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Loss Reduction in Radial Distribution Systems by Optimal Voltage Regulator Placement Using Fuzzy Logic

N. Visali, *Member, IAENG,* D.R. Srinivasan, N. Sreenivasulu

***Abstract* - The reduction of total loss in distribution systems is very essential to improve the overall efficiency of power delivery. This can be achieved by placing automatic voltage regulators at proper locations in Radial Distribution Systems (RDS). In this paper, two novel methods are proposed for selecting the optimal number, location and tap setting of voltage regulators in RDSs. The first method is an analytical method named as back tracking algorithm and the second method is based on Fuzzy logic The aim of proposed methods is to maintain the voltage within the acceptable limits and reduce the total losses in the RDS by maximizing the objective function, which represents the net savings on capital investment on VRs and capitalized costs of energy losses.**

The effectiveness of the proposed methods is illustrated with two examples a 47 bus practical RDS and a 69 bus RDS. The results obtained from both the methods are presented and compared.

***Index Terms* - Fuzzy expert systems, Radial distribution system, Tap position, Voltage regulator**

I INTRODUCTION

In the operation of a distribution system, control of reactive power and voltage are very important. A proper control of voltage will improve voltage profile, which reduces the system loss and improves the system efficiency. The different methods that are generally used to maintain the voltages in RDS are by providing Shunt capacitors, Voltage Regulators (VRs) and by employing conductor grading in RDS.

Reactive power control and voltage control of RDS using shunt capacitors and voltage regulators is respectively reported in [1-3]. The voltage stability analysis of radial distribution networks is presented in [4].

In [5], neural networks for combined control of capacitor banks and voltage regulators in distribution systems are presented. The optimal placement of voltage regulators in RDS is presented in [6] in which the authors have not considered the effect of load variation on selection and placement of voltage regulators. A.N. Ng et. al [7] have proposed the capacitor allocation problem by approximate reasoning using fuzzy capacitor placement

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N. Visali is with the Department of Electrical and Electronics Engineering, JNTUA College of Engineering, Pulivendula, Kadapa, Andhra Pradesh, India. (Phone: 09440202996; e-mail: nvisali@gmail.com).

D. R. Srinivasan is with the Department of Mechanical Engineering, JNTUA College of Engineering, Pulivendula, Kadapa, Andhra Pradesh, India. (e-mail: srinivasandrs@gmail.com).

N. Sreenivasulu is with the Department of Electrical and Electronics Engineering, Srinivasa Ramanujan Institute of Technology, Anantapur, Andhra Pradesh, India. (e-mail: nsratp@gmail.com).

In this paper, two new algorithms are proposed which gives the best location, optimal number and tap setting of VRs ensuring the bus voltage variations within ±5% of rated voltage and minimizing the losses. The voltage regulators, which are determined by the proposed methods, will optimize the savings in capital cost of VR and cost of energy loss in RDS and in addition maintain the acceptable voltage limits at all buses. The proposed methods are easy and simple to implement for any radial distribution system since it is independent of the size of the system. The first method of approach (back tracking algorithm) is illustrated with a 19 bus RDS in the next section. The second method of approach (Fuzzy based voltage regulator placement), a fuzzy expert system containing a set of heuristic rules is illustrated with two examples to determine the VR placement in the RDS.

II PROCEDURE FOR DETERMINING OPTIMAL LOCATION AND NUMBER OF VOLTAGE REGULATORS USING BACK TRACKING ALGORITHM

The vector based distribution load flow method [8] is used to calculate the voltage at each bus, total real and reactive power losses in the system.

Consider a typical branch of a RDS and can be represented by a single line equivalent circuit as shown in Fig 1.

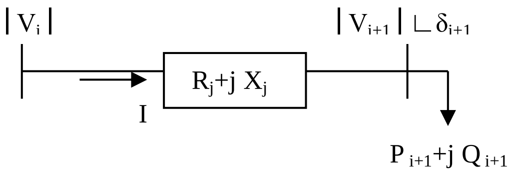

Fig 1 Single line equivalent circuit

The voltage at bus i+1 can be calculated as

$$|V_{i+1}| = \left(P_{i+1} \times R_j + Q_{i+1} \times X_j - 0.5 \times |V_i|^2\right) - \left(\left(R_j^2 + X_j^2\right)\left(P_{i+1}^2 + Q_{i+1}^2\right) - \left(P_{i+1} \times R_j + Q_{i+1} \times X_j - 0.5 \times |V_i|^2\right)^2\right)^{1/2} \quad (1)$$

where

i=1,2,…… number of buses.

j=1,2,……. number of branches

In order to have better voltage profile for given load conditions at all buses, the voltage at each bus should be between specific limits of V_{min} and V_{max}. This requires that the maximum percentage voltage drop along the feeder should be less than a definite percentage of rated voltage. If this requirement is not satisfied, the voltage regulators are to

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be employed at the proper buses so as to improve the voltage profile, which in turn also reduces the losses in the system.

In order to reduce the losses, it is necessary to install VR at each bus, so as to improve the voltage profile, which leads to minimizing the cost of losses.

The objective function is formulated as maximizing the cost function,

$$\text{Max.F} = K_e \times \Delta P \times 8760 \times LLf - K_{VR} \times N(\alpha + \beta) \qquad (2)$$

where

ΔP = Reduction in total real power loss due to installation of VR in kW
= (Real power loss before installation of VR – Real power loss after installation of VR)
K_e = Cost of energy in Rs./kWh
LLf = Loss load factor = 0.8 × $(Lf)^2$ + 0.2×Lf
Lf = load factor
N = Number of voltage regulators
K_{VR} = Cost of each VR in Rs./unit
α = the rate of annual depreciation charges on VR
β = Operation and maintenance charges of VR.
(Generally it is taken as percentage of cost of VR)

This optimization problem consists of two sub problems, that of optimal placement and optimal choice of tap setting of VRs. The first sub problem determines the location and number of VRs to be placed and the second sub problem decides the tap positions of VR. The first step involves the selection of VRs at the buses where the voltage is violating the upper and lower limits.

To illustrate the approach let the voltage regulators are located initially at buses 8, 11, 13 and 18 as shown in Fig 2a. The optimal number and placement of voltage regulators required is obtained by applying the proposed backtracking algorithm.

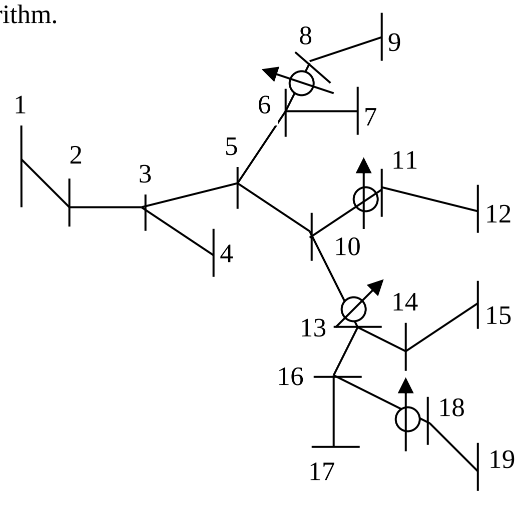

Fig 2a The 19 bus RDS with Voltage regulators at buses 8,11,13 and 18

It is proposed to reduce the number of VRs in a practical system by shifting the VR's to the junction of laterals (such as from buses 11 and 13 to bus 10) and observe the voltage profile and also the objective function by computing voltages at each bus. If it satisfies the above two constraints, then this will be taken as optimal position for the single VR at bus 10 instead of two VRs at buses 11 and 13 (shown in Fig 2b). This procedure is repeated starting from the tail end buses towards the source bus and find the optimal number and location of VRs.

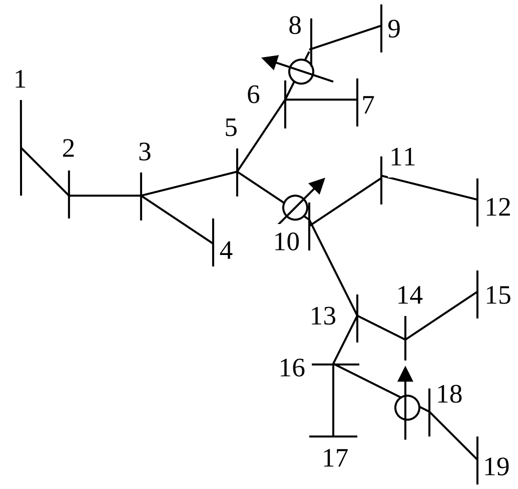

Fig 2b The 19 bus RDS after installation of Voltage regulators at buses 8,10 and 18

A. Selection of Tap Position of VRs

After finding the optimal number and location of VRs, tap position of a VR is to be determined as follows:

In general, VR position at bus 'j ' can be calculated as

$$V_j' = V_j \pm tap \times V_{rated} \qquad (3)$$

where

tap = tap position of VR
V_j' = voltage at bus 'j' after installation of VR at bus j.
V_j = voltage at bus 'j' before installation of VR at bus j.
V_{rate} = Rated voltage.
'+' for boosting of voltage. '-' for bucking of voltage.

Tap position (tap) can be calculated by comparing voltage obtained before VR installation with the lower and upper limits of voltage

The voltage at all buses is computed by load flow analysis [8, 9] for every change in tap setting of VRs, till all bus voltages are within the specified limits. Then obtain the net savings, with above tap settings for VRs.

III ALGORITHM FOR OPTIMUM VOLTAGE REGULATOR PLACEMENT IN RDS USING BACK TRACKING ALGORITHM

Step 1: Read line and load data.
Step 2: Run load flows for the base system and compute the voltage at each bus, total real and reactive power losses of the system.
Step 3: Identify the buses, which have violation in voltage limits.
Step4: Obtain optimal number and location of VRs by using back tracking algorithm
Step 5: Obtain the optimal tap position of VR using Eqn. (3), so that the voltage is within the specified limits.
Step 6: Again run the load flows with VR, then compute voltage at all buses, total real and reactive power

losses. If voltages are not within the limits, repeat from step 3.

Step 7: Determine the reduction in total real power loss and net saving by using objective function (Eqn. (2)).

Step 8: Print results.

Step 9: Stop.

IV IMPLEMENTATION ASPECTS OF FUZZY BASED VOLTAGE REGULATOR PLACEMENT

The Fuzzy Expert System (FES) contains a set of rules, which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy inference, whereas in a conventional Expert System, a rule is either fired or not fired. For the VR placement problem, rules are defined to determine the suitability of a bus where VR is placed. Such rules are expressed in the following form:

If premise (antecedent), THEN conclusion (Consequent)

For determining the suitability of a particular bus for VR placement, sets of multiple-antecedent fuzzy rules have been established. The inputs to the rules are the bus voltages in p.u., power loss indices and the output consequent is the suitability of bus where VR is going to be placed. The rules are summarized in the fuzzy decision matrix in Table I. The consequents of the rules are in the shaded part of the matrix.

The fuzzy variables power loss index, voltage and VR placement suitability are described by the fuzzy terms high, high-medium/normal, medium/normal, low-medium/normal and low. The fuzzy variables described by linguistic terms are represented by membership functions. These are graphically shown in Figs 3 to 5.

Table I Decision matrix for determining suitable VR locations

And		Voltage				
		Low	Low-Norm-al	Nor-mal	High-Nor-mal	High
Power Loss Index (PLI)	Low	Low-Med.	Low-Med.	Low	Low	Low
	Low Med.	Med.	Low-Med.	Low-Med.	Low	Low
	Med.	High-Med.	Med.	Low-Med.	Low	Low
	High-Med.	High-Med.	High-Med.	Med.	Low-Med.	Low
	High	High	High-Med.	Med.	Low-Med.	Low-Med.

A. Fuzzy Inferencing and Defuzzification Process

After the FES receives inputs from the load flow program, several rules may fire with some degree of membership. The fuzzy inference methods are used to determine the aggregated output from a set of triggered rules.

The MAX-MIN METHOD [10, 11] involves truncating the consequent membership function of each fired rule at the minimum membership value of all the antecedents. A final aggregated membership function is achieved by taking the union of all the truncated consequent membership functions of the fired rules. For the voltage regulator problem, resulting VR placement suitability membership function, μs, of node i for k fired rules is

$$\mu_S (i) = \max_k [\min [\mu_p (i), \mu_v (i)]]$$

where μ_p and μ_v are the membership functions of the power loss index and voltage level respectively.

Once the suitability membership function of a bus is calculated, it must be defuzzified in order to determine the buses of suitability ranking.

The centroid method of defuzzification is used; this finds the centre of area of the membership function. Thus, the VR suitability index is determined by:

$$S = \int \mu_s (z).z\, dz / (\int \mu_s (z)\, dz)$$

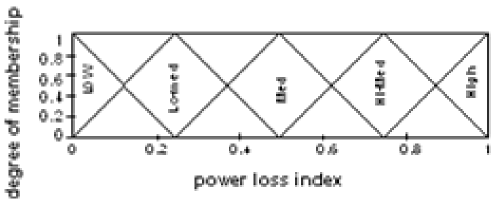

Fig 3 Power loss index membership function

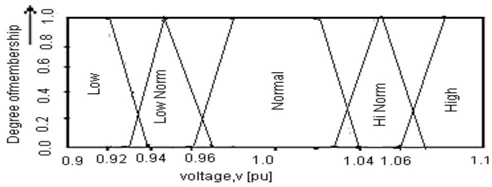

Fig 4 Voltage membership function

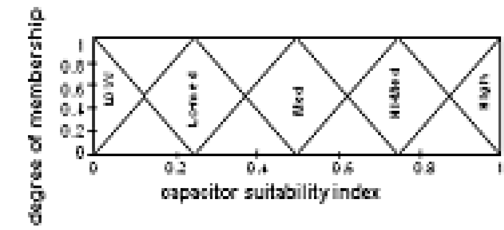

Fig 5 Voltage Regulator suitability index membership function

V ALGORITHM FOR OPTIMUM VOLTAGE REGULATOR PLACEMENT IN RDS USING FUZZY LOGIC

Step 1: Read line and load data.

Step 2: Run load flows for the base system and compute the voltage at each bus, total real and reactive power losses of the system.

Step 3: Run the load flow program by placing VR at each bus, considering one bus at a time, and calculate the power losses of the system.

Step4: The power-loss indices and the per-unit bus voltages are the inputs to the fuzzy expert system.

Step 5: The outputs of FES are defuzzified using centroid defuzzification method. This gives the ranking of

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VR suitability.

Step 6: Find the minimum value of VR suitability index at which the voltages are minimum and the buses which are having minimum suitability index are the best suitable nodes for a VR placement.

Step 7: Obtain the optimal tap position of VR using Eqn. (3), so that the voltage is within the specified limits.

Step 8: Again run the load flows with VR, then compute voltage at all buses, total real and reactive power losses. If voltages are not within the limits, repeat from step 3.

Step 9: Determine the reduction in total real power loss and net saving by using objective function (Eqn. (2)).

Step 10: Print results.

Step 11: Stop.

VI RESULTS AND ANALYSIS

The proposed methods are illustrated with two radial distribution systems of 47 bus and 69 bus.

A. Example 1

Consider a 47 bus existing practical RDS in Anantapur town, Andhra Pradesh, India. The line and load data is given in Appendix and the single line diagram is shown in Fig 6. For the positioning of voltage regulators, the upper and lower bounds of voltage are taken as ±5% of base value. The voltage regulators are of 11kV, 200MVA with 32 steps of 0.00625 p.u. each.

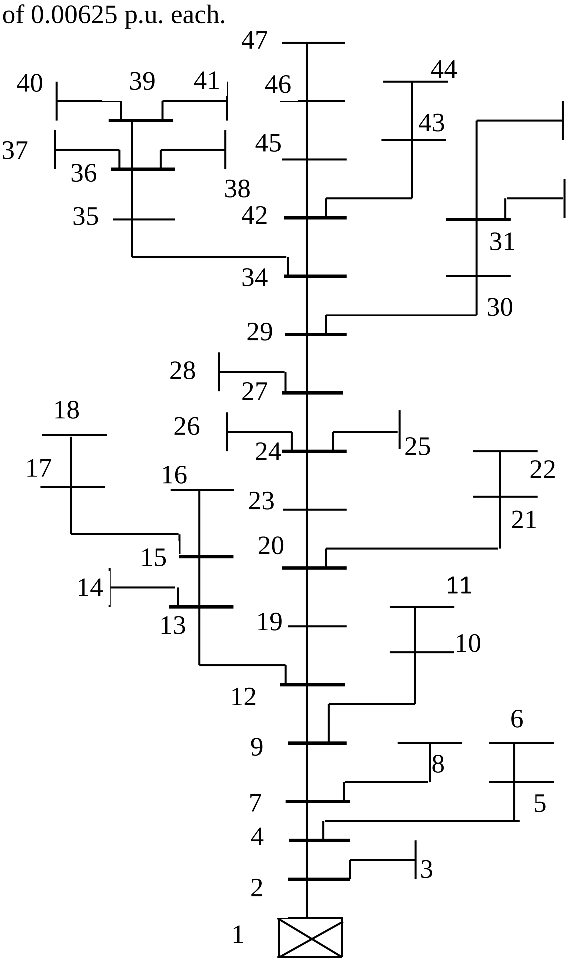

Fig 6 Single line diagram of 47 bus practical RDS

Load flow solution of 47 bus RDS without and with voltage regulators is given in Table II. Observing the voltage levels in first column of Table II, it is found that all bus voltages except at bus 1 violate the lower limit of 0.95 p.u. Ideally, voltage regulators are to be installed at all buses except at bus 1. However, in practice, it is not economical to have voltage regulators at all buses and hence by applying the proposed methods the optimal number of voltage regulators required to maintain the voltage profile within the above limits is determined. By applying the proposed back tracking algorithm for this system it is found that voltage regulators at buses 2, 36 and 42 are sufficient to maintain the voltages within limits at all buses. By applying the fuzzy based VR placement method it is found that two voltage regulators at 2^{nd} bus is sufficient to maintain the voltages within limits at all buses.

Table II Load flow results with and without voltage Regulators

Bus No.	Bus voltages without VR placement	Bus Voltages with Voltage regulators at 2, 36, 42 buses (Back Tracking method)	Bus Voltages with Voltage regulators at 2^{nd} bus (Fuzzy based method)
1	1.0000	1.0000	1.0000
2	0.9378	1.0378	1.0440
3	0.9376	1.0377	1.0439
4	0.9132	1.0160	1.0224
5	0.9128	1.0156	1.0220
6	0.9126	1.0155	1.0218
7	0.9090	1.0122	1.0187
8	0.9087	1.0120	1.0184
9	0.9004	1.0046	1.0110
10	0.9001	1.0043	1.0108
11	0.8997	1.0040	1.0105
12	0.8911	0.9963	1.0028
13	0.8863	0.9921	0.9986
14	0.8861	0.9919	0.9984
15	0.8852	0.9911	0.9977
16	0.8848	0.9908	0.9973
17	0.8846	0.9905	0.9971
18	0.8842	0.9902	0.9967
19	0.8839	0.9900	0.9965
20	0.8760	0.9830	0.9896
21	0.8754	0.9825	0.9891
22	0.8751	0.9822	0.9888
23	0.8555	0.9645	0.9716
24	0.8536	0.9632	0.9699
25	0.8533	0.9630	0.9697
26	0.8531	0.9628	0.9696
27	0.8508	0.9607	0.9675
28	0.8507	0.9607	0.9674
29	0.8480	0.9583	0.9651
30	0.8469	0.9573	0.9641
31	0.8455	0.9561	0.9629
32	0.8452	0.9558	0.9626
33	0.8452	0.9559	0.9626
34	0.8438	0.9546	0.9614
35	0.8420	0.9530	0.9598
36	0.8375	1.0490	0.9558
37	0.8373	1.0488	0.9557

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38	0.8372	1.0487	0.9556
39	0.8362	1.0480	0.9547
40	0.8359	1.0477	0.9545
41	0.8357	1.0476	0.9543
42	0.8381	1.0495	0.9564
43	0.8373	1.0489	0.9557
44	0.8370	1.0486	0.9554
45	0.8344	1.0466	0.9532
46	0.8333	1.0457	0.9522
47	0.8330	1.0454	0.9519

The percentage of total real power loss, net saving and % voltage regulation for this system is shown in Table III.

Table III Summary of results of 47 bus RDS

Parameter	Base case	With VRs	
		VR at buses 2, 36, 42 Back Tracking method)	VR at bus 2 (Fuzzy based method
Total real power loss (%)	16.684	13.095	12.965
Net saving (Rs.)	-----	2,79,380/-	3,26,170/-
Voltage regulation (%)	16.7039	4.6964	4.8106

It is observed from Table III, without voltage regulators in the system the percentage of total real power loss is 16.684 and percentage of voltage regulation is 16.7039. With voltage regulators at optimal locations (obtained with Back tracking method)) of buses 2, 36 and 42 the percentage of total real power loss is reduced to 13.095 and percentage voltage regulation is reduced to 4.6964. The optimal net saving is Rs.2, 79,380/-. The two voltage regulators at optimal location (obtained with Fuzzy logic VR placement method)) of bus 2 the percentage of total real power loss is reduced to 12.965 and percentage voltage regulation is reduced to 4.8106. The optimal net saving is Rs.3, 26,170/-.

B. Example 2

The proposed methods are also tested with 69 bus RDS. The line and load data of this system is given in [12]. The summary of test results is presented in Tables IV respectively.

Table IV Summary of results of 69 bus RDS

Parameter	Base case	With VRs	
		VR at bus 57 (Back Tracking method)	VR at bus 6 (Fuzzy based method)
Total real power loss (%)	5.932	5.337	5.237
Net saving (Rs.)	-----	1,12,980/-	1,37,490/-
Voltage regulation (%)	9.0811	4.3502	2.9496

It is observed that, from Table IV, without voltage regulators in the system the percentage of total real power loss is 5.932 and percentage of voltage regulation is 9.0811. With voltage regulator at optimal location (obtained with Back tracking method) of bus 57 the percentage of total real power loss is reduced to 5.337 and percentage voltage regulation is reduced to 4.3502. The optimal net saving is Rs.1, 12,980/-. The two voltage regulators at optimal location (obtained with Fuzzy logic VR placement method)) of bus 2 the percentage of total real power loss is reduced to 5.237 and percentage voltage regulation is reduced to 2.9496. The optimal net saving is Rs.1, 37,490/-.

VII CONCLUSIONS

In this paper, two novel methods for finding optimal number, location and tap setting of voltage regulators in RDS have been proposed which ensure the voltages at all buses of the RDS are within the limits resulting in better voltage regulation. In addition the proposed algorithms reduce the total power loss that maximizes the net savings of the system. The effectiveness of the proposed methods is illustrated with a practical existing 47 bus system and a 69 bus system. From the results it is observed that at most of the buses the voltage limits are violated for the base case (without VRs). Instead of placing the VRs at all violated buses, using proposed methods the optimal location and number of voltage regulators with tap positions is obtained satisfying the voltage limits at all buses, minimizing the losses thereby maximizing the net savings.

By comparing the above two proposed methods it is found that the Fuzzy based VR placement method gives a better voltage profile and higher savings with less number of VRs than back tracking algorithm method.

APPENDIX

Line Parameters: R= 0.6108Ω/km X= 0.3521Ω/km

Table A Line & load data of 47 bus practical RDS

Branch No.	**From bus**	**To bus**	**Length (km)**	**Bus No.**	**P (kW)**	**Q (kVAr)**
1	1	2	4.57	1	0	0
2	2	3	0.58	2	0	0
3	2	4	1.84	3	50.4	37.8
4	4	5	0.73	4	80	60
5	5	6	0.73	5	50.4	37.8
6	4	7	0.34	6	50.4	37.8
7	7	8	0.69	7	80	60
8	7	9	0.75	8	80	60
9	9	10	0.28	9	0	0
10	10	11	0.95	10	80	60
11	9	12	0.87	11	80	60
12	12	13	2.65	12	80	60
13	13	14	0.93	13	0	0
14	13	15	0.67	14	40	30
15	15	16	0.92	15	80	60

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16	15	17	0.95	16	80	60
17	17	18	0.93	17	50.4	37.8
18	12	19	0.85	18	80	60
19	19	20	0.97	19	60	45
20	20	21	0.82	20	80	60
21	21	22	0.77	21	50.4	37.8
22	20	23	2.95	22	80	60
23	23	24	0.29	23	50.4	37.8
24	24	25	0.56	24	0	0
25	24	26	1.5	25	80	60
26	24	27	0.47	26	50.4	37.8
27	27	28	0.29	27	0	0
28	27	29	0.48	28	40	30
29	29	30	0.87	29	0	0
30	30	31	1.29	30	50.4	37.8
31	31	32	0.82	31	50.4	37.8
32	31	33	1.06	32	80	60
33	29	34	0.96	33	50.4	37.8
34	34	35	0.79	34	0	0
35	35	36	2.25	35	40	30
36	36	37	0.6	36	40	30
37	36	38	1.05	37	50.4	37.8
38	36	39	1.05	38	50.4	37.8
39	39	40	0.95	39	80	60
40	39	41	1.09	40	50.4	37.8
41	34	42	2.69	41	80	60
42	42	43	0.78	42	0	0
43	43	44	0.8	43	80	60
44	42	45	3	44	80	60
45	45	46	1.5	45	80	60
46	46	47	1.08	46	80	60
				47	50.4	37.8

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