New Calculation Method for Power Loss Allocation in Radial Distribution Networks Without Dispersed Generation

Ljupco Trpezanovski[1], Metodija Atanasovski[2] and Tomce Mijovski[3]

Abstract – **In this paper is presented a new method for calculation the power loss allocation caused by electricity consumers in radial distribution network, without dispersed generation. The method is based on the application of network load-flow calculation results. With known voltage drop and current decomposition of each branch a simple procedure for calculation the complex power losses in the branches is applied. The power loss allocation analyze is conducted on an example of radial network with the proposed new method and other two known methods.**

Keywords – **Radial distribution network, power loss allocation, methods for loss allocation.**

I. Introduction

In the past two decades a lot of countries performed technical and economic restructuring in their power systems (PS) management. These changes in governing, exploitation and planning of the PS development from technical and economic aspects are known as deregulation in the PS. Nowadays, deregulation enables open market and trading on concurrent base in electricity production and delivery. With implementation of deregulation and market economy the processes for electricity production, transmission and distribution are divided in several, separate independent companies. Each of the participants on the electricity market, as are electricity: producers, consumers, transmission and distribution operators, in certain way participate in creating and covering the costs for the power and energy losses. Deregulation of electricity sector and application of market economy in the management of electricity, actualize the need for calculation the loss allocation and costs covering for energy losses during the energy transmission and distribution. It is a difficult problem to make right and fair allocation of the costs for losses covering, among the all participants in the electricity market. For solving of this problem, significant attention should be pay on defining algorithms and methods which fulfil several conditions. Some of the principals for defining methods for loss allocation [1] are recalled and stressed in the paper. A loss allocation technique should be:

− easy to understand and based on real data of the network;
− carefully designed to avoid discrimination between user;
− able to recover the total amount of the losses;
− consistent with the rules of competitive electricity markets;
− economically efficient, avoiding cross-subsidization between users;
− able to send out economic signals aimed at increasing the efficiency of the network;
− able to provide correct signals concerning the size and location of loads;
− applicable to different situation, e.g. following the time evolution of the generator and load patterns.

Therefore in the past few years several methods for calculation of loss allocation in the networks caused by electricity producers and consumers are reported in the relevant literature. These methods can be divided according two criterions. The first one is according to the type of the network and the methods can be for transmission or distribution networks. The second one is according of the approach on the problem for loss allocation and the methods can be with marginal, average and actually approach.

In this paper a new method for power loss allocation caused only by the loads is presented. This method is with actual approach and is concern for radial distribution networks (RDN) without dispersed generation (DG) sources (explained in section II). The technique of the proposed method is based on the results of the load-flow calculation given in section III. Because during the calculations are used voltage drops and decomposition of the currents in the network branches, the method proposed in sections IV and V, is named as *Voltage Drop Current Decomposition Power Loss Allocation* (ΔUCDPLA). The loss allocation is calculated for a real RDN without DG with the proposed new method and two other methods reported in [4] and [5]. In the section VI, the results of the conducted analysis are compared and shown in table. The conclusions are drawn in the section VII.

II. Radial Distribution Network Properties and Modelling

For easier understanding and defining the algorithm of the proposed new method for power loss allocation, all line (branch) capacitances are neglected. Thus, overhead and cable RDN lines are presented only with serial impedances. One line diagram of the part with n branches and (n+1) nodes of middle voltage (MV) level RDN is shown on Fig. 1. The node marked with index 0 is with known voltage magnitude, held on constant value U_0 with HV/MV transformer regulation.

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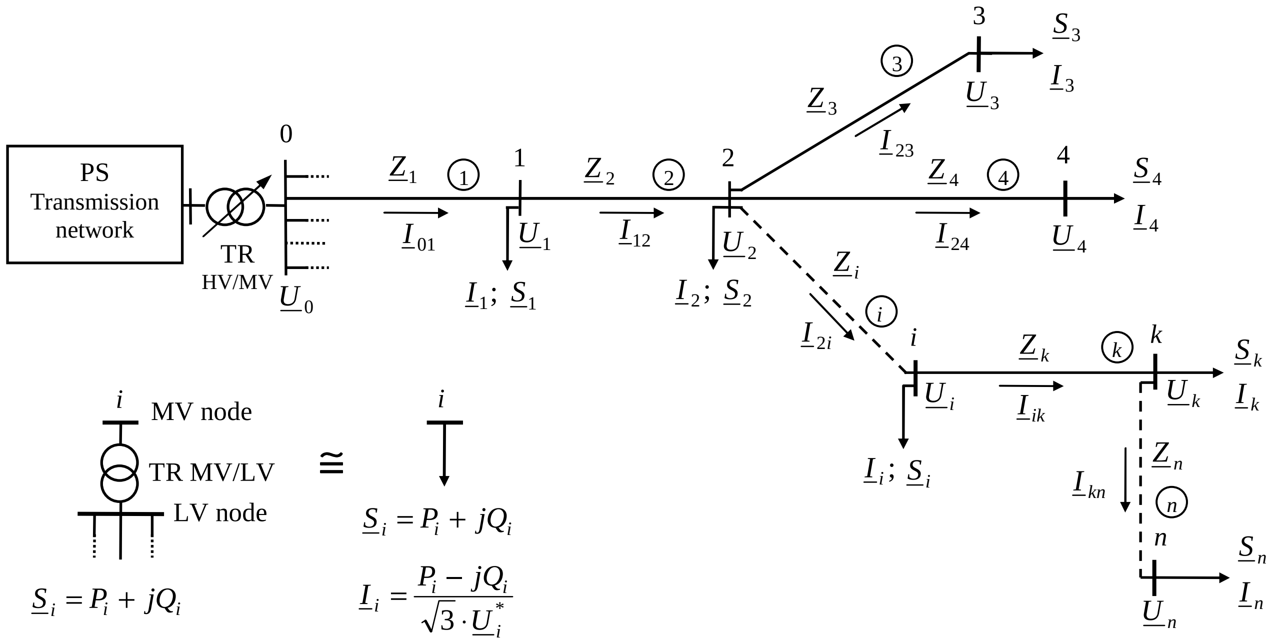

Fig. 1. One line diagram of MV radial distribution network without distributed generation.

Phase angle of this voltage is taken 0^0 and it will be a reference angle for the phase angles of the voltages in the rest *n* nodes of the network. Ordering of nodes and branches indexes is according to the rule of oriented ordering [2]. The nodes are indexed with numbers from 0 to *n*. The indexes of the branches are marked with circled numbers from 1 to *n*. Voltage, active and reactive power and current of the load connected in any node, have the same index as the index of the corresponding node. Because the RDN is without DG the directions of the branch currents are uniformly ordered from the node 0 to the loads in other nodes. The branch currents are signed with indexes of two numbers. The first number is equal with the node index where the current enters in the branch (branch beginning node). The second number is equal with the node index where current exits from branch (branch end node), which is the same number of the branch index.

Actually, the loads are connected on the low-voltage (LV) sides on the distribution transformers which MV sides are connected in one of the RDN nodes. If the losses in the distribution MV/LV transformers are neglected it is allowed to consider that the loads are directly connected on the MV nodes. This approximation and way of loads connection on the RDN are shown in the left bottom part on Fig. 1.

The following quantities are known for the network from Fig. 1:

- voltage in the MV node 0 in the substation: $\underline{U}_0 = U_0 \angle 0^0$;
- serial branch impedances: $\underline{Z}_g = R_g + jX_g$, *g*=1, 2,….., *n*;
- apparent power of the loads: $\underline{S}_i = P_i + jQ_i$, *i*=1, 2,….., *n*.

If there are no loads in some nodes that nodes can be treated as the nodes with connected loads with zero power.

For each node *i* (*i*=1, 2, ..., *n*) there is a set of branches $\{G_{0i}\}$ forming the path through which starting from the node 0, the node *i* can be reached. Through the branch *g* (*g*=1, 2, ..., *n*) flow the current of the load connected at the branch end node *i* (according to oriented ordering *i*=*g*) and currents of the loads connected in the nodes with index *i* >*g* which can be reached on forward direction through the branch *g*. The set of these nodes for the branch *g* is signed as $\{J_{gi}\}$.

III. LOAD-FLOW CALCULATION FOR RDN

The proposed method for power loss allocation is based on the load-flow calculation results. For a working scenario with known values of the branch serial impedances and load powers, taking into account that the voltage U_0 is also known, a load-flow calculation can be conducted for RDN. As a very proper load-flow method for radial networks is taken *Current Summation Method* (CSM) [3]. This is an iterative method based on multi-calculations "forward" and "backward" until the accuracy of calculated values is achieved. The procedure "backward" starts from the node with index *n* and goes down to the node with index 0. During this procedure the currents of the loads and currents in all branches are calculated. The procedure "forward" starts from the node with index 0 and goes up to the node with index *n*. During this procedure the voltages from new iteration in all nodes are calculated. When the accuracy of the values of node voltages is achieved the calculation procedure stops. The results obtained by CSM load-flow analyse are:

- node voltages in RDM: $\underline{U}_i$ for *i*=1, 2, …, *n*;
- load currents in the nodes: $\underline{I}_i$ for *i*=1, 2,….., *n* and
- total branch currents for branches *g*=1, 2,….., *n*:

$$\underline{I}_{pg} = \sum_{i \in \{J_{gi}\}} \underline{I}_i \,, \tag{1}$$

where *p* (*p*<*g*) is the beginning node of the branch *g* and $i \in \{J_{gi}\}$, for nodes $i \geq g$ which can be reached in forward direction through the branch *g*.

IV. Power loss allocation in branches

With known voltages in all nodes *i*=0, 1, 2, …, *n* of RDM, the voltage drop $\Delta \underline{U}_g$ on each branch *g*=1, 2,….., *n* can be easy calculated. Therefore, for the branches from Fig. 1, the voltage drops are: $\Delta \underline{U}_1 = \underline{U}_0 - \underline{U}_1$ for branch 1, $\Delta \underline{U}_2 = \underline{U}_1 - \underline{U}_2$ for branch 2 and generally for any branch *k* with the beginning node *i*:

$$\Delta \underline{U}_k = \underline{U}_i - \underline{U}_k, \; k>i. \tag{2}$$

Using the branch *g* current $\underline{I}_{pg}$ and voltage drop obtained by Eq. (2), the complex power loss $\Delta \underline{S}_g$ for any branch *g*=1, 2,….., *n* is obtained by the Eq. (3):

$$\Delta \underline{S}_g = \sqrt{3} \Delta \underline{U}_g \cdot \underline{I}_{pg}^* . \tag{3}$$

If the branch current in Eq. (3) is expressed by Eq. (1), than the total power losses in the branch *g* are expressed as:

$$\Delta \underline{S}_g = \sqrt{3} \Delta \underline{U}_g \cdot \left(\sum_{i \in \{J_{gi}\}} \underline{I}_i \right)^* , \tag{4}$$

or:

$$\Delta \underline{S}_g = \sum_{i \in \{J_{gi}\}} \left(\sqrt{3} \Delta \underline{U}_g \cdot \underline{I}_i^* \right). \tag{5}$$

In the sum of Eq. (5) the first addend for *i*=*g* represents the power losses caused by the current $\underline{I}_g$ which is the current of the load connected in the node *g*. This addend is expressed as:

$$\Delta \underline{S}_g^{(g)} = \sqrt{3} \Delta \underline{U}_g \cdot \underline{I}_g^*, \; g \in \{J_{gi}\} \tag{6}$$

where with the superscript (*g*) is marked that the losses are caused by the current from load connected in node *g*. The rest addends in the sum of Eq. (5) represent the losses caused by currents $\underline{I}_i$ of other loads $\underline{S}_i$ connected in nodes *i* and supplied with electricity through the branch *g*. In generally these addends are given with Eq. (7):

$$\Delta \underline{S}_g^{(i)} = \sqrt{3} \Delta \underline{U}_g \cdot \underline{I}_i^*, \; i \in \{J_{gi}\}, \; i>g. \tag{7}$$

The conjugate values of the load currents in Eqs. (6) and (7) can be expressed through the node voltages (where the loads are connected) and corresponding load powers. According to the suggested replacements the power loss allocation in branch *g*, caused by the load connected at the end of branch *g* or any of the rest loads connected in nodes *i* supplied through this branch, the Eqs. (6) and (7) are given in form:

$$\Delta \underline{S}_g^{(i)} = \frac{\Delta \underline{U}_g}{\underline{U}_i} \cdot \underline{S}_i = \frac{\Delta \underline{U}_g}{\underline{U}_i} \cdot \left(P_i + jQ_i \right), \; i \in \{J_{gi}\}, \; i \geq g. \tag{8}$$

The total power losses in any branch *g* of the RDN, can be calculated as a sum of power losses in that branch allocated to the load connected to the end of the branch and other loads which are supplied through concerning branch, or as:

$$\Delta \underline{S}_g = \sum_{i \in \{J_{gi}\}} \Delta \underline{S}_g^{(i)}, \; g=1, 2, \ldots, n. \tag{9}$$

From above explanations it is obvious that power loss allocation calculations for any branch of the RDN without DG, can be easy conducted with known node voltages and load powers.

V. New power loss allocation method

The total power losses in the RDN: $\Delta \underline{S}_N = \Delta P_N + j\Delta Q_N$ are obtained as a sum of the power losses in each branch calculated by Eq. (9). With Eqs. (10) are presented apparent, active and reactive power losses, separately for the entire network:

$$\Delta \underline{S}_N = \sum_{g=1}^{n} \Delta \underline{S}_g,$$

$$\Delta P_N = Re\left(\sum_{g=1}^{n} \Delta \underline{S}_g \right), \; \Delta Q_N = Im\left(\sum_{g=1}^{n} \Delta \underline{S}_g \right). \tag{10}$$

Obtaining the total power loss allocation in the entire network, separately from each load connected in node *i* and signed as $\Delta \underline{S}_i^{\Sigma} = \Delta P_i^{\Sigma} + j\Delta Q_i^{\Sigma}$, can be performed on two ways. The first way is for summation of power loss allocation by the load *i* in all branches $g \in \{G_{0i}\}$, applying the equations:

$$\Delta \underline{S}_i^{\Sigma} = \sum_{g \in \{G_{0i}\}} \Delta \underline{S}_g^{(i)}, \; \Delta P_i^{\Sigma} = Re\left(\sum_{g \in \{G_{0i}\}} \Delta \underline{S}_g^{(i)} \right),$$

$$\Delta Q_i^{\Sigma} = Im\left(\sum_{g \in \{G_{0i}\}} \Delta \underline{S}_g^{(i)} \right), \text{ for } i=1, 2, \ldots, n. \tag{11}$$

According to the second way, the total power loss allocation in the entire network, separately from each load connected in node *i* can be calculated directly with Eqs. (12), applying voltage drops on all branches $g \in \{G_{0i}\}$, voltage and power(s) of the load connected in node *i*:

$$\Delta \underline{S}_i^{\Sigma} = \frac{\underline{S}_i}{\underline{U}_i} \cdot \sum_{g \in \{G_{0i}\}} \Delta \underline{U}_g = \frac{\left(P_i + jQ_i \right)}{\underline{U}_i} \cdot \sum_{g \in \{G_{0i}\}} \Delta \underline{U}_g . \tag{12}$$

If Eq. (12) divides on real (*Re*) and imaginary (*Im*) parts, the total active and reactive power loss allocation by the load in node *i* are:

$$\Delta P_i^{\Sigma} = Re\left(\frac{\underline{S}_i}{\underline{U}_i} \cdot \sum_{g\in\{G_{0i}\}} \Delta \underline{U}_g\right),$$

$$\Delta Q_i^{\Sigma} = Im\left(\frac{\underline{S}_i}{\underline{U}_i} \cdot \sum_{g\in\{G_{0i}\}} \Delta \underline{U}_g\right), \text{ for } i=1, 2,..., n. \quad (13)$$

Usually, for practical analysis the interest is focused on active power loss allocation of each load, expressed in percentage of the total active power loss in the RDN. These values are calculated with the Eq. (14):

$$\Delta p_i^{\Sigma} = \frac{\Delta P_i^{\Sigma}}{\Delta P_N} \cdot 100[\%], \text{ for } i=1, 2,..., n. \quad (14)$$

According to the used quantities and procedures for new method technique definition, the method is named as *Voltage Drop Current Decomposition Power Loss Allocation* or shortly ΔUCDPLA.

VI. Application of the new ΔUCDPLA method

The proposed new method is tested on real overhead radial distribution network [2], shown on Fig. 2. This test RDN consists of 5 lines (branches), 6 nodes (including the node with index 0) and 5 loads. All lines are from the same bare conductor Al/Fe 35/6 with r =0,8353 W/km and x =0,37 W/km. The line lengths are: l_1=2,5 km, l_2=6,0 km, l_3=0,4 km, l_4=0,5 km and l_5=0,6 km. Voltage in node 0 is $\underline{U}_0$=(10,25+*j*0) kV.

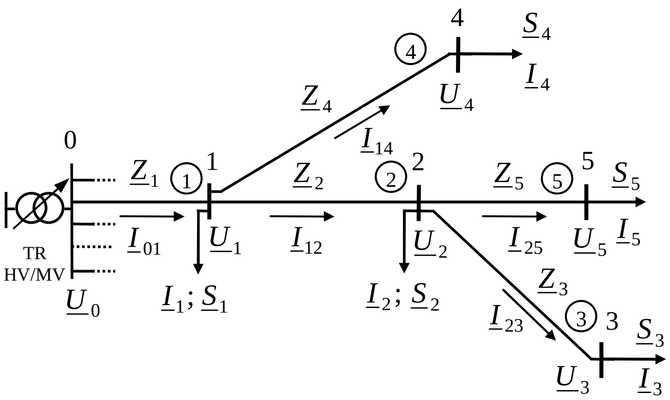

Fig. 2. Middle voltage test RDN without DG.

The maximum values in kVA are taken for the powers of the node loads. The powers are: $\underline{S}_1$=(400+*j*130), $\underline{S}_2$=(180+*j*60), $\underline{S}_3$=(140+*j*40), $\underline{S}_4$=(200+*j*70), $\underline{S}_5$=(100+*j*30). Three different methods are used for power loss allocation calculations on the test RDN from Fig. 2. The first one is *Power Summation Method for Loss Allocation* (PSMLA) [4], the second is *Branch Current Decomposition Loss Allocation* (BCDLA) [5] and the last is the proposed method ΔUCDPLA in section V.

Some of the obtained loss allocation results conducted by three methods are given in Table I. In the first column are assigned the node number with proper connected load. In other columns for each method and each node (load) active power loss allocation results in absolute value in kW and in % are given. The last row shows total power loses in RDN.

TABLE I
POWER LOSS ALLOCATION FOR THE LOADS OF TESTED NETWORK.

Method / Node *i* - Load *i*	PSMLA ΔP_i^{Σ} [kW]	PSMLA Δp_i^{Σ} [%]	BCDLA ΔP_i^{Σ} [kW]	BCDLA Δp_i^{Σ} [%]	ΔUCDPLA ΔP_i^{Σ} [kW]	ΔUCDPLA Δp_i^{Σ} [%]
1 – $\underline{S}_1$	13,644	38,97	9,509	27,17	9,508	27,17
2 – $\underline{S}_2$	8,964	25,60	8,788	25,11	8,725	24,93
3 – $\underline{S}_3$	5,387	15,39	6,820	19,49	6,902	19,72
4 – $\underline{S}_4$	4,428	12,65	4,982	14,24	4,933	14,10
5 – $\underline{S}_5$	2,587	7,39	4,896	13,99	4,926	14,08
Σ loss	35,01	100	34,995	100	34,994	100

Comparing the results in Table I, it can conclude that the results obtained with the new method are correct.

VII. Conclusion

In this paper is presented a new effective, robust and fast method for power loss allocation in RDN without DG sources. The method is based on load-flow results application and procedure for branch current decomposition on current addends which belong to the loads. Method application is demonstrated on a test RDN. The obtained results for power loss allocation with a proposed new method are verified through their comparison with the results obtained with already published methods. Furthermore, this method can be a base for establishing a new energy loss allocation method.

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