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A New Technique to find the effect of Active Power Loading on Voltage Stability and Algorithm to improve Voltage Stability of Radial and Meshed Power Systems

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Abstract
This paper will analyze the impact of active power on voltage stability of radial and meshed systems and a new algorithm is proposed which would indicate the amount and location at which the active power is to be reduced to improve the voltage stability of entire power system or set of buses that are prone to voltage instability. A new sensitivity matrix named Active Power L-Index sensitivity matrix is been proposed. The proposed approach is simple and easy to be implemented into large power systems. The proposed approach has been applied to several Indian rural distribution networks and IEEE 14-bus test system which demonstrated applicability of the proposed approach.
Index Terms- L-index matrix, Jacobian matrix, sensitivity, Active Power L-Index sensitivity matrix

I. Introduction

According to [1], voltage stability refers to the ability of a power system to maintain steady voltages at all buses in the system after being subjected to a disturbance from a given initial operating condition. It depends on the ability to maintain/restore equilibrium between load demand and load supply from the power system. The increased load and generation in many systems without a corresponding augmentation of the transmission infrastructure has resulted in the overloading of the transmission lines. As a result, the transmission lines operate near their steady state limits. The transmission of large amounts of power through the lines results in the large voltage drops. Sudden disturbances like line generator outage or faults in the transmission lines may result in conditions that the transmission system may not be able to supply the load demand. This could manifest as a drop in the system bus voltages which may be sudden or progressive. If the necessary remedial measures are not taken, then this may lead to the blackout or collapse of the whole system. As a result of a number of voltage stability incidents reported from various countries, there is a widespread interest in understanding, characterizing and preventing this phenomenon. This paper is essentially concerned with analyzing the effect of active power on voltage stability.

II. Motivation

The increasing number of power system blackouts in many countries in recent years, is a major source of concern. Power engineers are very interested in preventing blackouts and ensuring that a constant and reliable electricity supply is available to all customers. Incipient voltage instability, which may result from continues load growth or system contingencies, is essentially a local phenomenon. However, sequences of events accompanying voltage instability may have disastrous effects, including a resultant low-voltage profile in a significant area of the power network, known as the voltage collapse phenomenon. Severe instances of voltage collapse, including the August 2003 blackout in North - Eastern U.S.A, Canada, France, Japan, etc.[[2]- [4]], have highlighted the importance of constantly maintaining an acceptable level of voltage stability. The design and analysis of accurate methods to evaluate the voltage stability of a power system and predict incipient voltage instability, are therefore of special interest in the field of power system protection and planning.

Static and dynamic approaches are used to analyze the problem of voltage stability. Dynamic analysis provides the most accurate indication of the time responses of the system [5]. Voltage stability indices is to predict which bus/line/path is most critical from the voltage stability perspective by assessing at the various parameters of the power system at a particular operating condition. In [7], an index called L-index is calculated for all the load buses in the system based on the elements and the voltage phasors. The load buses whose L-index values are near 1 indicate that they are prone to voltage instability.

In the literature not much work has been done to study the effect of active power loading on the behavior of variation of L-Indices. In the [6], the effect of reactive power on the voltage stability is been studied. Lot of experiments are done and simulations were carried out to find out the effect of active power on voltage stability. Several practical rural radial distribution feeders in India have been successfully analyzed and plots of L-Index and variation of L-Index with the variation of active power are section.

In this paper the effect of reducing real power at a bus on the remaining buses for radial and meshed systems is found out. Active Power L-Index Sensitivities(L_P) matrix which gives the information of the change in value of L-Index [7] with change in real power at any bus in the system has been proposed. A new method is developed to improve the stability of the system using Active Power L-Index sensitivities approach(L_P) which is applicable to improve the stability of radial and meshed systems. Linear programming optimization technique has been used to get location and amount of active power to be changed to make system stable.

III.LITERATURE REVIEW

A. L-Index

This method is proposed in [7] to find the buses which are most prone to voltage instability. In this method the Y_{bus} matrix of the system is split into rows and columns of generators and load buses.

$$\begin{bmatrix} I_G \\ I_L \end{bmatrix} = \begin{pmatrix} Y_{GG} & Y_{GL} \\ Y_{LG} & Y_{LL} \end{pmatrix} \begin{bmatrix} V_G \\ V_L \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} V_L \\ I_G \end{bmatrix} = \begin{pmatrix} Z_{LL} & F_{LG} \\ K_{GL} & Y_{GG} \end{pmatrix} \begin{bmatrix} I_L \\ V_G \end{bmatrix} \quad (2)$$

$$F_{LG} = - [Y_{LL}]^{-1} [Y_{LG}] \quad (3)$$

$$L_j = \left| 1 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \right| \quad (4)$$

where the subscript

“G” :- refers to the generator buses in the system

“L” :- refers to the load buses in the system

A L-index value away from 1 and close to 0 indicates a large voltage stability margin. The maximum of L-indices(L_{max}) of the buses to which it corresponds is the most critical bus. Also the summation of the squares of the L indices of the individual buses(ΣL^2) is used as a relative indicator of the overall voltage stability of the system at different operating conditions [8].

B. Participation Factors

The participation factor has been proposed in [9]. It is developed as follows. Consider the load flow jacobian

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{pmatrix} H & N \\ M & L \end{pmatrix} \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} \quad (5)$$

Although both P and Q changes affect system conditions, it is possible to study the effects of reactive power injections on the voltage stability by setting ΔP(P constant) and deriving the Q-V sensitivities at different loads. Thus the Equ.5 can be written as

$$\Delta Q = [L - M H^{-1} N] \Delta V = J_R \Delta V \quad (6)$$

$$J_R = \xi \Lambda \eta \quad (7)$$

where

Λ :- left eigen matrix of J_R

η :- right eigen matrix of J_R

ξ :- eigenvalues of J_R

The participation factors for the bus *k* and the critical mode *i* are defined as $\xi_{ki}\eta_{ik}$

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IV. EFFECT OF ACTIVE POWER LOADING ON L-INDEX

L-index for the 15 bus radial system given in Appendix Table VII is calculated at each bus, but for better visualization of pattern of variation of L-Index the points are connected with a solid line as shown in the Fig. 1. To examine the active power loading effect the 15 bus system is slightly altered. All the branch impedances and loads are considered to be equal in each iteration, and P load is increased in each step at all the buses from 200KW to 400KW in steps of 25KW and pattern of variation of L-Index is plotted in Fig. 2. From the Fig. 2 it is observed that the pattern of variation of L-Index doesn't change as the loads are increased but as the P load is increased the each pattern get lifted up i.e the system is moving towards voltage instability.

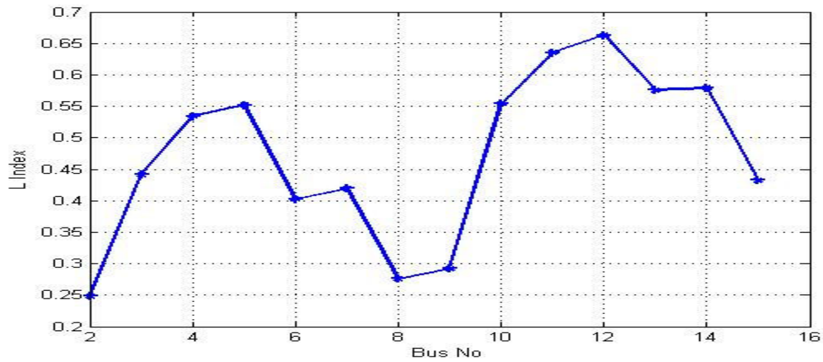

Figure 1: variation of L-Index for 15 bus radial system.

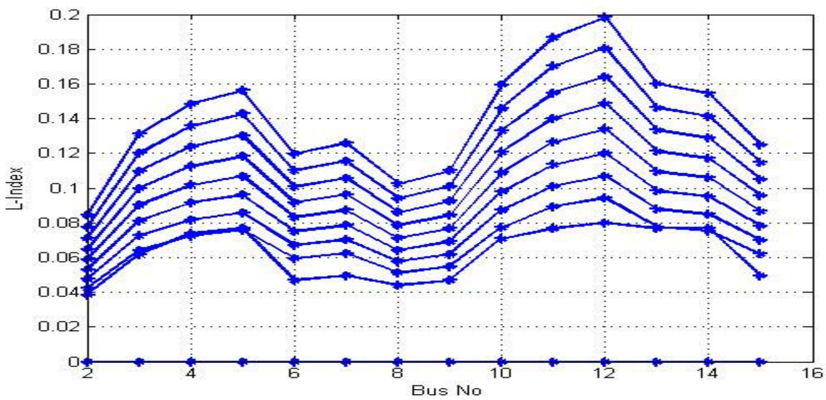

Figure 2: Variation of L-Index for 15 bus radial system when active power is changed

V. DERIVATION OF ACTIVE POWER L-INDEX SENSITIVITIES

L-Index as introduced in section would predict voltage stability.
Let {1,2,3..........g} be no of generator buses
{g+1,g+2,g+3..........n} be no of load buses

$$L_j = \left| 1 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \right| \tag{8}$$

where the subscript
"G" :- refers to the generator buses in the system
"L" :- refers to the load buses in the system
Squaring the equation Equ.8 we get

$$L_j^2 = \left(\left| 1 - \sum_{i=1}^{i=g} F_{ji} \frac{V_i}{V_j} \right| \right)^2 \tag{9}$$

Let $K_j = L_j^2$
differentiating Equ.9 we get

$$\frac{\Delta K_j}{\Delta V_J} = -2\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right) \quad (10)$$

From the newton's power flow equation we have

$$\begin{bmatrix}\Delta P\\ \Delta Q\end{bmatrix} = \begin{pmatrix}J_{11} & J_{12}\\ J_{21} & J_{22}\end{pmatrix}\begin{bmatrix}\Delta\theta\\ \Delta V\end{bmatrix} \quad (11)$$

In order to see the effect of change in real power, make ΔQ as zero. By doing so we have

$$[J_{11}]\,\Delta\theta + [J_{12}]\Delta V = \Delta P \quad (12)$$

$$[J_{21}]\,\Delta\theta + [J_{22}]\Delta V = 0 \quad (13)$$

Rewriting Equ. 12 we get

$$[J_{11}]\,\Delta\theta = \Delta P - [J_{12}]\Delta V \quad (14)$$

$$\Delta\theta = [J_{11}]^{-1}\,\Delta P - [J_{11}]^{-1}[J_{12}]\Delta V \quad (15)$$

Substituting Equ.15 in Equ. 13

$$[J_{21}]\,[J_{11}]^{-1}\Delta P - [J_{21}]\,[J_{11}]^{-1}\,[\,J_{12}]\Delta V + [J_{22}]\Delta V = 0 \quad (16)$$

$$[J_{21}]\,[J_{11}]^{-1}\Delta P = ([J_{21}]\,[J_{11}]^{-1}\,[\,J_{12}]\Delta V - [J_{22}])\,\Delta V \quad (17)$$

$$([J_{21}]\,[J_{11}]^{-1}[J_{12}] - [J_{22}])^{-1}\,(\,[\,J_{21}]\,[J_{11}]^{-1}\,)\Delta P = \Delta V \quad (18)$$

Let $([J_{21}]\,[J_{11}]^{-1}[J_{12}] - [J_{22}])^{-1}\,(\,[\,J_{21}]\,[J_{11}]^{-1} = J_{RP}$

Let the elements of J_{RP} be

$$J_{RP} = \begin{pmatrix} b_{g+1,g+1} & b_{g+1,g+2} & \cdots & b_{g+1,n}\\ b_{g+2,g+1} & b_{g+2,g+2} & \cdots & b_{g+2,n}\\ \vdots & \vdots & \ddots & \vdots\\ b_{n,g+1} & b_{n,g+2} & \cdots & b_{n,n}\end{pmatrix} \quad (19)$$

$$\Delta V_j = \sum_{i=g+1}^{i=n} b_{ji}\Delta P_i \quad (20)$$

From Equ.10 we get

$$\Delta K_j = -2\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)\Delta V_j \quad (21)$$

Substituting Equ.20 in Equ.21

$$\Delta K_j = -2\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)\sum_{i=g+1}^{i=n} b_{ji}\Delta P_i \quad (22)$$

As $\Delta K_j = 2L_j\Delta L_j$
As $\Delta K_j = 2L_j\Delta L_j$

$$\Delta L_j = -\frac{1}{L_j}\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)\sum_{i=g+1}^{i=n} b_{ji}\Delta P_i \quad (23)$$

$$-\left|\frac{1}{L_j}\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)\sum_{i=g+1}^{i=n} b_{ji}\Delta P_i\right| = L_p$$

This is called Active Power L-Index sensitivity matrix.

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VI. NEW ALGORITHM FOR IMPROVEMENT OF VOLTAGE STABILITY

1. Calculate L-Index of all the load buses as given in section in section III-A
2. Calculate the Active Power L-Index sensitivity matrix as given in section V
3. Choose a limit for the L-Index, let it be L_{limit}.
4. Find the buses which is having L-Index more than L_{limit}, let the buses be [B_2 B_5 B_7].
5. Find ΔL_{red}, ΔL_{red} is taken for the buses which are exceeding $L_{limit.}$ ΔL_{red} = [ΔL_2 ΔL_5 ΔL_7].
6. Find the reduced Active Power L-Index Sensitivity matrix (L_{rp}), this matrix would relate ΔL_{rp} and ΔP_{red} where ΔP_{red} = [P_2 P_5 P_7].
7. $\Delta L_{red} = \Delta L_{rp}\, \Delta P_{red}$
8. Take $\Sigma\, \Delta P_{red}$ as the objective function
9. Now perform optimization minimizing objective function satisfying the constraints $\Delta L_{min} \le \Delta L \le \Delta L_{max}$ where
   $\Delta L_{min} = \Delta L_{actual} - \Delta L_{limit}$
   $\Delta L_{max} = [1] - L_{actual}$
10. From the above algorithm it will be known that the amount of active power to be reduced at each bus for increasing the voltage stability.

VII. EXPERIMENTAL RESULTS

In order to illustrate the effectiveness of the algorithm the proposed method is implemented on 15 bus system with its loads increased four times of the base case given in Appendix Table VII.

From the above we get

$$\Delta V_j = \sum_{i=g+1}^{i=n} a_{ji}\Delta Q_i \tag{24}$$

$$\Delta V_j = \frac{\Delta K_j}{2\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)} \tag{25}$$

$$\Delta K_j = 2\left(1-\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j}\right)\left(\sum_{i=1}^{i=g} F_{ji}\frac{V_i}{V_j^2}\right)\sum_{i=1}^{i=g} a_{ji}\Delta Q_i \tag{26}$$

Let us take limit for L-Index (L_{limit}) as 0.5.

Buses exceeding L_{limit} are [B_4 B_5 B_{10} B_{11} B_{12} B_{13} B_{14}].

ΔLred = [ΔL_4 ΔL_5 ΔL_{10} ΔL_{11} ΔL_{12} ΔL_{13} ΔL_{14}]

ΔL_{max} = [0.53477 0.55196 0.55438 0.63536 0.66316 0.57598 0.57918]

ΔL_{min} = [0.034772 0.05196 0.054382 0.13536 0.16316 0.075981 0.079177]

Imposing the condition $\Delta L_{min} \le \Delta L \le \Delta L_{max}$ and running optimization program, the values of active power to be reduced are obtained in Table V. From the sensitivity matrix it can be seen that each row is having a maximum element in that row.

In order to show the consistency of the L-Index sensitivities method ΔL is calculated for the 15th bus system given in Fig.3 reducing the real load (P) by 120KW at 12th bus from L-Index sensitivities method. ΔL is calculated as (L-Index (with real load reduced)) – (L-Index(with actual load)) from the conventional method as given in Section III-A. Values of ΔL from both methods is tabulated in Table IV. From the Table IV it can be seen that the values of ΔL as obtained from the both methods are very much close to each other so it can concluded that L-Index sensitivities method derived in section V is correct.

TABLE-I
L-INDEX VALUE FOR THE ABOVE SYSTEM

Bus no	L-Index
2	0.24834
3	0.44128
4	0.53477
5	0.55196
6	0.40247
7	0.41961
8	0.27638
9	0.29233
10	0.55438
11	0.63536
12	0.66316
13	0.57598
14	0.57918
15	0.43284

TABLE-II
SENSITIVITY MATRIX OF A 15 BUS EXPERIMENT SYSTEM

	2	3	4	5	6	7	8	9	10	11	12	13	14	15
2	0.03488	0.049293	0.056216	0.057482	0.04499	0.046093	0.036493	0.03741	0.05809	0.064528	0.066744	0.059308	0.059556	0.046966
3	0.056945	0.11593	0.13221	0.13519	0.073451	0.075251	0.059578	0.061076	0.13662	0.15176	0.15697	0.13948	0.14006	0.076676
4	0.069214	0.14091	0.18762	0.19184	0.089276	0.091464	0.072415	0.074235	0.16605	0.18446	0.19079	0.19794	0.19877	0.093197
5	0.071575	0.14571	0.19402	0.24592	0.092321	0.094584	0.074885	0.076768	0.17172	0.19075	0.1973	0.20469	0.20555	0.096376
6	0.05042	0.071254	0.081261	0.083091	0.13084	0.13387	0.052751	0.054078	0.08397	0.093276	0.096479	0.08573	0.086089	0.13627
7	0.052299	0.073909	0.084289	0.086187	0.13571	0.16877	0.054717	0.056093	0.087099	0.096752	0.10007	0.088925	0.089297	0.143135
8	0.037318	0.052738	0.060145	0.061499	0.048134	0.049314	0.074348	0.07611	0.06215	0.069038	0.071408	0.063453	0.063718	0.050248
9	0.038741	0.054749	0.062438	0.063844	0.04997	0.051194	0.077183	0.10943	0.064519	0.07167	0.074131	0.065872	0.066148	0.052164
10	0.072259	0.1471	0.16776	0.17154	0.093203	0.095487	0.0756	0.077501	0.23359	0.25871	0.26736	0.17699	0.1773	0.097296
11	0.084453	0.17193	0.19608	0.20049	0.10893	0.1116	0.088358	0.09058	0.27301	0.39521	0.40814	0.20686	0.20772	0.11372
12	0.08886	0.1809	0.20631	0.21095	0.11462	0.11742	0.092969	0.095306	0.28725	0.41584	0.50713	0.21765	0.21856	0.11965
13	0.074997	0.15268	0.20329	0.20787	0.096734	0.099105	0.078465	0.080437	0.17992	0.19987	0.20673	0.28838	0.21537	0.1889
14	0.075463	0.15363	0.20456	0.20916	0.097336	0.099721	0.078953	0.080937	0.18104	0.20111	0.20801	0.21581	0.25668	0.10161
15	0.053792	0.07602	0.086696	0.088649	0.13959	0.14283	0.05628	0.057695	0.089586	0.099515	0.10293	0.091465	0.091847	0.17235

TABLE III
REDUCED SENSIVITY MATRIX OF 15 BUS EXPERIMENT SYSTEM

	4	5	10	11	12	13	14
4	0.18762	0.19184	0.16605	0.18446	0.19079	0.19794	0.19877
5	0.19402	0.24592	0.17172	0.19075	0.1973	0.20469	0.20555
10	0.16776	0.17154	0.23359	0.25871	0.26736	0.17699	0.17773
11	0.19608	0.20049	0.27301	0.39521	0.40814	0.20686	0.20772
12	0.20631	0.21095	0.28725	0.41584	0.50713	0.21765	0.21856
13	0.20329	0.20787	0.17992	0.19987	0.20673	0.28838	0.21537
14	0.20456	0.20916	0.18104	0.20111	0.20801	0.21581	0.25668

TABLE IV
COMPARISION OF ΔL FROM BOTH METHODS

Bus no	ΔL from L-Index sensitivities	ΔL from conventional method
2	0.0080092	0.0074559
3	0.018836	0.017441
4	0.022895	0.021141
5	0.023676	0.021852
6	0.011577	0.010747
7	0.012009	0.011144
8	0.008569	0.0079736
9	0.0088957	0.0082757
10	0.032083	0.029609
11	0.048976	0.044981
12	0.060855	0.055704
13	0.024807	0.022881
14	0.024962	0.023021
15	0.012352	0.01146

TABLE V
OPTIMAL AMOUNT OF ACTIVE POWER TO BE REDUCED IN 15 BUS RADIAL SYSTEM

Bus no	Amount of real power to be reduced
4	0
5	0
10	0
11	0.12159
12	0.2
13	0
14	0.051117

TABLE VI
OPTIMAL AMOUNT OF ACTIVE POWER TO BE REDUCED IN IEEE 14 BUS SYSTEM

Bus no	Amount of power to be reduced
4	0
5	0.22485
7	0.20017
9	0.15241
10	0.24133
11	0.16807
12	0.096743
13	0.12373
14	0.15785

VIII. CONCLUSIONS

This paper is essentially concerned with the analyzing and improvement of voltage stability of radial power systems and meshed power systems. Pattern of variation of L-Index is been observed and their dependence on the real power loading is studied. A new algorithm is found to optimally reduce the amount of active power to improve the voltage stability to the required level. A new sensitivity matrix Active Power L-Index Sensitivity(L_P) which would relate the change in real power effect on the voltage stability is proposed. Buses at which the Active Power have to be reduced to improve the voltage stability are identified.

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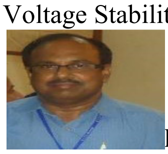

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APPENDIX

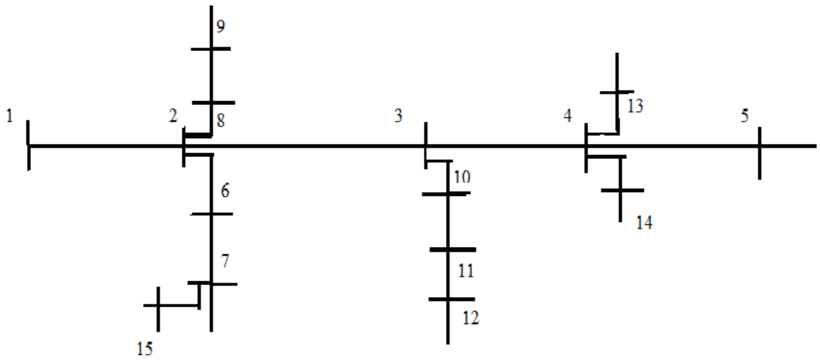

TABLE VII
LINE DATA AND NOMINAL LOAD DATA OF 15 BUS SYSTEM

Node	PL_o (kW)	QLo (kVAR)	Sending end	Receiving node	R (ohms)	X (ohms)
1	0	0	1	2	1.35309	1.32349
2	44.1	44.1	2	3	1.17024	1.14464
3	70	70	3	4	0.84111	0.82271
4	140	140	4	5	1.52348	1.02760
5	44.1	44.1	2	8	2.01317	1.35790
6	140	140	8	9	1.68671	1.13770
7	70	70	2	6	2.55727	1.72490
8	70	70	6	15	1.08820	0.73400
9	44.1	44.1	6	7	1.25143	0.84410
10	140	140	3	10	1.79553	1.21110
11	70	70	10	11	2.44845	1.65150
12	44.1	44.1	11	12	2.01317	1.35790
13	70	70	4	13	2.23081	1.50470
14	140	140	4	14	1.19702	0.80740
15	140	140				