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Development of Minimum Cost Capacity Model for Power System Component Expansion (MCCM)

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Abstract: This model forms the basis for determining the number of lines of a given specification to be added to an existing power network, in order to correct the line overload problem. The approach first determines the line type to be recommended. The (MCCM) model is used to identify the lines to be augmented as a result of particular line overload. The susceptance across the right of way is determined at minimum cost. Power system stability is a complex concept that has challenged power system engineers for many years. That is stability and control problem are functions of transmission disturbances in terms of overload problems. Therefore for economic reason, power systems are designed to be operated close to their steady state stability limit thereby eliminating overload problems.

Index Terms: Minimum cost capacity model, lines addition, (impedance, reactive, susceptance), network analysis, power system component.

1. INTRODUCTION

The choice of an optimal plan for the expansion of a transmission network is a difficult task and no satisfactory solution has yet been found. The size and locations of the generating plans are usually known. However, difference in demand patterns or in generation availability from those expected can change the flows in a network. Nevertheless, the network is expected to transmit power from the generating units to load centers as required. The procedure using a decoupled load flow approach to find the minimum cost capacity additions are required to accommodate, Known changes in demands and generation. An expansion schedule involving linear and dynamic programming methods was produced. The required input data items are the yearly load and generator nodes and magnitude, the initial transmission grid, the cost of losses and the cost of permissible line additions are giving in per mile. The program of Kattenbael et al tests for reliability by solving the yearly load flows for overloads in single outages. [1]

Garver and Adams and Dell have solved a similar problem using linear programming. Puntel et al and Sullivan defined the problem such that the susceptance is installed in the rights of way to minimize the costs of installing transmission line capacity and of penalizing overloads in each of the transmission lines. Minimization is carried out by first computing a gradient vector. The computation uses an adjunct network based on Tellegen's theorem. These concepts have been extended by this work by comparing qualitative and quantitative methods of system planning. Phase shifters were used where possible to correct line overloads. [2]

In this work, simple methods are used to determine the number of lines of each specification to be added to a network to eliminate system overloads at minimum cost. The coherency approach developed by Bennon et al is used as a yardstick to determine which lines should be augmented as a result of overloads in some lines. Then a static optimization procedure based on the steepest-descent algorithm determines the new admittance to be implemented along these rights of way. The method is expected to reduce the size of alternative planning networks with considerable savings in cost. An overall economic analysis is not carried out except for adding lines minimum cost to eliminate overloads. [3]

Symbol

φ_i^{Max}	Maximum phase angle difference in line
Y_k	Admittance of line K
X	Impedance of a line
N	Number of overloaded lines in the system
M	Number of rights of way to the augmented
C_1	Unit line costs
L	Number of lines required for addition in a particular right of way.
ϕ	$\Psi - \Psi^{max}$

2. MATHEMATICAL FORMULATION:

The mathematical formulation of the problem and assumption can be stated as follows:

- From a given list of possible line addition the line which results in the smallest phase angle difference should be

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recommended for addition to the network. This approach has been suggested in previous study for rights of way with more than one line.

- Determine for particular line overload(s), which rights of way should be augmented to alleviate or eliminate the line overload(s) problems.
- Using the steepest descent procedure we can determine the new admittance across these rights of way such lines are added at minimum cost overloads eliminated.
- Determine the number of lines needed for minimum cost elimination of overload which result in the smallest phase angle difference. [4]

3. CHOICE OF LINE TYPE

For each line *i*, determine given by the product of line rating and reactance with the smallest Ψ_i is chosen for additions to the network. [5]

Determine the rights way to be augmented with the coherency relationship used by Bennon et al the rights of way to be augmented are determined by assuming a linear relationship between the transmission capacity and the admittance. This relationship is given by

$$\Psi_k = e^T y^{-1} e_i \; y_i \; \Psi_i$$

$$q = \frac{\partial \psi_i}{\partial y_i} \Bigg| \frac{\partial \psi_k}{\partial y_k}$$

Where $\dfrac{\partial \psi_i}{\partial y_i} = e^T y^{-1} e_i \; \Psi_i$ (1)

$$\frac{\partial \psi_k}{\partial y_k} = e^T y^{-1} e_k \; \Psi_k \qquad (2)$$

Dividing equation (1) x (2)

We have

$$= \frac{\dfrac{\partial \Psi_k}{\partial yi}}{\dfrac{\partial \Psi_k}{\partial y_k}} = \frac{e^T y^{-1} e_i \; \Psi_i}{e^T y^{-1} e_i \; \Psi_k} = q \qquad (3)$$

This means that:

$$q = \frac{\partial \Psi_k}{\partial y_i} \Big/ \frac{\partial \Psi_k}{\partial y_k} = \frac{e^T y^{-1} e_i \; \Psi_k}{e^T - y^{-1} e_i \; \Psi_k} \qquad (4)$$

From equation (1) which determines the effect of capacity changes in line *i* on the power flow in line k.

For a line *i* terminating at busbars P_1 and P_2 we have

$$e_i = \begin{bmatrix} 0 \\ 1 \\ -1 \\ 0 \end{bmatrix} \qquad (5)$$

For *i* = k, q from equation (1) is equal to 1.0. The rights of way to be augmented preferentially are those with q ≥ 1.0 which has been that the component with higher values of q will have considerable effect on line and for capacity changes in line *i*. [6]

These phase differences are computed using the DC approximation of the load flow with initial generation and consumption value but different line parameters depending on the line addition. [7]

Static optimization technique

Once the rights of way to be augmented have been determined as in the previous case, the static optimization problem can be stated as follows. [8]

Minimize the phase angle difference ϕ_k for the overloaded line K so that the overloads are cleared by changing by changing the admittance of line *i*. Make these changes by adding lines at minimum cost. Thus we want to minimize: [9]

$$J = \sum_{K=1}^{N} \left(\psi_k - \psi_k^{\max} \right) + \sum_{i=1}^{M} C_i y_i \qquad (6)$$

For *N* overloads and *M* rights of way to be augmented subject to:

The satisfaction of the DC load flow equations

$y \geq 0$

The absolute value of Ψ, i.e. $|\Psi|$, is the relevant quantity here. Equation (3) can be rewritten as:

$J = J_1 + J_2$

The gradient vector is also given as:

$$\frac{\partial J}{dy} = \frac{dJ_1}{dy} + \frac{dJ_2}{dy} \qquad (7)$$

$\partial J_2/dy_i$ is a constant (C_i) which is supplied with the line specification, while

$$\frac{dJ_1}{dy} = \frac{d\phi}{dy}$$

Where $\phi = \Psi - \Psi^{max}$. It should be noted that Ψ and Ψ^{max} described in previous case, are not necessarily equal.
In matrix form:

$$\frac{dJ}{dy} = \begin{bmatrix} \partial\phi(1, \quad 1)/\partial y_1 + C_1 \\ \partial\phi(2, \quad 2)/\partial y_2 + C_2 \\ \vdots \qquad\qquad \vdots \\ \partial\phi(M, \quad M)/\partial y_M + C_M \end{bmatrix} \qquad (8)$$

Note that

$$\frac{\partial J}{\partial y_1} = \sum_{K=1}^{N} \frac{\partial \psi_k}{\partial y_1} + C_i \qquad (9)$$

Thus we get the new vector

$$y_1 = y - \alpha \frac{\partial J}{\partial y_1} \qquad (10)$$

α is some scalar parameter that controls the magnitude of the step. An engineering judgment is required in the choice of α. Its objective is to ensure that the minimization of *J* along a given direction, too small a value of α causes too much iteration to be carried out to clear the overload, although convergence characteristic is eventually achieved. However, when α is very large, then the oscillations around the minimum value may occur. *N* may vary in the course of the steepest-descent algorithm, in which case the overloads may be cleared one after the other. [10]

Calculation of the number of lines required when y has been determine from equation (10), the impedance is computed as:

$$1/X^{eq} = 1/X_1 + L/X_2 \qquad (11)$$

Where X_1 is the impedance of line K to be augmented, X_2 is the impedance of each of the lines to be added and L is the number of lines of impedance X_2 required.

From equation (11) we have

$$L = \frac{X_1 X_2 - X^{eq} X_2}{X_1 X^{eq}} \qquad (12)$$

Where X^{eq} is the equivalent impedance of lines L_i (i = 1 to N)
Since only integer values of L is required

$$L \geq \frac{X_1 X_2 - X^{eq} X_2}{X_1 X^{eq}} \qquad (13)$$

4. CASE STUDY

A simple six-bus seven-line system shown in figure (1) is used as test data for case study. To network data is given in table 1 and 2. Table 3 shows the candidate lines for addition.

After the initial load flow, line 5-6 was overloaded (about 26%). The coherency values for the lines are shown in Table 4 with respect to line 5-6. This table shows that changes made to the susceptance of line 1-5 would have a marked effect on the power flow of line 5-6. A negative coherency value (line 1-6) indicates that the construction of a new line on 1-6 will increase the flow on 5-6. [11]

That is the candidate lines for addition in table 3, line type 2 has the minimum phase angle difference. Hence this line type is chosen for addition to the network on the right of way 1-5. [12]

With the value α = 30 assumed in caution (4), six extra lines of type 2 are required on the right of way 1-5 to eliminate the line overload in lie 5-6 completely. The number of lines that can be generated when will used different values of α, can be obtained. [13,14,15]

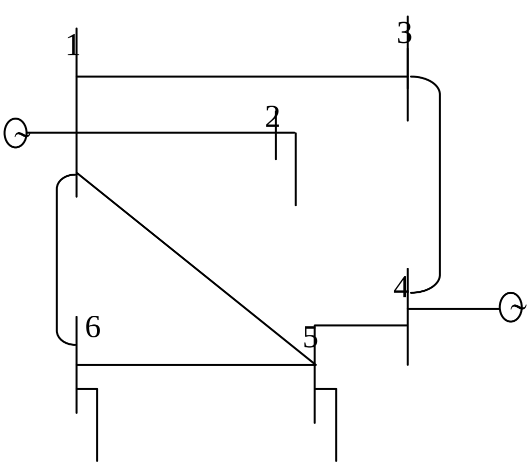

Figure 1: Sample Network

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Table 1: System Bus Data

Bus	Power Injections MW
1.	1620
2.	-140
3.	0.0
4.	1300
5.	-1940
6.	840
Slack bus (Bus 3)	

Table 2: Line Data

Line	From Bus	To Bus	XP.U	Capacity P.U
1	1	2	0.008	5.0
2	1	3	0.020	2.0
3	1	5	0.020	5.0
4*	1	6	0.005	15.0
5	3	4	0.020	2.0
6	4	5	0.005	27.0
7	5	6	0.030	1.0

* Double line represented by a single line
Assumed data

Table 3: Specifications of candidate lines for addition

Type	X (P.U)	Capacity (P.U)	Capacity X $(P.U)^2$	C_i
1	0.02	5.0	0.10	0.1
2	0.01	1.0	0.01	0.1
3	0.03	2.0	0.06	0.1

Base MVA = 100.00

Table 4: Coherence values of the lines

Line	Coherence
1 - 2	0.0000
1 - 3	0.0700
1 - 5	1.4121
1 - 6	-0.4250
3 – 4	0.0770
4 – 5	0.1174
5 - 6	1.0000

5. CONCLUSION

A simple technique formulation has been presented in this work for strengthen a network to alleviate line overloads at minimum cost. The satisfactory performance of the method depends on the appropriate choice of α. However, instead of adding many lines in 1-5 as shown above, lines that have higher voltage may be substituted instead.

Recommendation

Analysis for illustration for load forcast for generation capacity

In a large system the daily load curve during a time of rapid early morning load increase displayed the following loads in GW during successive five minute intervals.

Time (Mins)	Load (GW)
46	19.30
47	19.78
48	19.96
49	20.31
50	20.69

It is true that a straight line approximation would suffice to describe the duration of periods of the form y = a + bx. We can calculate the best values for coefficients a and b by least squared estimation and load forecast during period 55minutes.

Case 1:

For the line y = a + bx through data points (x, y) define the error for any point (x, y) as:

$$e_i = y_i - a - bx_i \qquad (14)$$

The sum of squares of the error value

For N points is

$$J = \sum_{i=1}^{N} eiei$$

$$J = \sum_{i=1}^{N} (yi - a - bxi)(yi - a - bxi) \qquad (15)$$

Using regression analysis

$$\Sigma\ y_i^{\ 2} - 2a \quad \Sigma\ y_i - 2b\ \Sigma xy_i = 0 \qquad (16)$$

$$Na^2 + b^2 \quad \Sigma xi^2 + 2ab\ \Sigma x_i = 0 \qquad (17)$$

Taking partial derivatives of J with respect to a and b.

$$\frac{\partial J}{\partial a} = -\Sigma y_i + 2Na + 2b\ \Sigma xi \qquad (18)$$

$$\frac{\partial J}{\partial b} = -2\Sigma x_i y_i + 2a\ \Sigma\ xi + 2b\ \Sigma xi^2 \qquad (19)$$

For best values of a and b set

$$\frac{\partial J}{\partial a} = \frac{\partial J}{\partial b} = 0$$

$$\Sigma y_i = Na + b\ \Sigma xi$$

$$\Sigma x_i y_i = a\ \Sigma\ xi + b\ \Sigma xi^2 \qquad (20)$$

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Which are the normal equations to be solved for a and b.

Table 5: Sum of square of data

X	Y	X^2	XY
46	19.30	2116	887.80
47	19.78	2209	929.66
48	19.96	2304	958.08
49	20.31	2401	995.19
50	20.69	2500	1034.50
240	100.04	11530	4805.23

$$\Sigma y_i = Na + b\,\Sigma xi$$

:. 100.04 = 5a + 240b

4805.23 = 240a + 11530b

Solving for a and b

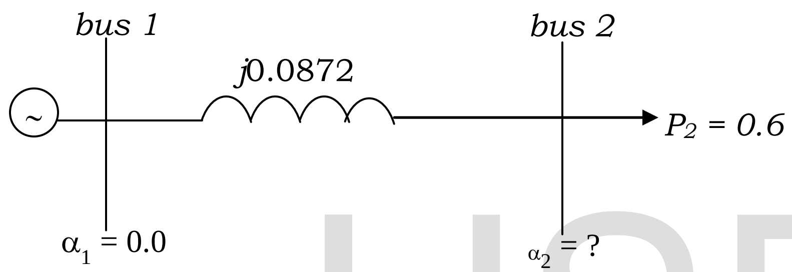

Figure 2: Simple two bus system representation

$V_1 < \alpha_1$

$V_2 < \alpha_2$

$X_{21} = j0.\ 0872$

$b_{21} = 1/X_{\cdot 21} = 11.47$

$P_{21} = 11.47\ (\alpha_2 - \alpha_1) = -0.6 = 11.47\alpha_2 =$

$$\alpha_2 = \frac{-0.6}{11.47} = -0.523\ rad$$

In the absence of loses $P_1 = 0.6$ pu

Case 4: Newton Raphson method

$$\begin{bmatrix} \Delta P_2 \\ \Delta Gj \end{bmatrix} \begin{bmatrix} \frac{\partial P_2}{\partial \alpha_2} & \frac{\partial P_2}{\partial |V_2|} \\ \frac{\partial Q_2}{\partial \alpha_2} & \frac{\partial Q_2}{\partial |V_2|} \end{bmatrix} \begin{bmatrix} \Delta \alpha_2 \\ \Delta |V_2| \end{bmatrix} \qquad (21)$$

From the load flow equations

$$P_i = |V_i| \sum_{j=1}^{n} |V_j| \| \ddot{Y} \cos(\alpha_i - \alpha_j + \theta y) \qquad (22)$$

a = 4.12 , b = 0.33

Forest for x = 55

Y = 4.12 + 0.33 x 55

= 22.27 GW

Generating capacity (GW) = 22.27 GW

Case 3: Appling the simplifying assumptions

- DC Load flow method

$/V_1/ = /V_2/ = 1.0$

Y_{shunt} is neglected as well as Q_2 (= IV sin ϕ = 0)

$$Q_i = |V_i| \sum_{j=1}^{n} |V_j| \ddot{Y} \sin(\alpha_i - \alpha_j + \theta y) \qquad (23)$$

$$Yi_j = Yij \quad \exp\left(-\theta\, \ddot{y}\right) \qquad (24)$$

$$Y_{12} = \frac{1}{j0.0872} = -j11.47$$

$$Y_{12} = j11.47 = 11.47 \;\llcorner\; -\Pi/2 \;\; => \theta_{12} = \Pi/2$$

$$Y_{22} = -j11.47 + jo.022b \div -j11.45 => \theta_{22} = \Pi/2$$

$$\frac{\partial P_2}{\partial \alpha_2} = -|V_1||V_2|Y_{12} \sin(\alpha_2 - \alpha_1 + \theta_{12})$$

Iteration 1:

$$\frac{\partial P_2}{\partial \alpha_2}\Big|_0 = -11.47 \sin -\Pi/2 = 11.47$$

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$$\frac{\partial Q_2}{\partial \alpha_2} = |V_1||V_2|Y_{12}\cos(\alpha_2 - \alpha_1 + \theta_{12}) = 0.0$$

$$\frac{\partial P_2}{\partial |V_2|} = 2|V_2|Y_{22}\cos\theta_{22} + |V_1|Y_{12}\cos(\alpha_2 - \alpha_1 + \theta_{12}) = 0.0$$

$$\frac{\partial Q_2}{\partial |V_2|} = 2|V_2|Y_{22}\sin\theta_{22} + |V_1|Y_{12}\sin(\alpha_2 - \alpha_1 + \theta_{12}) =$$

11.43

The Jacobian matrix:

$$[J] = \begin{bmatrix} \frac{\partial P_2}{\partial \alpha_2} & \frac{\partial P_2}{\partial |V_2|} \\ \frac{\partial Q_2}{\partial \alpha_2} & \frac{\partial Q_2}{\partial |V_2|} \end{bmatrix}$$

$$[J] = \begin{bmatrix} 11.47 & 0.0 \\ 0.0 & 11.43 \end{bmatrix}$$

$$P_2^{(0)} = |V_1||V_2|Y_{12}\cos(\alpha_2 - \alpha_1 + \theta_{12}) + |V_2|^2 Y_{22}\cos(\alpha_2 - \alpha_1 + \theta_{12})$$

$= 0.0$

Similarly $Q_2^{(0)} = -0.02$

$\Delta P_2^{(0)} = P_2 - P_2^{(0)} = -0.6$

$\Delta Q_2^{(0)} = Q_2 - Q_2^{(0)} = -0.3 + 0.02 = -2.28$

$$\begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}\begin{bmatrix} \Delta\alpha \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

$$\begin{bmatrix} 11.47 & 0 \\ 0 & 11.43 \end{bmatrix}\begin{bmatrix} \Delta\alpha^{(0)} \\ \Delta V^{(0)} \end{bmatrix} = \begin{bmatrix} -0.6 \\ -2.28 \end{bmatrix}$$

$$\begin{bmatrix} \Delta\alpha^{(0)} \\ \Delta V^{(0)} \end{bmatrix} = \begin{bmatrix} -0.05244 \\ -0.0244 \end{bmatrix}$$

$$|V_2|^{(i)} = |V_2|^{(D)} + |\Delta V_2|^{(D)} = 1.0 - 0.0244 = 0.9756$$

$$|\Delta\alpha_1|^{(i)} = |\alpha_2|^{(0)} + |\Delta\alpha_2|^{(D)} = 0.0 - 0.05244 = -0.05244$$

Iteration 2:

$$[J_1] = \begin{bmatrix} 11.18 & -0.601 \\ -0.05 & 10.85 \end{bmatrix}$$

$P_2^{(1)} = 0.586 \Rightarrow \Delta P_2^{(1)} = P_2 - P_2^{(1)} = -0.014$

$Q_2^{(1)} = -0.295 \Rightarrow \Delta Q_2^{(1)} = Q_2 - Q_2^{(1)} = -0.005$

Hence:

$$\begin{bmatrix} \Delta\alpha \\ \Delta|V_i| \end{bmatrix} = [J_1]^{-1}\begin{bmatrix} -0.014 \\ -0.005 \end{bmatrix} = \begin{bmatrix} 0.00129 \\ -0.00044 \end{bmatrix}$$

$$|V_2|^{(2)} = 0.9756 - 0.00044 = 0.97516$$

$$\Delta\alpha_2^{(2)} = -0.05244 + 0.00129 = -0.05115\,rad$$

Case 5:

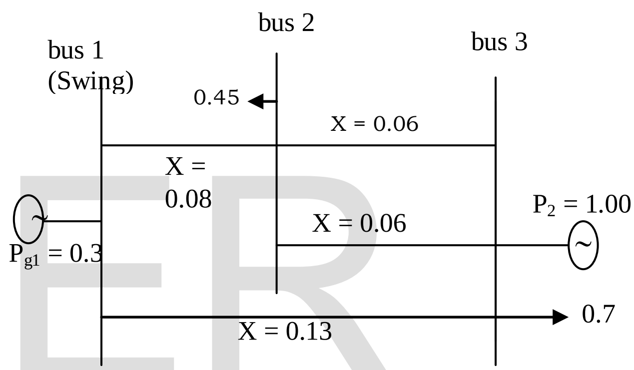

Figure 3: 3-bus system with all parameters in per unit

Example to show how technique works:
The above 3-bus system with all parameters in per unit on a system with base of 100 MVA . Computing using the load flow technique:

i. The voltage angles

ii. The MW flow in each circuit

iii. The percent loading in each circuit assuming the MW capacity to be 75MW

$$X_{12} = 0.08 \Rightarrow b_{12} = \frac{1}{0.08} = 12.5$$

$$X_{13} = 0.13 \Rightarrow b_{13} = \frac{1}{0.13} = 7.69$$

The parallel combination of the circuit on buses 2 and 3.

$$X_{23} = \frac{(0.06)(0.06)}{0.06 + 0.06} = 0.03 \Rightarrow b_{23} = \frac{1}{0.03} = 33.33$$

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The bus susceptance matrix [B_{bus}}

$$\begin{bmatrix} 20.19 & -12.5 & -7.69 \\ -12.5 & 45.83 & -33.33 \\ -7.69 & -33.33 & 41.02 \end{bmatrix}$$

This is a singular matrix and as the slack bus angle is fixed at zero degree; all the elements corresponding to bus 1 are eliminated:

$$\left[B_{reduced}\right] = \begin{bmatrix} 45.83 & -33.33 \\ -33.33 & 41.02 \end{bmatrix}$$

If $B.\alpha = \Delta P$

:. $\alpha = B^{-1}\Delta P$

$\Delta P_2 = -0.45$

$\Delta P_3 = 1.00 - 0.75 = 0.25$

From B. $\alpha = \Delta P$

$$\begin{bmatrix} \alpha_2 \\ \alpha_3 \end{bmatrix} = \begin{bmatrix} 45.83 & -33.33 \\ -33.33 & 41.02 \end{bmatrix}^{-1} \begin{bmatrix} -0.45 \\ 0.25 \end{bmatrix} = \begin{bmatrix} -0.013 \\ -0.0046 \end{bmatrix} rad$$

Line flows

Line: $P_{12} = b_{12}\ (\alpha_1 - \alpha_2) = 12.5\ (0.0 + 0.013)$

$= 0.1625$ pu

1 – 2 = 16.25MW

Line: $P_{13} = b_{13}\ (\alpha_1 - \alpha_3) = 7.69\ (0.0 + 0.0046 = 0.0354$pu

1 – 3 = 3.54MW

Line: $P_{23} = b_{23}\ (\alpha_2 - \alpha_3) = 33.33\ (-0.013 + 0.0046)$

2 – 3 = -0.2799pu = -27.99MW

The negative sign means that the flow is actually from line 3 to 2. The flow in each circuit is 13.995 MW. i.e.

$$\frac{27.99MW}{2} = 13.995MW$$

% loading (with a capacity of 75MW):

Line 1- 2: $\frac{16.25}{75} \times 100\% = 21.66\%$ (25)

Line 1 – 3: $\frac{3.54}{75} \times 100\% = 4.72\%$

For each line 2 – 3: $\frac{13.995}{75} \times 100\% = 18.66\%$

As the % loadings are less than 100, this means there no are overloaded lines.

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