A New Methodology For Distribution System Feeder Reconfiguration

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Abstract**—**Distribution System Automation (DSA) is being carried out very seriously world over to enhance the reliability of the system and to minimize the huge losses that are occurring in the Distribution System. Feeder Reconfiguration (FR) is an important sub-problem of the overall distribution system automation process. Basic concept of feeder reconfiguration is to arrive at the best set of sectionalizing switches to be opened for a given set of tie switch such that the system performance is enhanced. In this paper a novel criterion is proposed based on the slope of the curve between the feeder losses verses receiving end voltage. Application of this criterion results in the most minimal loss configuration for any given loading condition. An existing switching indices criterion and switching algorithm criterion has been considered and the results are compared with that of the proposed slope criterion which results in the most minimal loss configuration. General MATLAB programs are developed to these criterions to obtain the best switching option.

Keywords**—**Distribution system, reconfiguration, sectionalizing switch, Tie switch. Switching Algorithm, Weighing Factor, Voltage Index, Ohmic Index, Decision Index, Switching Index.

I. INTRODUCTION

THE main purpose of electric power system is to efficiently generate, transmit and distribute electrical energy. The need for steady power supply with minimum power interruption and fast supply restoration has also increased. To meet these demands the automation of distribution system is widely adopted. FR is one of the vital operations to be carried out in successful implementation of the DSA. Feeder configuration can be varied so that the load is supplied at the cost of possible minimal line losses, increased system security and enhanced power quality. Several attempts have been made in the past to obtain an optimal feeder configuration for minimizing losses in distribution systems [1-8]. Civanlar et al. [1] considered one feeder pair at a time for loss reduction and derived a formula to estimate the loss reduction which would result from carrying out a particular switching option. Shirmohammadi et.al [2] determined a low-loss configuration by applying an optimal load flow analysis to the system with all switches closed. The system is returned to a radial configuration by opening the branches with the least current, considering one loop at a time. Baran et.al. [3] used a branch exchange method and suggested a mechanism to reduce the number of switching options and also developed the approximate power flow method to estimate the loss reduction. Liu et al. [4] developed two loss minimization algorithms in which the authors consider one feeder pair at a time to obtain the optimal solution. Chen et.al. [5] presented a method to derive an optimal switching plan to achieve energy loss minimization for short- and long-term operation of distribution systems.. The other approaches to feeder reconfiguration considering the ability of system transformers and feeders, power loss, and voltage profiles have been presented [9-11].Kashem et.al [12] proposed a technique to determine the switching combinations, select the status of the switches and find the best combination of switches for minimum loss. Chan et.al [13] proposed a new technique to solve the distribution feeder reconfiguration problem for loss reduction and service restoration.

II. PROBLEM STATEMENT

A distribution network is reconfigured by opening any sectionalizing switch and closing any tie switch, such that the power from the main station is re-routed. A whole feeder or a part of a feeder may be served from another feeder by closing a tie switch linking the two feeders while an appropriate sectionalizing switch must be opened to maintain the radial structure of the network so that the resulting radial distribution system has the desirable performance. Amongst the several criteria developed earlier for optimal network reconfiguration, a loss minimization criterion is being widely used. In the context of loss reduction, the problem to be addressed in this paper is to identify the tie/sectionalizing switches that should be closed/opened to achieve the maximum reduction by using slope criterion and comparing the results with switching indices criterion. In normal distribution operations, feeder reconfiguration can be used to minimize line losses. The operational constraints have to be identified and satisfied. Meanwhile, the final network just remains radial with all the loads connected. Sample 5 bus system shown in Fig. 1 is used as working example in this paper. Following assumptions are made in implementation of the proposed criterion.

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1. The load transferred during the feeder reconfiguration is assumed to be within the thermal rating of the feeder to which the load is transferred.
2. All the line sections connecting the buses of the same feeder have sectionalizing switches and line sections connecting the buses of different feeder has tie switches

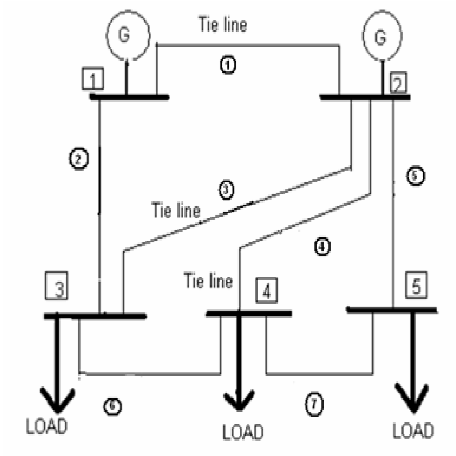


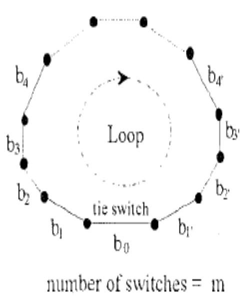
Fig: 1 Sample 5 Bus system

III. SWITCHING INDICES CRITERION

Extensive numerical computation is often required if the conventional load flow technique has to be used, considering the large solution space involved. An efficient search scheme is therefore desirable. This criterion solves the switching problem with minimum numerical burden [13]. Under normal operational state, the network is considered for loss reduction, and under restorative state, the network is considered for load reconnection.

A. *Weighing factor:*

For a loop created by closing a specific lie switch, a weighing factor w is defined for each sectionalizing switch according to its distance to this specific tie switch. If there are m number of switches in a loop as shown in Fig.2. The weighing factor for the tie switch and two neighboring switches are assigned the value 1/m. Branches b2, b2', and b3, b3' are 3/m. All the rest can be assigned in a similar manner.



Branch	ω
b_0 b_1 $b_{1'}$	1/m
b_2 $b_{2'}$ b_3 $b_{3'}$	3/m
b_4 $b_{4'}$ b_5 $b_{5'}$	5/m
b_6 $b_{6'}$ b_7 $b_{7'}$	7/m
⋮	⋮

Fig: 2 Switch weighing factor in a loop

B. *Voltage index:*

A voltage index $\mu_v(n)$ can be defined for a particular branch n (from i to j) by

$$\mu_v(n) = \exp\frac{\left(w \times \Delta V^2{}_n\right)}{\Delta V^2{}_{av}} \tag{1}$$

Where

ΔV_n : the voltage drop between two terminals of Branch n

$\Delta V^2{}_{av}$: the mean square voltage drop of all branches

w **:** weighing factor

C. *Ohmic index:*

Line constants R and Y can also be used to minimize Equation (1). Low current flow is expected for high $R|Y|^2$ value. An ohmic index $\mu_L(n)$ can be defined as

$$\mu_L(n) = \exp\left(\frac{-wR|Y|^2}{R_{av}Y^2{}_{av}}\right) \tag{2}$$

Where

R : the branch resistance for a given line

Y : the branch admittance for the given line.

R_{av} : the average branch resistance for a chosen loop

Y_{av} : the average branch admittance for a chosen loop

w : weighing factor

D. *Decision index*:

The decision index $\mu_D(n)$ can now be defined for the decision *set* D by using the product operation of indices $\mu_L(n)$ and $\mu_v(n)$ as

$$\mu_D(n) = \mu_v(n) \times \mu_L(n) \tag{3}$$

Under normal operational state, the optimal decision can be obtained by

$$Max(\mu_D(n)) = Max(\mu_v(n) \times \mu_L(n)) \tag{4}$$

For restorative state, the optimal decision can be obtain by

$$Min(Max(\mu_D(n))) = Min(Max(\mu_v(n) \times \mu_L(n))) \tag{5}$$

Reconfiguration should start from the upstream loops, that is, according to the order of the maximum power flow calculated for each loop. If a switch has already been selected in the previous loop, it will be eliminated from searching in the next loop. Computer simulations were conducted to show the effectiveness of this algorithm.

E. *Stepwise procedure*

1. Start
2. Read the network data and switch information.
3. Close all the tie switches, create a meshed loop, run AC Load flow.
4. The switching indices $\mu_L(n)$ and $\mu_v(n)$ are computed for all the branches.

5. Find the optimal solution with maximum $\mu_D(n)$ for all the lines in the loop.
6. Open the selected loop switch starting from the source loop.
7. If there is constraint violation, close the chosen switch, open the switch with the second largest $\mu_D(n)$ for the loop. Go to (6)
8. Else reconfiguration is done.
9. Stop.

It shows that closing the line 2-4 and opening the line 4-5 gives the minimum amount of losses.

IV. SWITCHING ALGORITHM CRITERION

Distribution systems are normally configured radially for effective coordination of their protective systems. Most distribution networks use sectionalizing-switches that are normally closed and tie-switches that are normally opened [1]. From time to time, modifying the radial structure of the feeders by changing the on/off status of the sectionalizing and tie switches to transfer loads form one feeder to another may significantly improve the operating conditions of the overall system.

In this method, all the possible switching options obtained from the combination of the tie-switch and its two neighbors are selected and the infeasible combinations in the selection are omitted [1]. The minimum loss configuration in the selected combinations is identified. Finally, an extensive search is carried out by changing the switching status one at a time, by either moving to the left of the open branch in the configuration obtained, and the configuration with maximum loss reduction is determined.

A. *Determination of switching status:*

In general, any tie/sectionalizing switches can be closed or opened to perform various network reconfigurations without creating any closed loop or leaving out any branch unconnected. Any configuration which forms a closed loop or leaving one or more branches unconnected is classified as infeasible Switching combination for network configuration. To avoid any infeasible combination the connectivity from the source to all the nodes of the system are checked. If a valid path exists, the configuration is a feasible one, otherwise it is infeasible. There are three possible switching combinations for a line which forms a switch group [1]. If a sectionalizing switch is opened during reconfiguration, this open branch and its adjoining branches again form a switch group. In this way all branches can form switch groups of their own, recursively.

If there are n tie switches in a system, there will be n switch groups forming 3^n different switching combinations. Each switch position in a switching combination is found out by using the formula shown in Equation No. 1

$$SC_i = \lfloor SP_{ij} \,..........SP_{i2}, SP_{i1} \rfloor \tag{6}$$

The switch positions of the j^{th} switch in i^{th} combination ,SP_{ij} can be obtained from the Equation No. 2

$$SP_{ij} = \left[(i-1) \big/ 3^{j-1} \right] \bmod 3 \tag{7}$$

Where, i is the combination number (one of 3^n), j is the switch number (one of n) and SC_i are the positions of the various switches in the i^{th} switching combinations.

The switching positions SC_i obtained above will be a 3-digit number containing the combination of 0,1 and 2 where 0,1 and 2 status represent the combination with tie switch open(zero connect),the right neighbor open(left-connect)the left neighbor open(right-connect) respectively. For zero-connect, the configuration will remain unchanged, but for left-connect or right-connect, the configuration will change according to the left or right-connect logic.

Left and right-connect logic are developed using the power flow in the adjoining branches of the tie-branch in the system. If the left-connect is performed, then the power flow of the right branch of the tie branch will be shifted to the tie branch [1]. Similarly, when the right-connect is performed, the power flow of the left branch of the tie-branch will be shifted to the tie-branch.

When a branch is left unconnected due to the opening of the sectionalizing switches or a closed loop is created due to the closing of the tie-switches, infeasible combinations result. These infeasible combinations must be identified and eliminated from the total combinations. The infeasible combinations are determined by checking the connectivity of each branch in the network. For each combination among all the nodes, select each node one after another, check its connectivity and make its connectivity active if it has the feasible connectivity. This procedure is repeated for all the nodes in the network.

B. *Calculation of losses using distance flow method:*

Power flow equations for a radial distribution network using real power, reactive power, voltages at the sending and receiving ends of a branch are shown in Equation No. 8,9,10.

$$P_{i+1} = P_i - \left[r_i \left(P_i^2 + Q_i^2 \right) \big/ V^2_{\ i} \right] - P_{Li+1} \tag{8}$$

$$Q_{i+1} = Q_i - \left[X_i \left(P_i^2 + Q_i^2 \right) \big/ V^2_{\ i} \right] - Q_{Li+1} \tag{9}$$

$$V_{i+1}^{\ 2} = V_i^2 - 2(r_i P_i + x_i Q_i) + \left[\left(r^2_i + x_i^2 \right)\left(P^2_i + Q_i^2 \right) \big/ V_i^2 \right] \tag{10}$$

The above equations are called Distance flow equations, where, P_i, Q_i and V_i are the real, reactive power and voltage at the sending end and P_{i+1}, Q_{i+1} and V_{i+1} are the receiving end quantities respectively. The quadratic terms in the equations represent the losses o the branches and hence they are much smaller than the power terms P_i and Q_i. Hence, by dropping the second order terms the set of new branch equations can be written as shown in Equation 11, 12, 13.

$$P_{i+1} = P_i - P_{Li+1} \tag{11}$$

$$Q_{i+1} = Q_i - Q_{Li+1} \tag{12}$$

$$V_{i+1}^{\ 2} = V_i^2 - 2(r_i P_i + x_i Q_i) \tag{13}$$

The solution for the simplified Distance flow equations for a radial network can be obtained as per Equation No. 14, 15, 16.

$$P_{i+1} = \sum_{k=i+2}^{n} P_{LK} \tag{14}$$

$$Q_{i+1} = \sum_{k=i+2}^{n} Q_{LK} \tag{15}$$

$$V_{i+1}^{\ 2} = V_i^2 - 2\left(r_i P_i + x_i Q_i\right) \tag{16}$$

The power loss on a branch is calculated as per Equation No. 17.

$$Loss_i = \left[r_i \left(P_i^2 + Q^2{}_i\right) \Big/ V^2{}_i \right] \tag{17}$$

The total system loss is the sum of all the branch losses given by the Equation No. 18.

$$Total\ Loss = \sum_{i=0}^{n-1} Loss_i = \sum_{i=0}^{n-1} \left[r_i \left(P_i^2 + Q_i^2\right) \Big/ V_i^2 \right] \tag{18}$$

Unlike the other load-flow techniques that a lot of iterations and computational time, in the simplified Distance flow, power-flows are calculated in one cycle of iteration. Therefore, it is suitable for on-line implementation as it reduces the computational time.

C. *Finding the optimal configuration for loss minimization:*

The network reconfiguration for loss minimization is performed by opening and/or closing the sectionalizing and tie-switches in such a way that the radiality of the network is retained and at the same time power losses are minimized.

A systemic approach is employed to perform automatically all types of operations needed for

1. Finding the total combinations of the system.
2. Obtaining the feasible combinations.
3. Determining the switching status of the individual switches.
4. Estimating the losses for all the switching combinations.
5. Identifying the minimum loss configuration which might be a local or global minimum among the feasible switching combinations.
6. Finally making a search to find the global optimum for loss minimization by moving to the left or right of these of the open lines or tie lines, depending upon whether the right adjoining or the left adjoining branch of a tie switch is open.

Once the input parameters of the base configuration or any other configuration of a radial system under consideration, are fed to the algorithm, the algorithm automatically reassigns the branches and loads, for any other switching configuration. In the input data, apart from specifying the branches, branch impedances and loads we have to specify tie branches, the left and right neighboring branches to each of the tie branch and the node numbers on both sides of the tie branches [1]. The infeasible combinations are eliminated.

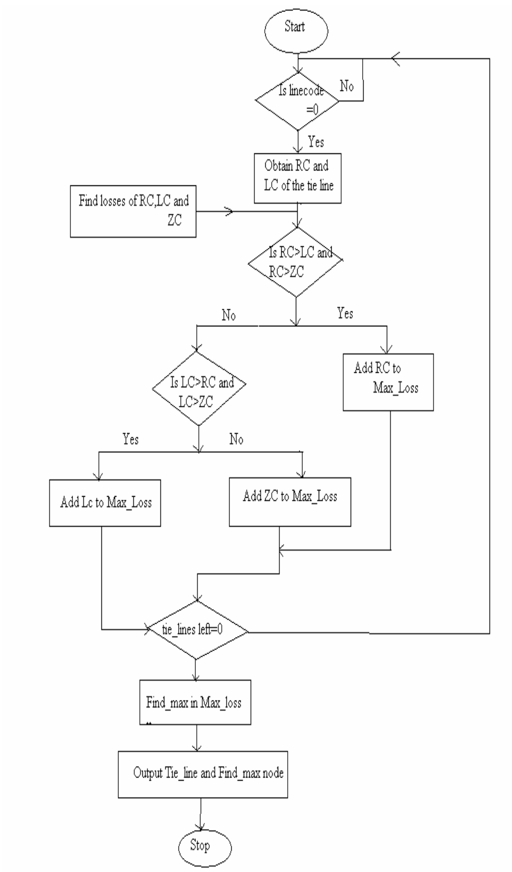
These switching configurations are formed according to the switching status found from the various switching combinations. The power flows are calculated for each branch of the switching configuration under consideration and the total power loss is estimated. Likewise the power loss in each of the remaining configurations is calculated. The configuration that gives minimum power loss is identified. To further narrow down a simplified extension of the above procedure is carried out by considering the connectivity of the combination.

The switch groups obtained from the combination found above are examined individually and the switching status of each switch group is found. If the connectivity of a switch group remains in the zero connect it, and then the switch group is unaltered [1]. If the connectivity of the switch group is towards left (left-connect), the connection is made to move towards right by opening the next neighbor of the right branch of the current tie switch and closing the current tie switch forming a new group (vice-versa happens with the right connect).For the newly formed combination the power loss is calculated and compared with the power loss in the combination estimated earlier. If it is less, then the current combination is considered as the best combination and the search is further carried out in the same direction otherwise the combination found earlier is considered as the best combination. The above procedure is applied to other switch groups in succession and the best combination is found.

D. *Stepwise procedure:*

1. Start
2. Initially the line code is checked for zero i.e. to check whether the line is a tie line.
3. If it is a tie line go to step 4 else to step 2.
4. The corresponding RC (Right connect) and LC (Left connect) of the line are determined.
5. Find losses of RC, LC and ZC.
6. If losses of RC>LC and RC>ZC then RC is added to the Max_Loss matrix else go to Step 7.
7. If LC>RC and LC>ZC then LC is added to Max_Loss matrix else ZC is added.
8. Checking is done whether any of the tie lines are left.
9. If yes go to step 4 else go to next step.
10. Find max in the Max_Loss matrix.
11. Open the max line and close the corresponding tie line.
12. Stop

E. Flowcharts representing the switching algorithm criterion:



E. LINE DATA FOR SWITCHING CRITERION:

Table 1

Bus nl	Bus nr	Line code = 0 for tie lines and =1 for other lines	Line num	Left connect	Right connect
1	2	1	1	5	2
1	3	1	2	0	0
2	3	1	3	5	6
2	4	1	4	5	7
2	5	1	5	0	0
3	4	1	6	0	0
4	5	1	7	0	0

G. OUTPUT OF SWITCHING ALGORITHM CRITERION:

Table 2

Closing Line	Opening line	Losses (MW)
1-2	1-3	6.966
2-3	3-4	5.885
2-4	4-5	5.727

V. PROPOSED SLOPE CRITERION

Now the results of the above approaches are compared with the proposed slope criterion. In a real system, loading of any bus in turn the feeder to which the bus is connected keeps varying from time to time. So it's not possible to maintain the same reconfigured network for all the loading conditions. It's practically impossible to reconfigure the network for every change in loading condition. So at discrete time intervals the network is reconfigured for a minimal loss network. To achieve this it is necessary to derive a criterion which eliminates certain switching options and also helps in selecting the best option which improves the system performance. In this paper a criterion based on the slope of the curve plotted between the feeder loss and the receiving end voltage is developed. The criterion is based on the slope obtained by differentiating the loss equation with respect to the receiving end voltage. The equation is called the slope equation as it corresponds to the differential equation of first order. To develop the criteria, a sample two bus system shown in fig. 3 is considered.

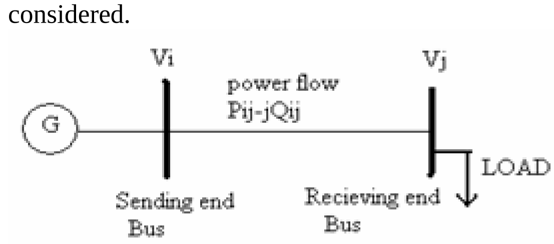


Fig. 3 Sample 2 bus system

$$I_{ij} = \left(P_{ij} - jQ_{ij}\right) \Big/ \left(V_i\angle\alpha_i - V_j\angle\alpha_j\right) \tag{19}$$

$$Loss_{ij} = I^2_{ij} \times R_{ij} \tag{20}$$

Substituting (19) in (20) we have

$$Loss_{ij} = \left(\left(P_{ij} - jQ_{ij}\right)^2 \Big/ \left(V_i\angle\alpha_i - V_j\angle\alpha_j\right)^2 \right) \times R_{ij} \tag{21}$$

The power flow in that particular section is given by

$$\left(P_{ij} - jQ_{ij}\right) = \left(V_j\angle\alpha_j\right)^* \left(V_i\angle\alpha_i - V_j\angle\alpha_j\right) / \left(R_{ij} + jX_{ij}\right) \tag{22}$$

So substituting (22) in (21):

$$Loss_{ij} = V_j^2\left(\cos\alpha_j - j\sin\alpha_j\right)^2 \times R_{ij} \Big/ \left(R_{ij} + jX_{ij}\right)^2 \tag{23}$$

Upon taking conjugate and eliminating the imaginary term and differentiating the resulting equation:

$$\partial\left(Loss_{ij}\right) \Big/ \partial\left(V_j\right) = \left(2\times V_j \times R_{ij}\left(\left(R^2{}_{ij} + jX^2{}_{ij}\right)\times A\right)\right) \Big/ \left(R^2{}_{ij} + X^2{}_{ij}\right)^2 \tag{24}$$

Where

$A=\left(\cos\left(2\times\alpha_j\right)\right)-\left(4\times R_{ij}\times X_{ij}\times\cos\alpha_j\times\sin\alpha_j\right)$

$Loss_{ij}$ - Loss in the particular line section.

V_j – Receiving end voltage.

R_{ij} – Sectional resistance.

X_{ij} – Sectional inductance.

α_j – Angle in degrees.

P_{ij} – Sectional real power.

Q_{ij} – Sectional reactive power.

Equation No.24 is used to compute the slope of each line section for base case (all tie switches open and the entire sectionalizing switch closed) and for selected switching options. The best switching option is selected in which the minimum number of line section slopes show a trend of higher rate of increase. This is justified as the slope decrease corresponds to decrease in the loss. In implementing the proposed criterion, initial selection of the possible switching options is carried out using the Civanlar's criterion.

Stepwise procedure

1. The base case (all tie switches opened and sectionalizing switches closed) load flow analysis for a particular loading condition is carried out.
2. The slope of each line section is computed using equation 5.
3. For all the selected switching options the slopes are computed.
4. The number of line sections having increasing slope in comparison with the base case are identified.
5. The best switching option is selected in which the minimum number of line section slopes show a trend of higher rate of increase. The losses are computed for this switching option and are checked for the reduction in value with the base case.

TABLE: 3

Case	Closing line	Opening line	Losses	No. of slopes increased
1.	1-2	1-3	6.966	3
2.	1-2	2-5	11.740	5
3.	1-2	3-4	5.876	1
4.	1-2	4-5	5 .728	0
5.	2-3	1-3	6.962	3
6.	2-3	2-5	11.701	5
7.	2-3	3-4	5.885	1
8.	2-3	4-5	5.729	0
9.	2-4	1-3	6.960	3
10.	2-4	2-5	11.691	5
11.	2-4	3-4	5.862	1
12.	2-4	4-5	5.727	0

Table 3 shows that case 4, 8 and 12 have zero lines whose slopes increased from base case. Amongst these we find that case 12 has the least amount of losses.

VI. CONCLUSION

A novel criterion for reconfiguring the distribution system network for any loading condition is proposed and the effectiveness of the criterion is demonstrated by comparing with another two existing methods on a standard distribution network and the results are test evaluated with the other standard methods.

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VIII. APPENDIX

TABLE 4: BUS DATA

Bus No	Bus code	Voltage Mag	Angle degree	Load MW	Load Mvar
1	1	1.06	0.000	0	0
2	2	1.00	-1.442	0	0
3	0	0.994	-4.284	45	15
4	0	0.989	-4.546	40	5
5	0	0.973	-5.209	60	10

TABLE: 4 CONTD.

Bus No	Generation MW	Generation Mvar	Injected qmin	Injected qmax	Injected Mvar
1	110.648	94.039	0	0	94.039
2	40	86.37	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0

TABLE: 5 LINE DATA

Bus Nl	Bus nr	R p.u	X p.u	(1/2)b p.u	Line code = 1 for lines >1 or <1 for trans.tap
1	2	0.02	0.06	0.030	1
1	3	0.08	0.24	0.025	1
2	3	0.06	0.18	0.020	1
2	4	0.06	0.18	0.020	1
2	5	0.04	0.12	0.015	1
3	4	0.01	0.03	0.010	1
4	5	0.08	0.24	0.025	1

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