than proposed CTDM as it first decomposes the branch power losses which are separately contributed by the real and imaginary components of the nodal injections. Thereafter, decomposing the crossed-terms by suggesting separate loss allocation factors for each real and imaginary components of nodal injections. Loss allocation factors are derived analytically. Proposed method is applied to both passive and active distribution systems to allocate loss allocation or/and remuneration to DGOs. The method also applied to RADNs for fair and judicious allocation of losses or loss incentives among the customers, DGOs and DNO. ECTDM is thoroughly investigated on standard test and real distribution systems while considering variation in system loading, load power factor and reactive power injections from DG units. Application results reveal supremacy of ECTDM over other existing LA methods on account of fairness, accuracy and robustness.

CHAPTER 6
CONCLUSIONS AND FUTURE SCOPE

Distribution systems are the sections of electric power system where power losses are significant due to line flows at relatively lower voltage levels. The utility should fairly charge this cost of transportation electricity from the end users and the procedure is called loss allocation (LA). The calculation of LA is a difficult problem on account of non-linearity involved. This problem becomes more complex and tedious in contemporary distribution systems equipped with DGs with topological variations on account of network reconfiguration. The deployment of DG normally contributes towards loss reduction. Similarly network reconfiguration (NR), which is an effort of DNO, also contributes towards loss reduction. On the other hand consumers are the source of distribution loss. Moreover, consumers with poor power factor cause comparatively more losses than the consumers with better power factor under identical loads. Under such conditions the distribution LAS becomes a difficult task on account of complexity of distribution network, bilateral flow of power and nonlinear nature of loss allocation problem. In fact no unique and perfect loss allocation method exists in the literature. Attempts are being made to develop fair and efficient loss allocation methods which are logically convincing and simple to implement. Several loss allocation methods have been suggested in literature which have employed different approaches and provide loss allocation in close proximity. These methods have different logics and philosophies, sometimes conflicting in allocating remuneration among DGOs and DNO providing different loss allocation to the stake holders. However, loss allocation and LAS should be judicious and should provide true reflection of the realistic operating conditions and the factors contributing in the net loss of distribution systems to satisfy various stake holders by a good degree.

In this thesis work three different loss allocation methods have been developed and proposed for contemporary distribution namely, branch current decomposition method (BCDM), cross-term decomposition method (CTDM) and exact cross-term decomposition method (ECTDM) for reconfigured active distribution systems (RADSs). A more judicious loss allocation and LAS are also proposed. All methods employ current summation approach though allocates losses in different manner. BCDM suggested virtual branch voltage drop along distribution lines by dynamically varying line reactance to overcome limitations of existing methods. This approach takes care of power factor while allocating losses or remunerations to load or DGOs, respectively. The CTDM method suggests new LAFs to bifurcate losses pertaining to the crossed-terms among contributing nodal injections in the branch under consideration. ECTDM is also using the approach of CDTM, but in a different manner, as it considers the actual loss contribution separately for active and reactive components of the contributing nodal currents thus truly considers power factor of the end users. All methods have been thoroughly investigated on 33-bus test distribution system and 83-bus practical distribution systems as case study 1 and case study 2. In order to investigate the effect of DGs, these systems were modified by placing DGs at suitable locations to have a more realistic picture of contemporary distribution systems. The investigation results of the proposed methods have been presented. The methods are also investigated for dynamically varying operating conditions pertaining to load demand, power factor of load and reactive power injection from DG units. The results of study are presented, validated and discussed.

A comparison results of these methods, for the case study 2, is presented at a glance. Fig. 6.1 compares loss allocation in passive distribution system and the net loss allocation in the presence of DGs is compared in Fig. 6.2. It can be observed from the figures that both BCDM and CTDM suggests almost same loss allocations to customers though these methods employ different circuit theory-based approaches, however, ECTDM produces different allocations along certain nodes. The percentage error produced using these methods while remunerating DGOs under wide varying loading is compared in Fig. 6.3. It can be observed that ECTDM is performing relatively better than other methods. However, the error is insignificant for all loadings considered and it is to be disbursed among DGOs, therefore practically all methods are seems to be at par. Fig. 6.4 compares the robustness of these methods against variation in load power factor; deteriorating power factor by 20% for Group-A nodes while improving by the same percentage for Group-B nodes keeping power factor of Group-C nodes unchanged. The figure clearly shows the dominance of ECTDM over BCDM and CTDM as it not only penalize most to Group-A nodes and rewards most to Group-B nodes but also least affecting the loss allocation to Group-C nodes. Finally, the comparison of the robustness of these methods while varying the reactive power injection from only one DG unit (DG 5) is presented in Fig. 6.5. It can be observed that all methods show comparable robustness, i.e. remunerations to other DG units are not affected and that of DG5 increases with the increase in reactive power injection.

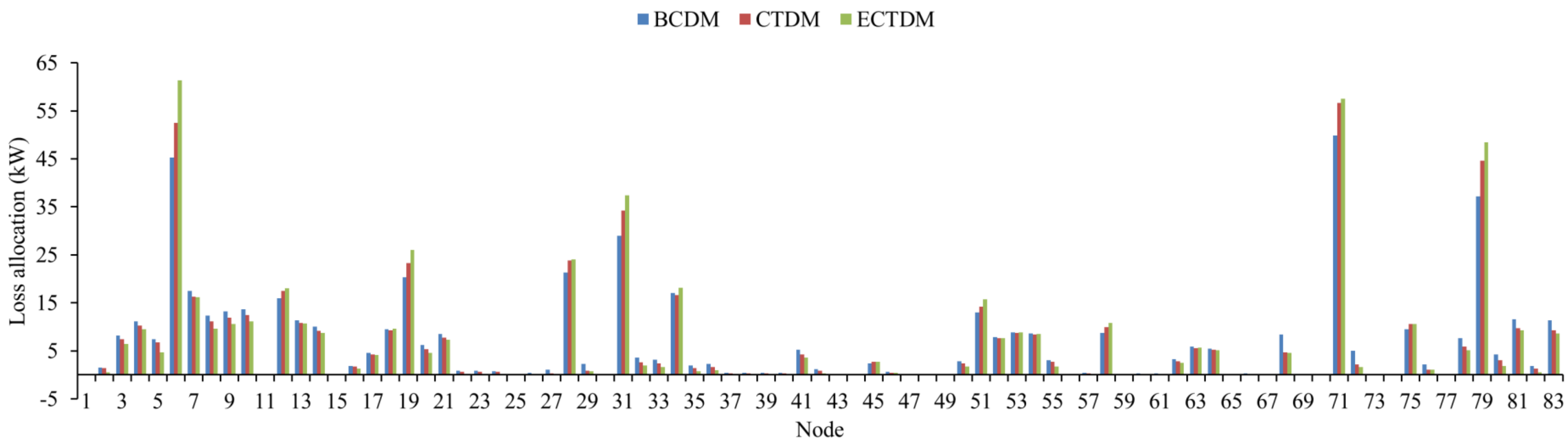


Fig. 6.1 Comparison of loss allocation without considering DGs

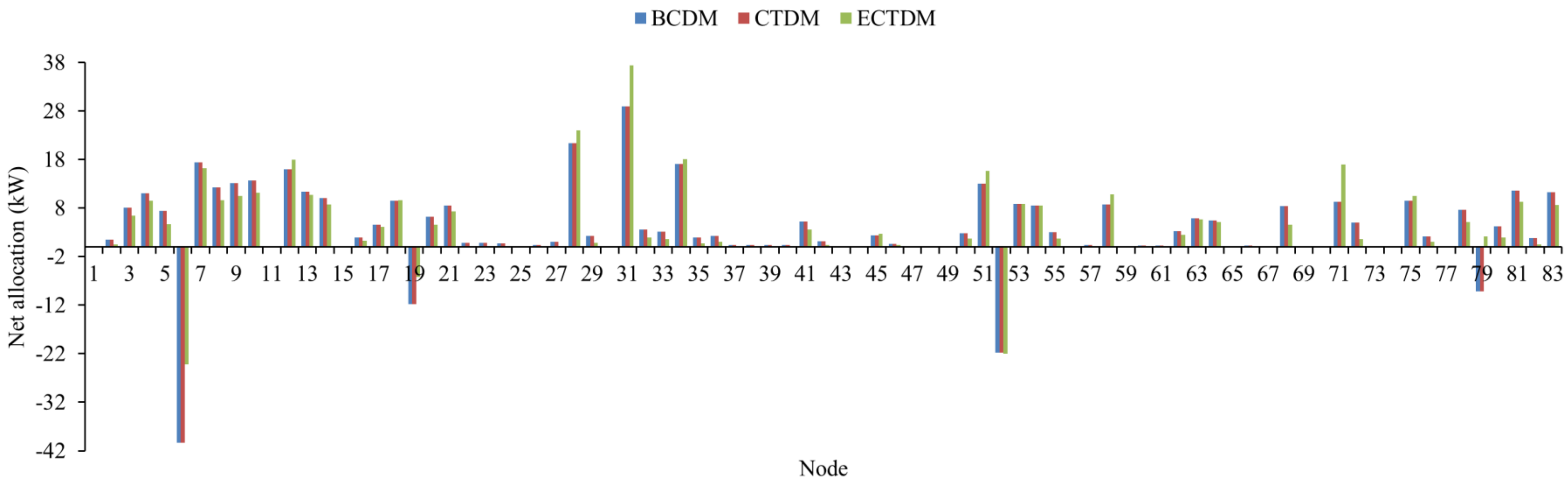


Fig. 6.2 Comparison of net loss allocation with DGs

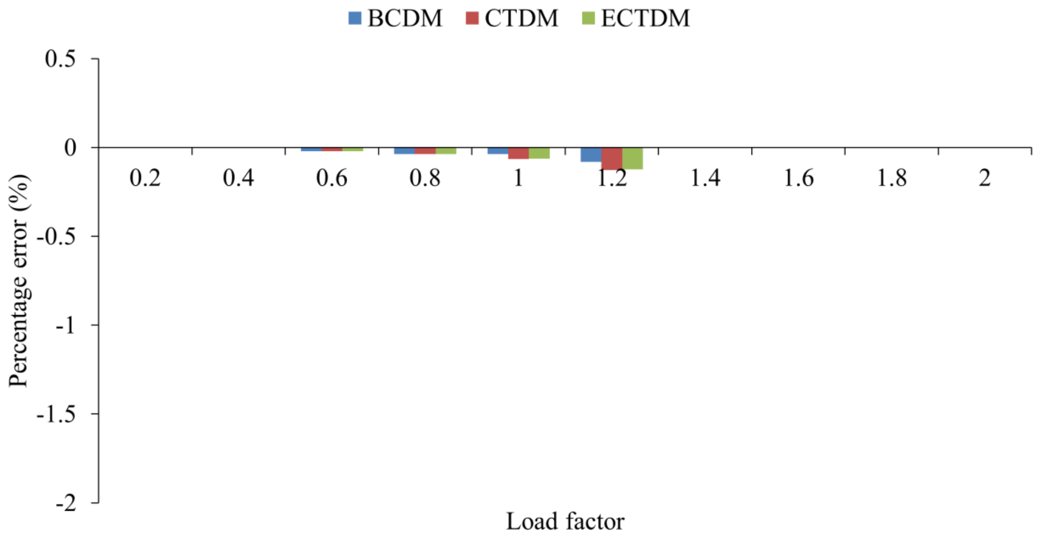
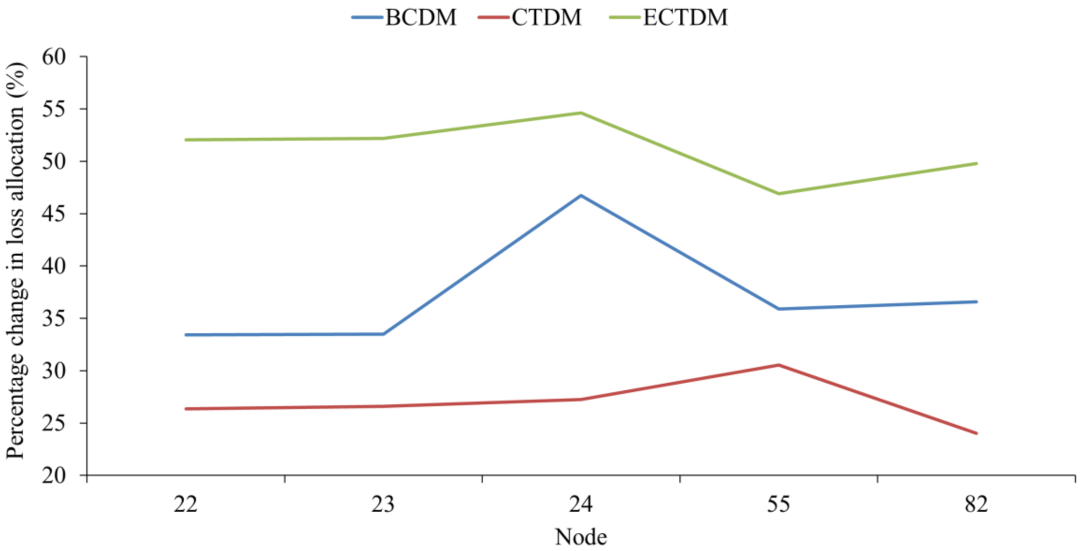
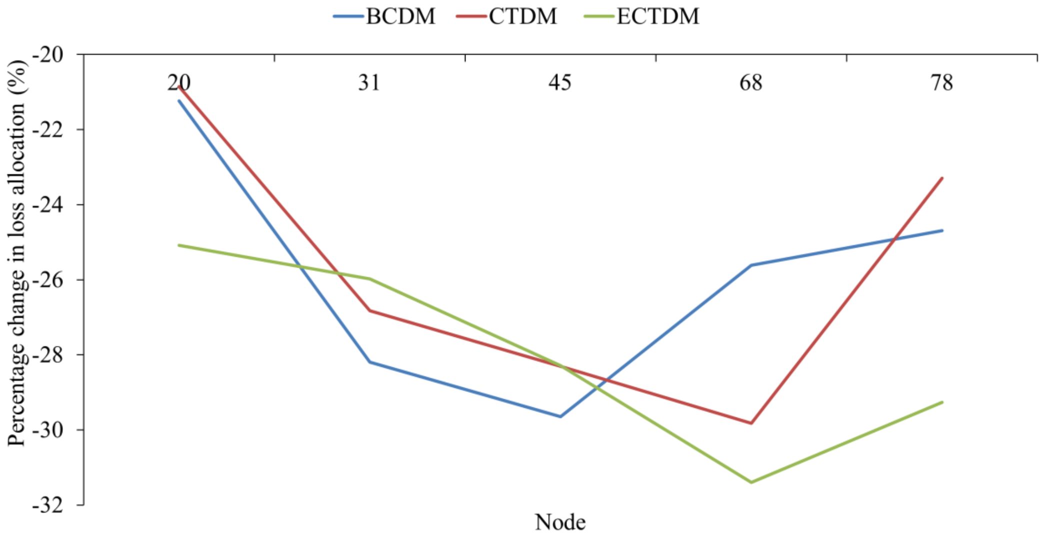


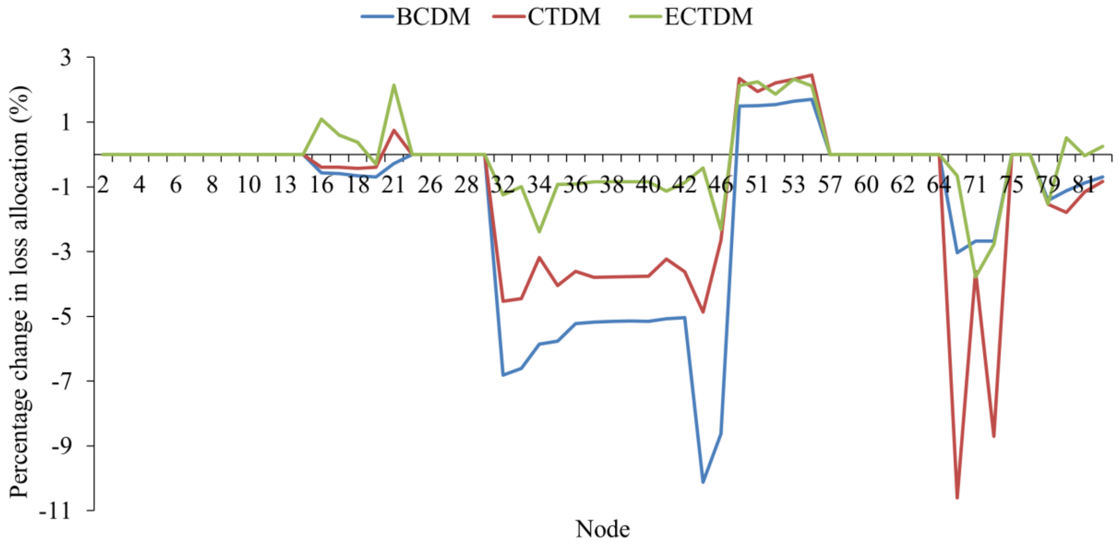
Fig. 6.3 Comparison of percentage error in remuneration allocation against variation in system loading



Group-A

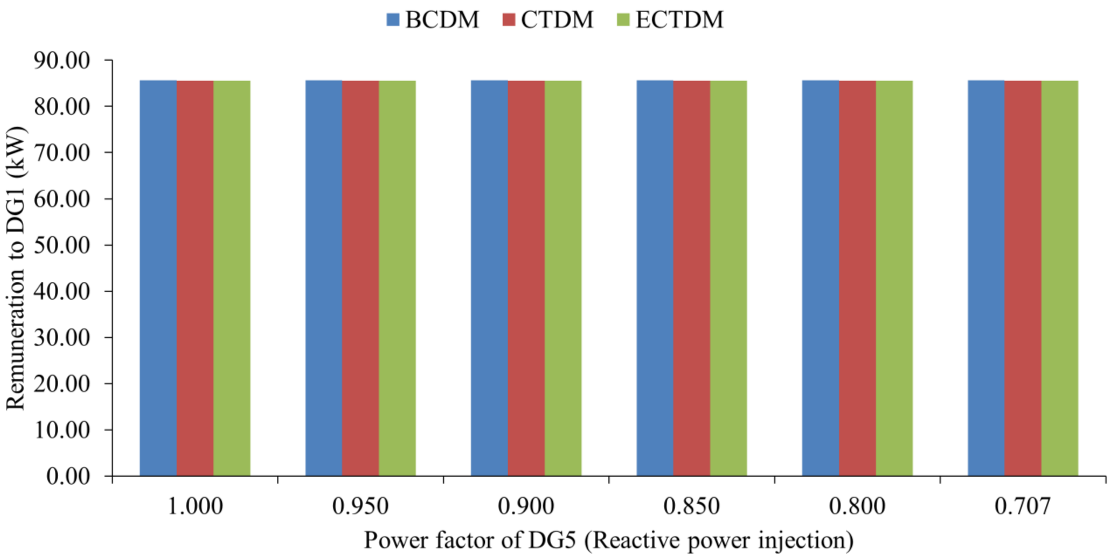


Group-B

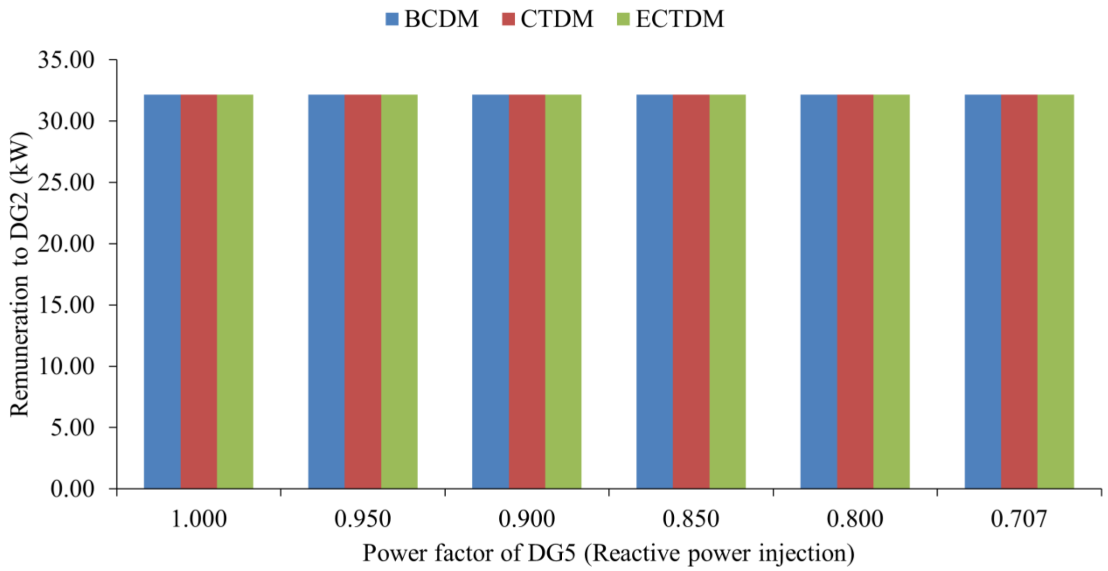


Group-C

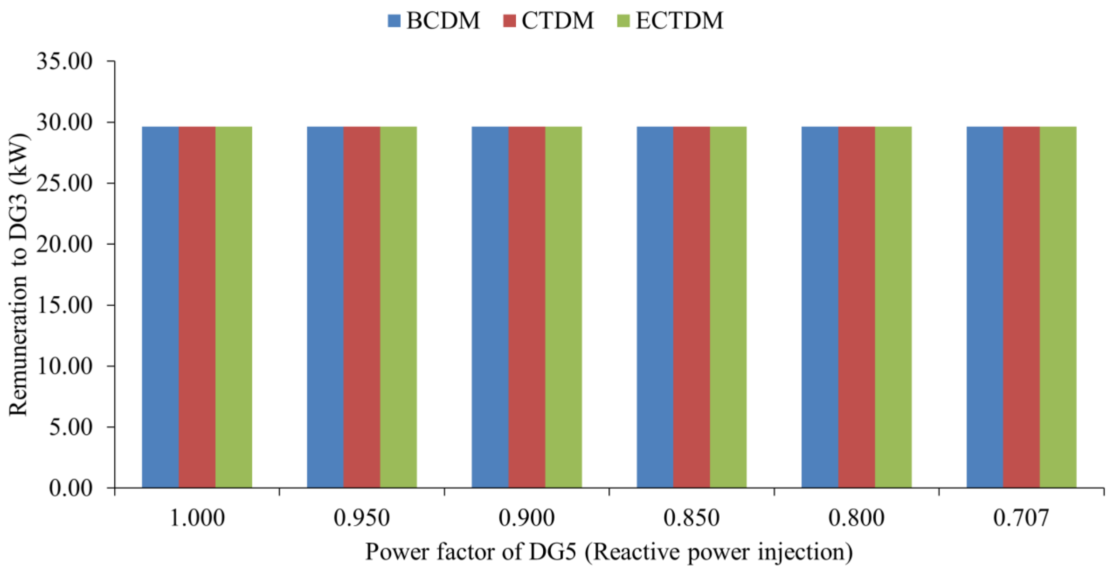
Fig. 6.4 Comparison of Percentage change in loss allocation for scenario 2



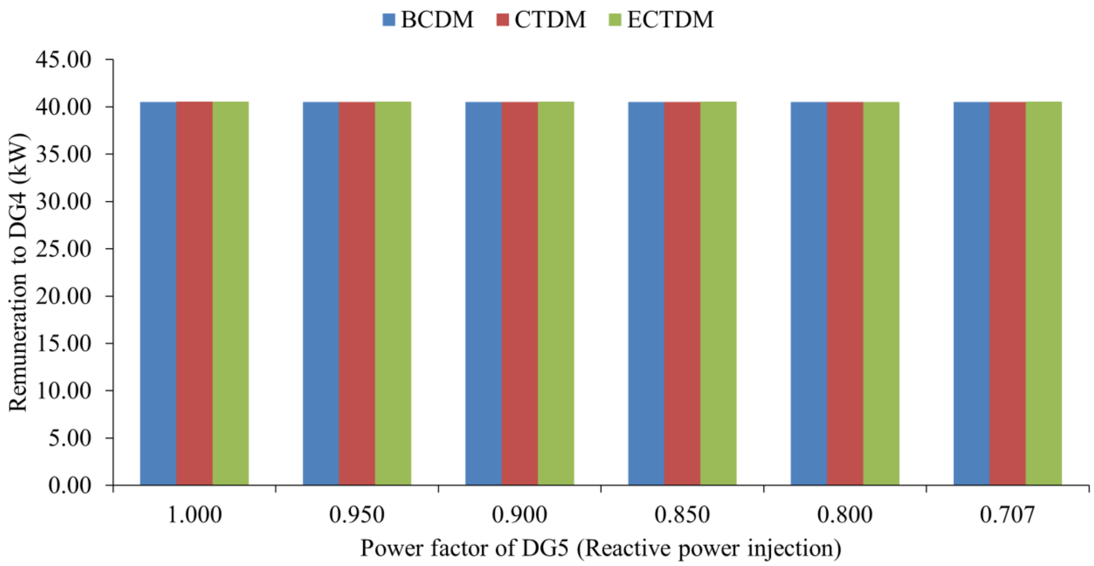
(a) Remuneration to DG1



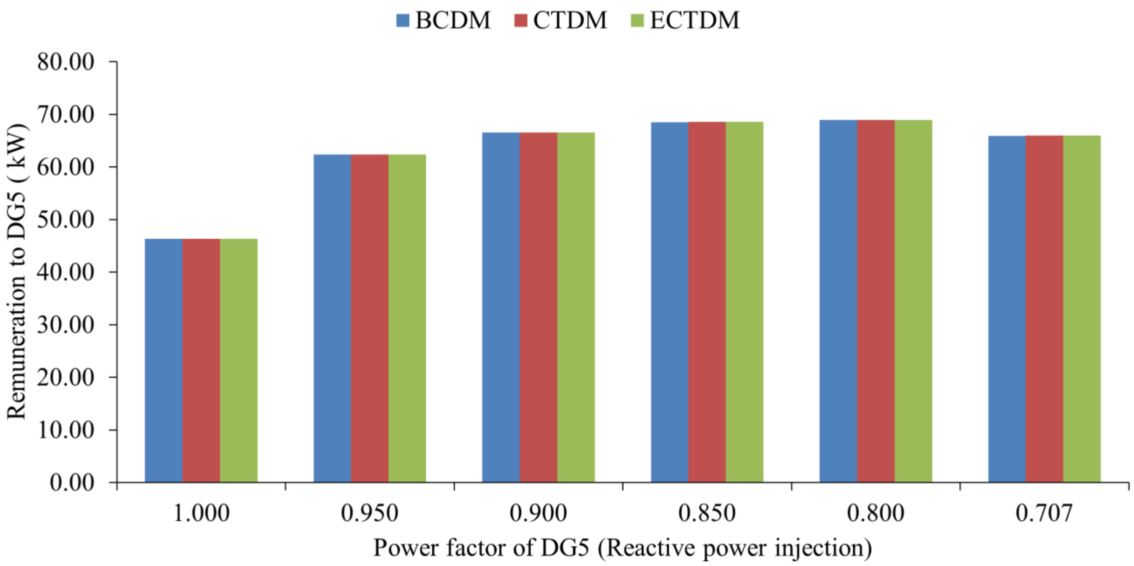
(b) Remuneration to DG2



(c) Remuneration to DG3



(d) Remuneration to DG4



(e) Remuneration to DG5

Fig. 6.5 Remuneration allocation to DGOs with variation in reactive power injection from DG5

From the abovementioned comparison it can be observed that all proposed methods are doing well, but it is ECTDM that has shown slightly better performance over BCDM and CTDM. It happen since ECTDM separately deals with the losses being contributed by active and reactive component of nodal injections.

CONCLUSIONS

Based upon the work presented in the thesis following conclusions may be drawn:

1. The proposed Branch Current Decomposition method (BCDM) provides comparable results with other existing methods [4, 5, 7, 15, 16] for loss allocation in passive distribution systems except at certain nodes where power factor is exceptionally poor. The proposed method penalizes the customer having poor power factor.
2. The power factor of loads is an important contributor in net loss of the distribution system. The effect of load power factors on LA has been investigated and comparison is also carried out with other established method. It has been found that Exact method [4] is showing inconsistency against the variation in load power factors. The BCDLA method [7] and proposed methods are sensitive to power factor of loads. They both penalize the consumers with poor power factor and incentivize the consumers with improved power factor. However, the penalties or incentives are more severe in proposed BCDM.
3. In active distribution systems with DGs, the proposed Branch Current Decomposition method (BCDM) provides different results than the existing methods. In others methods the remuneration to DGs are different with varying degree of incentives to DGs. However, in all other methods, the loss allocations to consumers get reduced though they have no contribution in loss reduction. It happened because incentives of DGs are partially diverted toward the LA of loads. Thus, DGOs will receive less remuneration and consequently loads will be allocated less losses. This cannot be said judicious allocation as DGOs will suffer whereas, consumers will get undue rebates against the loss reduction. However, in proposed method, the LAs of consumers are not affected by the presence of DGs. The proposed BCDM duly incentivise the DG operators (DGOs). The effect of DGs power factor on LA has also been investigated. It is found that proposed method provides comparatively more incentives to DGs having higher reactive power injections, which seems to be justified and realistic. This shows the proposed BCDM is more logical for active distribution systems as compared to other existing methods.

4. The network reconfiguration is an effort of distribution network operators (DNO) which also cause reduction of network loss. In the proposed LAS the DNO are duly compensated for their efforts in network loss reduction without affecting the loss allocation to consumers and DGOs.
5. The proposed cross-term decomposition method (CTDM) adopted a different approach in devising loss allocation. This method decomposes the crossed-terms of branch power loss using analytically derived loss allocation factor (LAF). Moreover, the decomposition of crossed-terms pertaining to remuneration allocated to DGOs is suggested using Superposition on injected currents from each individual. Application results of the proposed CTDM are nearly similar to those obtained by BCDM under identical conditions.
6. The proposed Exact crossed-term decomposition method (ECTDM) bifurcates crossed-terms associated with real and imaginary components of the currents by suggesting two different LAFs. Moreover, the proposed method is applicable to both passive as well as to active distribution systems. The LAFs suggested for both loads and DGs are derived analytically for both the components of the currents unlike CTDM. Application results of the proposed ECTDM are nearly similar to those obtained by BCDM and CTDM under identical conditions.
7. Comparative study of all the developed methods shows that ECTDM perform slightly better than BCDM and CTDM. The ECTDM penalizes the customer having poor PF and rewards the customer having improved PF with comparatively least effect on the loss allocation to other customer. Perhaps the better performance of ECTDM is on account of the fact that ECTDM separately deals with the losses contributed by active and reactive components of nodal injections.
8. All the proposed loss allocation methods are found to be comparable with existing established methods in passive distribution system. Though some of the existing methods are inconsistent with regards to variation of power factor. In active distribution systems with network reconfiguration facility, the combined effect of loss allocation method and LAS provides substantially better results than the existing methods as the developed methods provides due incentives to DGO and DNO without affecting the loss allocation to consumers.
9. The accuracy and performance of all proposed LA methods are more pronounced in large distribution systems.

SALIENT CONTRIBUTIONS

Salient contributions of the thesis may be summarized as below.

1. Developed a new Branch Current Decomposition method (BCDM) for loss allocation in distribution systems by suggesting separate virtual branch drops for allocating losses to loads and DG units.
2. Developed a new Cross-Term Decomposition method (CTDM) for loss allocation in distribution systems by introducing a loss allocation factors to allocate crossed-terms of losses.
3. Developed a new Exact Cross-Term Decomposition method (ECTDM) for loss allocation in distribution systems by bifurcating contributions of active and reactive power transactions from the end users and introducing separate LAFs for active and reactive components
4. Proposed a judicious and more realistic LAS to remunerate/penalize DGOs and DNO without affecting the loss allocation to consumers.

FUTURE RESEARCH SCOPE

In present work, the loss allocation methods are developed for fair allocation among different stake holders such as customers, DGOs and DNO while considering integration of DGs. In future extension of the present work the effect of congestion on loss allocation may be investigated. Future distribution systems would be equipped with battery energy storage systems (BESSs) for better management of power flows in distribution systems. Moreover, electric vehicles (EVs) may also become key assets of future distribution systems to participate in demand response. In future extension of the present work EV owners or BESS owners may also be included as stake holder in loss allocation and therefore their effect may be investigated while allocating incentives to customers participating in demand response programmes.

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APPENDIX A

The single-line diagrams, line and bus data of and other relevant data of various test distribution systems considered for simulation of different techniques throughout this thesis are given in this appendix.

1. 33-Bus Standard Test Distribution System

This test distribution system and its data are referred from [50]. It is a 12.66 kV distribution system with 32 sectionalizing switches and 5 tie-switches. The nominal active and reactive loadings are 3,715 kW and 2,300 kVAr respectively.

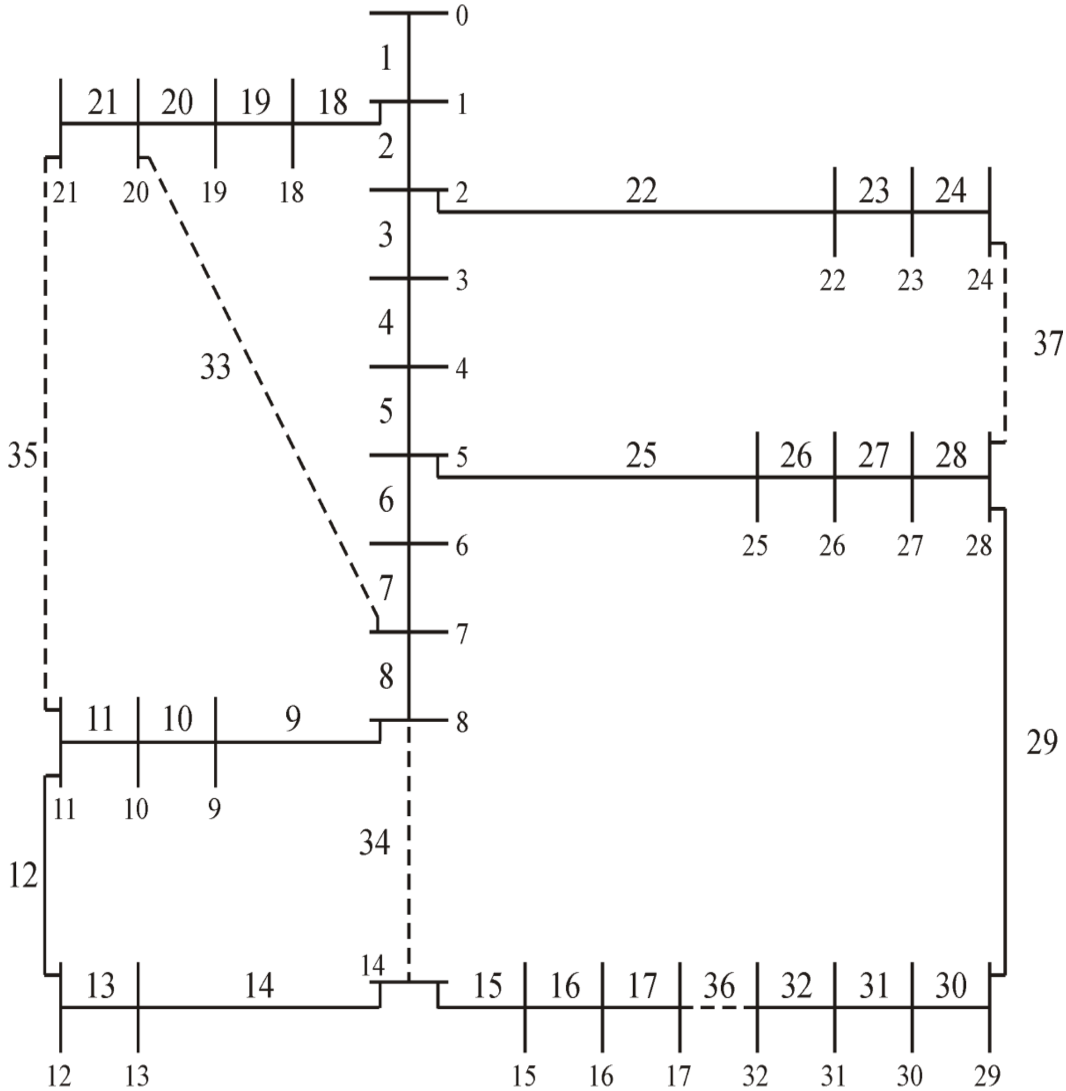

Fig. A.1. Single line diagram of 33-bus system

TABLE A.1 BUS DATA OF 33-BUS SYSTEM

Bus number	Load		Bus number	Load	
	Active load (kW)	Reactive load (kVAr)		Active load (kW)	Reactive load (kVAr)
1	0.00	0.00	18	90.00	40.00
2	100.00	60.00	19	90.00	40.00
3	90.00	40.00	20	90.00	40.00
4	120.00	80.00	21	90.00	40.00
5	60.00	30.00	22	90.00	40.00
6	60.00	20.00	23	90.00	50.00
7	200.00	100.00	24	420.00	200.00
8	200.00	100.00	25	420.00	200.00
9	60.00	20.00	26	60.00	25.00
10	60.00	20.00	27	60.00	25.00
11	45.00	30.00	28	60.00	20.00
12	60.00	35.00	29	120.00	70.00
13	60.00	35.00	30	200.00	600.00
14	120.00	80.00	31	150.00	70.00
15	60.00	10.00	32	210.00	100.00
16	60.00	20.00	33	60.00	40.00
17	60.00	20.00			

TABLE A.2 LINE DATA OF 33-BUS SYSTEM

Line number	Bus from	Bus to	Line resistance (Ω)	Line reactance (Ω)	Ampacity (A)
1	1	2	0.0922	0.0470	400
2	2	3	0.4930	0.2512	400
3	3	4	0.3661	0.1864	250
4	4	5	0.3811	0.1941	250
5	5	6	0.8190	0.7070	250
6	6	7	0.1872	0.6188	150
7	7	8	0.7115	0.2351	150
8	8	9	1.0299	0.7400	150
9	9	10	1.0440	0.7400	150
10	10	11	0.1967	0.0651	150
11	11	12	0.3744	0.1298	150
12	12	13	1.4680	1.1549	150
13	13	14	0.5416	0.7129	150
14	14	15	0.5909	0.5260	150
15	15	16	0.7462	0.5449	150
16	16	17	1.2889	1.7210	150
17	17	18	0.7320	0.5739	150
18	2	19	0.1640	0.1565	250
19	19	20	1.5042	1.3555	250

Continued …

TABLE A.2 (Continued …)
LINE DATA OF 33-BUS SYSTEM

Line number	Bus from	Bus to	Line resistance (Ω)	Line reactance (Ω)	Ampacity (A)
20	20	21	0.4095	0.4784	250
21	21	22	0.7089	0.9373	150
22	3	23	0.4512	0.3084	250
23	23	24	0.8980	0.7091	250
24	24	25	0.8959	0.7071	250
25	6	26	0.2031	0.1034	250
26	26	27	0.2842	0.1447	250
27	27	28	1.0589	0.9338	250
28	28	29	0.8043	0.7006	250
29	29	30	0.5074	0.2585	250
30	30	31	0.9745	0.9629	150
31	31	32	0.3105	0.3619	150
32	32	33	0.3411	0.5302	150
33	8	21	2.0000	2.0000	150
35	9	15	2.0000	2.0000	150
35	12	22	2.0000	2.0000	150
36	18	33	0.5000	0.5000	150
37	25	29	0.5000	0.5000	150

2. 83-bus Practical Distribution System

It is an 11.4 kV practical distribution network of Taiwan Power Company [57]. The system consists of 11 feeders, 83 normally closed sectionalizing switches, and 13 normally open tie switches. The nominal active and reactive loadings are 28,350 kW and 20,700 kVAr respectively.

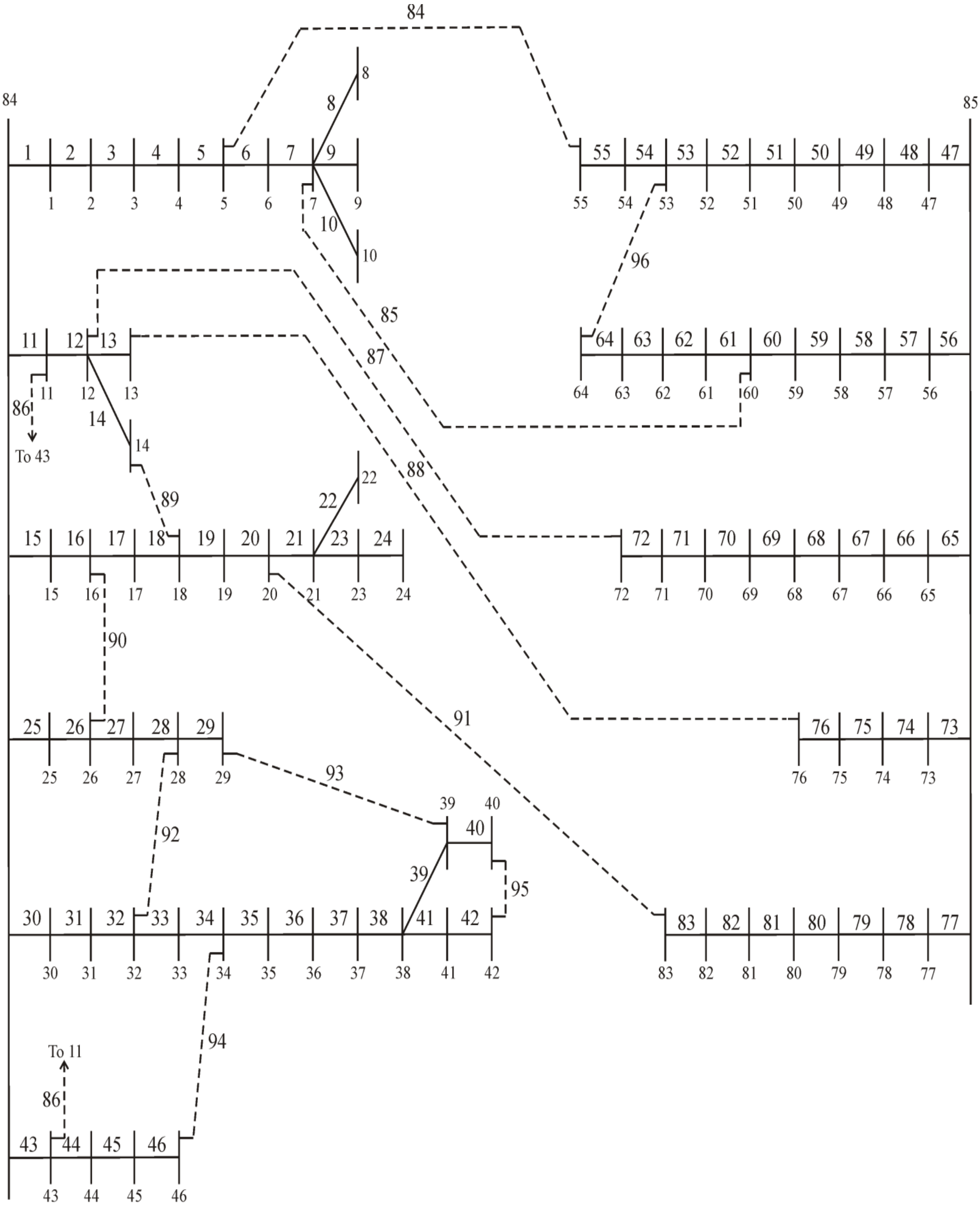

Fig. A.2. Single line diagram of 83-bus system

TABLE A.3 BUS DATA OF 83-BUS SYSTEM

Bus number	Load		Bus number	Load	
	Active load (kW)	Reactive load (kVAr)		Active load (kW)	Reactive load (kVAr)
1	0.00	0.00	44	30.00	20.00
2	100.00	50.00	45	800.00	700.00
3	300.00	200.00	46	200.00	150.00
4	350.00	250.00	47	0.00	0.00
5	220.00	100.00	48	0.00	0.00
6	1100.00	800.00	49	0.00	0.00
7	400.00	320.00	50	200.00	160.00
8	300.00	200.00	51	800.00	600.00
9	300.00	230.00	52	500.00	300.00
10	300.00	260.00	53	500.00	350.00
11	0.00	0.00	54	500.00	300.00
12	1200.00	800.00	55	200.00	80.00
13	800.00	600.00	56	0.00	0.00
14	700.00	500.00	57	30.00	20.00
15	0.00	0.00	58	600.00	420.00
16	300.00	150.00	59	0.00	0.00
17	500.00	350.00	60	20.00	10.00
18	700.00	400.00	61	20.00	10.00
19	1200.00	1000.00	62	200.00	130.00
20	300.00	300.00	63	300.00	240.00
21	400.00	350.00	64	300.00	200.00
22	50.00	20.00	65	0.00	0.00
23	50.00	20.00	66	50.00	30.00
24	50.00	10.00	67	0.00	0.00
25	50.00	30.00	68	400.00	360.00
26	100.00	60.00	69	0.00	0.00
27	100.00	70.00	70	0.00	0.00
28	1800.00	1300.00	71	2000.00	1500.00
29	200.00	120.00	72	200.00	150.00
30	0.00	0.00	73	0.00	0.00
31	1800.00	1600.00	74	0.00	0.00
32	200.00	150.00	75	1200.00	950.00
33	200.00	100.00	76	300.00	180.00
34	800.00	600.00	77	0.00	0.00
35	100.00	60.00	78	400.00	360.00
36	100.00	60.00	79	2000.00	1300.00
37	20.00	10.00	80	200.00	140.00
38	20.00	10.00	81	500.00	360.00
39	20.00	10.00	82	100.00	30.00
40	20.00	10.00	83	400.00	360.00
41	200.00	160.00	84	0.00	0.00
42	50.00	30.00	85	0.00	0.00
43	0.00	0.00			

TABLE A.4 LINE DATA OF 83-BUS SYSTEM

Line number	Bus from	Bus to	Line resistance (Ω)	Line reactance (Ω)	Ampacity (A)
1	84	1	0.1944	0.6624	500
2	1	2	0.2096	0.4304	500
3	2	3	0.2358	0.4842	500
4	3	4	0.0917	0.1883	500
5	4	5	0.2096	0.4304	500
6	5	6	0.0393	0.0807	500
7	6	7	0.0405	0.1380	250
8	7	8	0.1048	0.2152	250
9	7	9	0.2358	0.4842	250
10	7	10	0.1048	0.2152	250
11	84	11	0.0786	0.1614	500
12	11	12	0.3406	0.6944	500
13	12	13	0.0262	0.0538	250
14	12	14	0.0786	0.1614	250
15	84	15	0.1134	0.3864	500
16	15	16	0.0524	0.1076	500
17	16	17	0.0524	0.1076	500
18	17	18	0.1572	0.3228	500
19	18	19	0.0393	0.0807	500
20	19	20	0.1703	0.3497	250
21	20	21	0.2358	0.4842	250
22	21	22	0.1572	0.3228	250
23	21	23	0.1965	0.4035	250
24	23	24	0.1310	0.2690	250
25	84	25	0.0567	0.1932	500
26	25	26	0.1048	0.2152	500
27	26	27	0.2489	0.5111	500
28	27	28	0.0486	0.1656	500
29	28	29	0.1310	0.2690	250
30	84	30	0.1965	0.3960	500
31	30	31	0.1310	0.2690	500
32	31	32	0.1310	0.2690	250
33	32	33	0.0262	0.0538	250
34	33	34	0.1703	0.3497	250
35	34	35	0.0524	0.1076	250
36	35	36	0.4978	1.0222	250
37	36	37	0.0393	0.0807	250
38	37	38	0.0393	0.0807	250
39	38	39	0.0786	0.1614	250
40	39	40	0.2096	0.4304	250
41	38	41	0.1965	0.4035	250
42	41	42	0.2096	0.4304	250

Continued …

TABLE A.4 LINE DATA OF 83-BUS SYSTEM (Continued …)

Line number	Bus from	Bus to	Line resistance (Ω)	Line reactance (Ω)	Ampacity (A)
43	84	43	0.0486	0.1656	500
44	43	44	0.0393	0.0807	500
45	44	45	0.1310	0.2690	500
46	45	46	0.2358	0.4842	250
47	85	47	0.2430	0.8280	500
48	47	48	0.0655	0.1345	500
49	48	49	0.0655	0.1345	500
50	49	50	0.0393	0.0807	500
51	50	51	0.0786	0.1614	500
52	51	52	0.0393	0.0807	500
53	52	53	0.0786	0.1614	250
54	53	54	0.0524	0.1076	250
55	54	55	0.1310	0.2690	250
56	85	56	0.2268	0.7728	500
57	56	57	0.5371	1.1029	500
58	57	58	0.0524	0.1076	500
59	58	59	0.0405	0.1380	250
60	59	60	0.0393	0.0807	250
61	60	61	0.0262	0.0538	250
62	61	62	0.1048	0.2152	250
63	62	63	0.2358	0.4842	250
64	63	64	0.0243	0.0828	250
65	85	65	0.0486	0.1656	500
66	65	66	0.1703	0.3497	500
67	66	67	0.1215	0.4140	500
68	67	68	0.2187	0.7452	500
69	68	69	0.0486	0.1656	500
70	69	70	0.0729	0.2484	500
71	70	71	0.0567	0.1932	500
72	71	72	0.0262	0.0528	250
73	85	73	0.3240	1.1040	500
74	73	74	0.0324	0.1104	500
75	74	75	0.0567	0.1932	500
76	75	76	0.0486	0.1656	250
77	85	77	0.2511	0.8556	500
78	77	78	0.1296	0.4416	500
79	78	79	0.0486	0.1656	500
80	79	80	0.1310	0.2640	250
81	80	81	0.1310	0.2640	250
82	81	82	0.0917	0.1883	250
83	82	83	0.3144	0.6456	250
84	5	55	0.1310	0.2690	250

Continued …

TABLE A.4 LINE DATA OF 83-BUS SYSTEM (Continued …)

Line number	Bus from	Bus to	Line resistance (Ω)	Line reactance (Ω)	Ampacity (A)
85	7	60	0.1310	0.2690	250
86	11	43	0.1310	0.2690	250
87	12	72	0.3406	0.6994	250
88	13	76	0.4585	0.9415	250
89	14	18	0.5371	1.0824	250
90	16	26	0.0917	0.1883	250
91	20	83	0.0786	0.1614	250
92	28	32	0.0524	0.1076	250
93	29	39	0.0786	0.1614	250
94	34	46	0.0262	0.0538	250
95	40	42	0.1965	0.4035	250
96	53	64	0.0393	0.0807	250

PUBLICATIONS

Following papers have been published /accepted out of this thesis work.

List of Publications

1. Pankaj Kumar, N. Gupta, K. R. Niazi and A. Swarnkar, "Branch current decomposition method for loss allocation in contemporary distribution systems," ***International Journal of Electrical Power & Energy systems***, *Elsevier*, 2018, vol. 99, pp. 134-145, doi: 10.1016/j.ijepes.2018.01.004
2. Pankaj Kumar, N. Gupta, K. R. Niazi and A. Swarnkar, "Current decomposition method for loss allocation in distribution systems," ***IET Generation, Transmission & Distribution***, 2017, 11, (18), pp. 4599-4607, doi: 10.1049/iet-gtd.2017.1088
3. Pankaj Kumar, N. Gupta, K. R. Niazi and A. Swarnkar, "A Circuit Theory-based Loss Allocation Method for Active Distribution Systems," ***IEEE Transactions on Smart Grid***, 2019, vol. 10, (1), pp. 1005-1012. doi: 10.1109/TSG.2017.2757059
4. Pankaj Kumar, N. Gupta, K. R. Niazi and A. Swarnkar, "Cross-term decomposition method for loss allocation in distribution systems considering load power factor," ***Electric Power Components & Systems Journal, Taylor & Francis***, 2018, vol. 46, (2), pp. 218-229, doi: 10.1080/15325008.2018.1434840
5. Pankaj Kumar, N. Gupta, K. R. Niazi and A. Swarnkar, "Exact Cross-Term Decomposition Method for Loss Allocation in Contemporary Distribution Systems,"***Arabian Journal for Science and Engineering, Springer***, 2019, vol. 44, (3), pp. 1977-1988, doi: 10.1007/s13369-018-3230-2