# A Comprehensive Transmission Cost Allocation by Composite MW-mile & Composite MVA-mile Methods with Efficient ARR

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*Abstract*— **This paper proposes, comprehensive Transmission Cost Allocation (TCA) by Composite MW-mile & Composite MVA-mile methods with efficient revenue reconciliation. Both the users of transmission network (generator and load) are made accountable to pay transmission charges since both of them are equally benefited in sharing the transmission network. This is the exclusive identity of the work presented. The major work contribution includes, TCA to both the users in proportional to their share in network utilization (in penetration and withdrawal of both active and reactive power). Any independent method may fair way of allocating the cost but unfair to efficient Annual Revenue Reconciliation (ARR). The composite MW-mile and composite MVA-mile methods are suggested in this work to give 100% ARR. An AC power flow analysis is used in proposed composite MVA-mile method. Flexible Postage Stamp (POS) component of TCA is suggested for unremunerated revenue reconciliation with MW-mile or MVA-mile. The simulation results are obtained by for standard six bus system for different cases of line utilization. Comparative analysis of results obtained by proposed methods with existing have been carried out to support the findings.**

***Keywords—ARR, Composite MW-mile, Composite MVA-mile, Embedded cost, Transmission Cost.***

## I. INTRODUCTION

A key feature of an open access of transmission network is the needed to charge all the users of the transmission network on non-discriminatory basis for transmission services cost is theme of this paper. Various cost of transmission transaction are discussed in [1] such as operating, cost opportunity cost, embedded cost and reinforcement cost. In [2] the various Transmission Cost Allocation (TCA) paradigms are illustrated with examples. Postage Stamp (POS) and MW-mile methods are introduced in [3].

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An analytical method is developed in [4] to determine wheeling cost of transaction at buses with sensitivity index to determine relation between incremental line flows. The algorithms for transmission usage evaluation and alternative transmission pricing strategies are discussed with examples in [5]. The MW-mile approach with justified distribution factor for power flow tracing is purposed in [6]. The descriptions and summaries of computational procedures, and data requirements for embedded cost based TCA methods are discussed in [7]. The cost for usage of an individual transmission asset splits into a locational component and non-locational components [8]. Load flow based MW-mile and MVA-mile methods are discussed in [9]. TCA method proposed in [10] is designed with two functions of each circuit: the power flow between two points and assurance of system reliability. The power factor coefficient in calculating the cost for the transmission services based on reference power factors is incorporated with the MW-Mile method in [11]. An embedded cost based power flow method, needs special importance in design of TCA with complete recovery of cost over life time of transmission network [12]-[13]. Basic objectives of TCA are discussed in [14] in an open access of transmission network with TCA paradigms. The enactment of electricity act in [15] laid down the guidelines for TCA. An assessment of embedded cost is carried out for transmission network expansion in [16]. MW-method of evaluation of TCA is discussed in [17]. Two elements of TCA, location-ally derived by using the reverse MW-mile and POS approach based on per kW are used to recover the total transmission cost [18]. MW-mile and MVA-mile methods in [19], [20] are applied on Indian power utility to evaluate its effectiveness in providing fair transmission charges to load users. The MW-mile component includes active power for allocation of TCA without line losses [21]. An overview has been taken of different costs incurred in transmission transaction in [22]. The MVA-mile method of TCA is based on supplement cost using the components of transmission complex powers [23].

As per the method explained in most recent paper [11] the users are only being charged when the load power factor is below the reference power factor set by the utilities (e.g., penalty charge for load power factor less than 0.9) without considering the change of MW flow of the system. This paper introduces a power factor coefficient in calculating the cost for the transmission services based on reference power factors incorporated with the MW-mile method.

Based on these arguments in literature all the methods studied on embedded cost are allocating Transmission Cost (TC) to load users only. Again any independent method may a fair way of allocating the cost but unfair to give efficient ARR. In the deregulated power system, it is essential to implement a method that is fair to both the generator and load users in determining the cost of transmission usage. Power flow based MW-mile and MVA-mile methods of TCA are used for fair TCA. The TCA by MW-mile method may give insufficient Annual Revenue Reconciliation (ARR). MVA-mile method includes the cost of reactive power flow in TCA. Both the transmission network users (generator & load) are equally responsible to pay for actual used and unused capacities of the network. Hence this his paper is focusing on objectives such as unbiased TCA to the users of network (load and generators), sensitive TCA to users with line utilization, impact of active and reactive power flow on TCA with efficient ARR. Any independent method may unfair to efficient ARR. The composite MW-mile and composite MVA-mile methods are presented in this work.

This paper is organized as follows; Introduction in section I followed by formulation of composite MW-mile method of TCA in section II. The formulation of composite MVA-mile method of TCA and is mentioned in section III. The simulation results obtained with typical six bus transmission networks put in section IV. Section V concludes the paper.

## II. Composite Mw-mile Method

In this section the mathematical modelling of proposed composite MW-mile method of TCA is discussed in stepwise.

### A. Embedded Cost and ARR

Embedded cost is capital cost or investment on existing transmission facilities. ARR is evaluated as a payback amount per year for the prescribed duration. An embedded cost with chosen interest rate of its present value and payback period are used to determine ARR of the circuit. The embedded cost of the circuit is derived in $/ km for unit power transaction.

### B. Composite MW-mile Method

Composite MW-mile method as an improved MW-mile is suggested for TCA to both load and generator users. In this method the TCA is calculated in two parts: MW-mile component and concurrent POS components of TCA. In Composite MW-mile method DC power flow analysis is carried out in two steps. Initially for peak loaded and next for actual (current) loaded network. The direction of net power flow through circuit is analyzed as absolute, dominant and reverse variants of power flows. The maximum loading limit of any circuit is restricted to its base case power flow limit. The impact of a particular transaction made by individual generator on line flow is evaluated as MW flow through line by its independent operation to match the existing load while the other generators are set to their minimum or zero generation capacities. Similarly the impact of a particular transaction made by individual load on line flow is evaluated as MW flow through line by its own impact while the other loads are set to zero. The line flow obtained in such cases is treated as a new case flow. Net power flow through circuit is used for TCA evaluation is the difference between the base case and new case power flows. TCA to generator along with load user at '$k^{th}$' bus is mathematically formulated as below.

$$TC_{pgk}=\frac{1}{2}\sum_{i=1}^{m}\frac{L_i\cdot F_i\cdot \Delta P_{igk}}{\overline{P}_i} \quad \& \quad TC_{p\ell k}=\frac{1}{2}\sum_{i=1}^{m}\frac{L_i\cdot F_i\cdot \Delta P_{i\ell k}}{\overline{P}_i} \quad (1)$$

$TC_{pgk}$ and $TC_{p\ell k}$ are MW-mile components of TCA for generator and load users respectively, at '$k^{th}$' bus. $\Delta P_{igk}$ and $\Delta P_{i\ell k}$ are net MW flows imposed on the circuit *i,* by generator and load users respectively, while $\overline{P}_i$ is the rated MW capacity of the circuit *i.*

ARR is obtained for user at '$k^{th}$' bus is assessed by using TCA to generator and load users and total power transacted by each of them. The equation for ARR obtained is given below.

$$R_{pgk}=TC_{pgk}*P_{gk} \quad \& \quad R_{p\ell k}=TC_{p\ell k}*P_{\ell k} \quad (2)$$

$R_{pgk}$ and $R_{p\ell k}$ are ARR obtained for generator and load users. $P_{gk}$ and $P_{\ell k}$ are MW transacted by generator and load users at '$k^{th}$' bus.

Concurrent POS component of TCA is calculated to reconcile the unremunerated revenue. This is because the ARR obtained by MW-mile component is inefficient. The POS component of TCA to the generator along with load user at '$k^{th}$' bus for using the network in composite MW-mile method is formulated as below.

$$TC_{psgk} = \frac{\Delta UR_{pg} \cdot P_{gk}}{P_{tg}} \quad \& \quad TC_{ps\ell k} = \frac{\Delta UR_{p\ell} \cdot P_{\ell k}}{P_{t\ell}} \qquad (3)$$

$TC_{psgk}$ and $TC_{ps\ell k}$ are concurrent POS components of TCA to generator and users. $\Delta UR_{pg}$ and $\Delta UR_{p\ell}$ are unremunerated ARR obtained with the MW-mile component of TCA to generator and load users respectively. $P_{tg}$ and $P_{t\ell}$ are total MW transacted by generator and load users respectively.

ARR obtained for user at '$k^{th}$' bus is assessed by following equation with concurrent POS components of TCA to generator along with load users.

$$RP_{psgk} = TC_{psgk} * P_{gk} \quad \& \quad RP_{ps\ell k} = TC_{ps\ell k} * P_{\ell k} \qquad (4)$$

$RP_{psgk}$ and $RP_{ps\ell k}$ are ARR obtained from generator and load users respectively at '$k^{th}$' bus with concurrent POS components.

The new TCA to generator and load users at '$k^{th}$' bus by composite MW-method is formulated as below.

$$TC_{cpgk} = TC_{pgk} + TC_{psgk} \quad \& \quad TC_{cp\ell k} = TC_{p\ell k} + TC_{ps\ell k} \qquad (5)$$

$TC_{cpgk}$ and $TC_{cp\ell k}$ are new TCA to generator and load users respectively, at '$k^{th}$' bus by composite MW-mile method.

Total ARR calculated for generator and load users at '$k^{th}$' bus by Composite MW-mile method is given below.

$$R_{cpgk} = TC_{cpgk} * P_{gk} \quad \& \quad R_{cp\ell k} = TC_{cp\ell k} * P_{\ell k} \qquad (6)$$

$R_{cpgk}$ is total ARR obtained for generator users at '$k^{th}$' bus and $R_{cp\ell k}$ is total ARR obtained for load users at '$k^{th}$' bus with composite MW-mile method.

## III. Composite MVA-mile Method

Composite MVA-mile method as an improved MVA-mile method is suggested in this work with TCA to both users of the network. TCA in this method is also evaluated in two components so as reconcile total revenue based on embedded cost of the network. The composite MVA-mile method uses AC power flow analysis for determining the MVA flow in each circuit. The net MVA flow through circuit is evaluated for absolute, dominant and reverse variants of MVA flow. The two components of TCA include MVA-mile component and concurrent POS component. Initially the power flow analysis has been carried out at peak load (MVA) with equal generation. The power flow analysis in this step is treated as the base case MVA flow. The impact of a particular transaction made by individual generator on line flow is evaluated as MVA flow through line by its independent operation to match the existing load while the other generators are set to their minimum or zero generation capacities. Similarly the impact of a particular transaction made by individual load on line flow is evaluated as MVA flow through line by its own impact while the other loads are set to zero. The line flow obtained in such cases is treated as a new case flow. Net MVA flow through circuit is used for TCA evaluation is the difference between the base case and new case MVA flows. The MVA-mile components of TCA to generator and load users at '$k^{th}$' bus are mathematically formulated as below.

$$TC_{sgk} = \frac{1}{2}\sum_{i=1}^{m}\frac{L_i \cdot H_i \cdot \Delta S_{igk}}{\overline{S}_i} \quad \& \quad TC_{s\ell k} = \frac{1}{2}\sum_{i=1}^{m}\frac{L_i \cdot H_i \cdot \Delta S_{i\ell k}}{\overline{S}_i} \qquad (7)$$

$TC_{sgk}$ and $TC_{s\ell k}$ are the MVA-mile components of TCA to generator and load users respectively at '$k^{th}$' bus in \$/MVA. $\Delta S_{igk}$ and $\Delta S_{i\ell k}$ are the net MVA flows imposed on the circuit *i,* by generator addition and MVA withdrawal at '$k^{th}$' bus, while $\overline{S}_i$ is the rated MVA capacity of the circuit *i.*

ARR is obtained from user at '$k^{th}$' bus can be assessed by following equation with MVA-mile component of cost allocated to generator and load users.

$$R_{sgk} = TC_{sgk} * S_{gk} \quad \& \quad R_{s\ell k} = TC_{s\ell k} * S_{\ell k} \qquad (8)$$

$R_{sgk}$ and $R_{s\ell k}$ are ARR obtained from generator and load users respectively at '$k^{th}$' bus with MVA-mile component . The concurrent POS component of TCA is allocated to generator and load users along with composite MVA-mile component. This component of TCA to the load and generator users at '$k^{th}$' bus for using the network is formulated as below.

$$TC_{psgk} = \frac{\Delta UR_{sg} \cdot S_{gk}}{S_{tg}} \quad \& \quad TC_{ps\ell k} = \frac{\Delta UR_{s\ell} \cdot S_{\ell k}}{S_{t\ell}} \qquad (9)$$

$TC_{psgk}$ and $TS_{ps\ell k}$ are concurrent POS component of TCA to generator and load users at $k^{th}$ bus. $\Delta UR_{sg}$ and $\Delta UR_{s\ell}$ are unremunerated ARR obtained by MVA-mile components of TCA to generator and load users respectively. $S_{gk}$ and $S_{\ell k}$ are MVA transacted by generator and load users at '$k^{th}$' bus. $S_{tg}$ and $S_{t\ell}$ are total MVA transacted by generator and load users .

ARR is obtained for user at '$k^{th}$' bus can be assessed by following equation with concurrent POS component of TCA to generator and load users.

$$RS_{psgk} = TC_{psgk} * S_{gk} \quad \& \quad RS_{ps\ell k} = TC_{ps\ell k} * S_{\ell k} \qquad (10)$$

$RS_{psgk}$ and $RS_{ps\ell k}$ are ARR obtained from generator and load users at '$k^{th}$' bus with concurrent POS component.

The new TCA to generator and load users at $k^{th}$ bus by composite MVA-mile method is formulated below.

$$TC_{csgk} = TC_{sgk} + TC_{psgk} \quad \& \quad TC_{cs\ell k} = TC_{s\ell k} + TC_{ps\ell k} \qquad (11)$$

$TC_{csgk}$ and $TC_{cs\ell k}$ are TCA to generator and load users at '$k^{th}$' bus in composite MVA-mile method.

ARR obtained for generator and load users at '$k^{th}$' bus by composite MVA-mile method is formulated below.

$$R_{csgk}=TC_{csgk}*P_{gk} \quad \& \quad R_{cs\ell k}=TC_{cs\ell k}*P_{\ell k} \tag{12}$$

$R_{csgk}$ and $R_{cs\ell k}$ are ARR obtained from generator and load users at '$k^{th}$' bus by composite MVA-mile method.

## IV. Simulation And Results

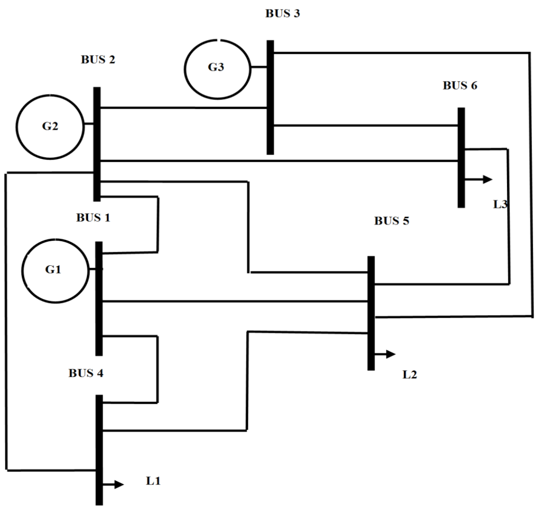



Figure1. Six Bus System

Fig.1 shows the single line diagram of a modified transmission network [12] used for simulation. The total length of transmission circuit is 940 km. The embedded cost of a 220 kV double circuit line is 4, 35,750 $ for one km run of the circuit [16]. The total ARR needed is equal to 41804363.64 $ for the span of 15 years with an annual interest rate of 6.9%.

TABLE I. TCA TO GENERATOR ALONG WITH LOAD USERS

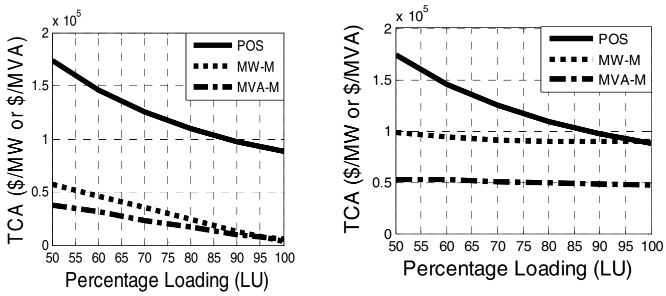
| Bus No. & User | Composite MW-mile Method ($/MW) | | | Composite MVA-mile Method ($/MVA) | | |
|---|---|---|---|---|---|---|
| | MW-mile Comp | POS Comp | New TCA | MVA-mile Comp | POS Comp | New TCA |
| For Absolute Variant | | | | | | |
| 1GU | 17054.98 | 41489.35 | 58544.33 | 9291.91 | 47831.08 | 57122.99 |
| 2GU | 17668.34 | 41489.35 | 59157.68 | 11520.10 | 47831.08 | 59351.18 |
| 3GU | 28195.25 | 41489.35 | 69684.59 | 16533.95 | 47831.08 | 64365.03 |
| 4LU | 45667.47 | 17991.50 | 63658.97 | 25107.71 | 36013.06 | 61120.76 |
| 5LU | 42835.11 | 17991.50 | 60826.61 | 26009.98 | 36013.06 | 62023.04 |
| 6LU | 44339.31 | 17991.50 | 62330.81 | 27510.37 | 36013.06 | 63523.43 |
| For Dominant Variant | | | | | | |
| 1GU | 12314.47 | 44060.63 | 56375.10 | 7877.53 | 49308.06 | 57185.59 |
| 2GU | 17083.86 | 44060.63 | 61144.49 | 11325.71 | 49308.06 | 60633.77 |
| 3GU | 26093.91 | 44060.63 | 70154.54 | 13783.35 | 49308.06 | 63091.40 |
| 4LU | 45667.47 | 20109.88 | 65777.35 | 22372.11 | 38194.33 | 60566.44 |
| 5LU | 38895.88 | 20109.88 | 59005.76 | 23438.12 | 38194.33 | 61632.45 |
| 6LU | 41223.13 | 20109.88 | 61333.01 | 26548.54 | 38194.33 | 64742.86 |
| For Reverse Variant | | | | | | |
| 1GU | 7573.95 | 46631.91 | 54205.86 | 6463.15 | 50785.04 | 57248.19 |
| 2GU | 16499.38 | 46631.91 | 63131.29 | 11131.32 | 50785.04 | 61916.36 |
| 3GU | 23992.57 | 46631.91 | 70624.48 | 11032.74 | 50785.04 | 61817.78 |
| 4LU | 45667.47 | 22228.26 | 67895.72 | 19636.52 | 40375.60 | 60012.11 |
| 5LU | 34956.64 | 22228.26 | 57184.90 | 20866.26 | 40375.60 | 61241.85 |
| 6LU | 38106.95 | 22228.26 | 60335.21 | 25586.70 | 40375.60 | 65962.30 |

Table I shows new TCA to Generator Users (GU) and Load Users (LU) by proposed composite MW-mile and composite MVA-mile methods along with its components. The new TCA is evaluated for absolute, dominant and reverse variants of MW as well as MVA flow for 70% network utilization.

TABLE II. ANNUAL REVENUE RECONCILIATION

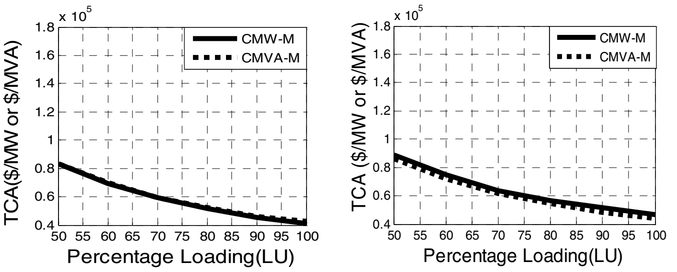
| Bus No. & User | Composite MW-mile Method ($/Year) | | | Composite MVA-mile Method ($/Year) | | |
|---|---|---|---|---|---|---|
| | MW-mile Comp | POS Comp | Total ARR | MVA-mile Comp | POS Comp | Total ARR |
| For Absolute Variant | | | | | | |
| 1GU | 2046598 | 4978722 | 7025320 | 1209964 | 6228413 | 7438377 |
| 2GU | 1855175 | 4356382 | 6211557 | 1210916 | 5027684 | 6238600 |
| 3GU | 3101477 | 4563828 | 7665305 | 1855995 | 5369209 | 7225204 |
| 4LU | 6165108 | 2428852 | 8593961 | 3406446 | 4886011 | 8292457 |
| 5LU | 4497687 | 1889107 | 6386794 | 2744669 | 3800231 | 6544900 |
| 6LU | 4212234 | 1709192 | 5921427 | 2626520 | 3438304 | 6064824 |
| Total | 21878279 | 19926084 | 41804364 | 13054511 | 28749853 | 41804364 |
| For Dominant Variant | | | | | | |
| 1GU | 1477736 | 5287275 | 6765012 | 1025788 | 6420741 | 7446529 |
| 2GU | 1793805 | 4626366 | 6420171 | 1190483 | 5182935 | 6373418 |
| 3GU | 2870330 | 4846669 | 7716999 | 1547230 | 5535005 | 7082235 |
| 4LU | 6165108 | 2714833 | 8879942 | 3035299 | 5181951 | 8217250 |
| 5LU | 4084067 | 2111537 | 6195604 | 2473277 | 4030406 | 6503683 |
| 6LU | 3916197 | 1910438 | 5826636 | 2534690 | 3646558 | 6181248 |
| Total | 20307244 | 21497120 | 41804364 | 11806767 | 29997597 | 41804364 |
| For Reverse Variant | | | | | | |
| 1GU | 908874 | 5595829 | 6504703 | 841612 | 6613069 | 7454680 |
| 2GU | 1732435 | 4896350 | 6628785 | 1170050 | 5338185 | 6508235 |
| 3GU | 2639183 | 5129510 | 7768693 | 1238465 | 5700802 | 6939266 |
| 4LU | 6165108 | 3000814 | 9165923 | 2664152 | 5477891 | 8142043 |
| 5LU | 3670448 | 2333967 | 6004415 | 2201885 | 4260582 | 6462467 |
| 6LU | 3620160 | 2111684 | 5731845 | 2442860 | 3854812 | 6297672 |
| Total | 18736209 | 23068155 | 41804364 | 10559023 | 31245341 | 41804364 |

Table II shows ARR obtained using the new TCA in table I, by proposed methods. The TCA to generator along with load users by proposed methods is found average. The TCA is improved compared to existing methods with reflection of all the essential parameters in the evaluation. Total revenue reconciliation by the composite MW-mile and composite MVA-mile methods for absolute, dominant and reverse variants of power flow are shown in columns 4 and 7 respectively. The total revenue reconciliation is divided into two parts. First part is revenue reconciliation by MW-mile or MVA-mile component and the second part is revenue reconciliation by concurrent POS component of TCA. Part wise ARR obtained by each component are presented in columns 2, 3 and 5, 6 for composite MW-mile and composite MVA-mile methods respectively.




(A) Generator User (B) Load User

Figure 2. TCA to Users by Existing POS, MW-Mile and MVA-Mile Methods




(A) Generator User (B) Load User

Figure 3. TCA to Users by Proposed Composite MW-Mile and Composite MVA-Mile Methods

Figs. 2 and 3 shows comparison of TCA to generator and load users by existing POS, MW-mile, MVA-mile and proposed composite Mw-mile, composite MVA-mile methods respectively. TCA is sensitive to change in MW or MVA flow through line. Generator users at bus 2 (part I of figs.2 and 3) and load users at bus 4 (part II of figs. 2 and 3) are allocated with TCA, which decreases with increase in line utilization for all absolute, dominant and reverse variants of power flow. Existing methods shows extremely wide variations in the magnitude of the TCA to users. The nature of the TCA curves is almost same, with higher value for the absolute variant and slightly reducing values for dominant and reverse.

The proposed composite MW-mile and composite MVA-mile methods are allocating minimum TCA to both the users sensitive to line MW or MVA flow. The TCA by proposed methods is having smooth nature. The TCA by composite MW-mile and composite MVA-mile methods are closer to each other hence both the methods are efficient in TCA allocation.

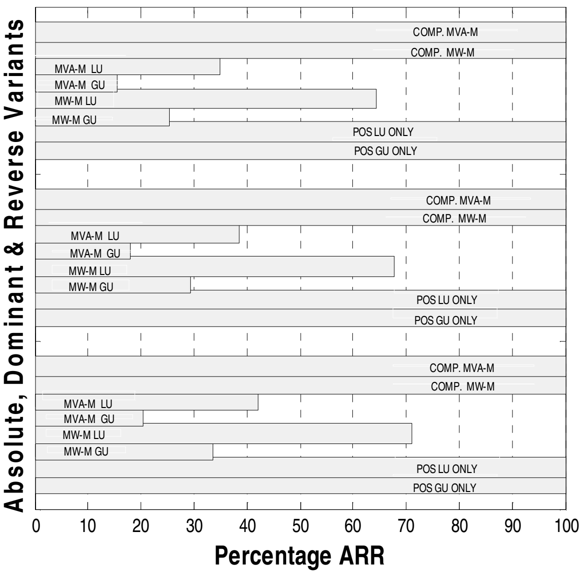



Fig: 4: Percentage ARR Obtained by Existing and Proposed Methods with Absolute, Dominant and Reverse Variants.

Fig. 4 shows the comparative analysis of percentage ARR obtained by TCA with existing and the proposed methods discussed in this work for absolute, dominant and reverse variants. This analysis in this work seeks to prove that many researches before this study worked out with load users for allocation of the network charges was inefficient. The TCA to generator along with load users is leading to reduce burden on load users. In the suggested method the MW-mile, MVA-mile and concurrent POS components with transmission network loading level gives total ARR which is efficient. For the absolute variant there is guarantee of entire revenue reconciliation while the reverse variant is leading to fair cost allocation (effect of counter flow). The revenue reconciliation by TCA to generator along with load users by proposed methods leads is 100%.

## V. Conclusion

The work presented in this paper includes comprehensive analysis of composite MW-mile and composite MVA-mile methods of cost allocation with improvement in existing postage stamp, MW-mile and MVA-mile methods. The proposed composite MW-mile and composite MVA-mile method allocates cost to both the beneficiaries (generator as well as load) of the transmission network. The cost allocation by proposed composite MW-mile and MVA-mile methods calculated with two components: MW-mile, MVA-mile components and concurrent POS component. An analysis of cost allocated by proposed methods shows that the values of the TCA to users are not only reasonable and moderate but also leading to contribute the 100% revenue reconciliation. The proposed TCA is providing the financial security to the transmission network owner by giving guarantee of revenue reconciliation. The analysis of the TCA shows that the absolute variant of power flow is giving highest value compared to the dominant and reverse. The reverse variant of power flow used is showing reduction in the net power flow through the line. This work seeks to prove that the TCA to generator along with the load users by proposed composite methods is competent enough, economically fair and practicable. The proposed methods are better options for TCA to users of transmission network than the existing methods in open accesses of transmission network. These methods may help in enhancing the transmission facilities with efficient ARR, and may relocate the big load consumers in the network to a point at which lower TCA is, to reduce the transmission cost of the power to be transacted.

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