REDUCTION OF LOSSES IN RADIAL DISTRIBUTION LINES USING FUZZY LOGIC

By

MOHD FARIZ BIN DAUD

FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Mohd Fariz bin Daud

ABSTRACT

Distribution system provides the final link between the high voltage transmission system and the customers. Radial distribution system with a single circuit main feeder is popular because of simple design and generally low cost. The power loss in a distribution system is significantly high because of lower voltage hence high current and losses (I^2R). Reduction of reactive power is beneficial to improve overall efficiency and reduce cost. This project is to analyze losses in radial distribution system and compensate the losses with an intelligent method using fuzzy logic. Fuzzy logic is used together with numerical approach to determine the suitable candidate node for capacitor placement at distribution load busbar to compensate losses in the line. This report will articulate the work that has been done by the author in the project for the purpose of fulfillment of the Final Year Project.

ACKNOWLEDGEMENTS

Firstly, the author would like to express sincere gratitude to his supervisor, Ir. Perumal Nallagownden for all the support and guidance given throughout the period of this project. His experience and knowledge has helped a lot in making this project as it is now.

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In the process of conducting the project, the author has faced difficulties and sometimes becomes uninspired. Thousand thanks again for those who helped a lot in motivating and encouraging the author in finishing the project, who inspires the author directly or indirectly.

Last but not least, the author would also like to acknowledge Ms. Nasreen Badruddin and Mr. Mohd. Zuki Yusoff, the EE Final Year Project Coordinators, for all the guidance given in realizing and fulfilling the objectives of the project.

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CHAPTER 1

INTRODUCTION

This chapter illustrates the introduction part of the project. Introduction will consists of background study, problem statement, objectives and scope of study.

1.1 Background of Study

Cost and effectiveness are the main criteria in designing a power distribution system to the consumers. In a distribution system, power loss is a major issue in delivering the service. Loss due to active component of current cannot be minimized because all active power must be supplied by the source. However, loss due to reactive component of current can be reduced by supplying part of the reactive power demand locally.

There are several solutions to serve the purpose of compensating the reactive power. One of the methods is installing shunt capacitors in a distribution system to reduce the reactive power losses. This project involve of reviewing the existing shunt capacitor placement method and introducing fuzzy logic method to determine the suitable candidate nodes in a distribution system for capacitor placement.

1.2 Problem Statement

Distribution network is the intermediate network between the transmission system and the consumers. The problems that may be found in the distribution network affect both the consumers and utilities especially in the industries. One of these problems is the problem of voltage drop that must be reduced to keep the voltage at loads points within standard limits. The voltage drop may arise when using lateral radial feeders with long distance or feeding large loads i.e. in industries where power is needed for inductive loads such as motors, compressor or ballast to generate and sustain a magnetic field in order to operate.

That kind of power to be compensated is the reactive power which is also known as non-working power. Reactive power is always associated with power factor. Higher loss of reactive power leads to low power factor. In other words, reduction of reactive power has the same meaning with improvement of power factor and reduction of reactive power can reduce the total power.

1.3 Objectives and Scope of Study

1.3.1 Objectives

The main objective of this project is to study on the compensation of reactive power in the radial distribution system and to come out with an intelligent method to compensate the losses. For this project, the fundamental objectives are:

- To conduct a study on the radial distribution system
- To conduct a study and understand the concept of reactive power and losses
- To review and identify the techniques available for reactive power compensation
- To come out with an effective method for the loss reduction
- To evaluate the performance of the applicable technique and compare the result with other methods

After the appropriate method is reviewed, it will be adopted in this loss reduction process. The result obtained will be compared with results from previous works using other methods.

1.3.2 Scope of Study

The scope of study is mainly on the distribution network – regarding the losses, method to find the node with highest loss, compensation of the losses and method to find the solution of the best approach for loss reduction. This project uses fuzzy logic methods or approach as a technique to find the best solution for reactive power compensation. The later part of this project concentrates on applying fuzzy logic technique in radial distribution system for the purpose of reducing the losses.

CHAPTER 2

LITERATURE REVIEW AND THEORY

2.1 Overview on Distribution System

Basically a complete electric power consists of generation, transmission and distribution [12]. Distribution is the part that connects the high voltage transmission network to the low voltage consumer service point. It consists of distribution substation which converts transmission voltages ranges from 11kV or 33kV to distribution voltages of 240V for single phase or 415V for three phase.

2.1.1 Radial Distribution System

Radial distribution system is a system which the power distributor connects to the supply at one end only. Through this type of distribution system, the end of the distributor nearest to the generating station would be heavily loaded. The advantage of this configuration is lower cost of implementation. However, the disadvantage is that, when the nearest distributor has power interruption, it will affect the entire network. Most of the network configuration in Malaysia uses this system.

2.2 Reactive Power Losses in Distribution System

Reactive power is non-working power in KVAR unit where its amount in one direction is equal to the one flowing in the opposite direction [12]. Average reactive power in a system is zero. Reactive power is associated with power factor. The relationship between active, reactive and apparent power can be seen from the power triangle.

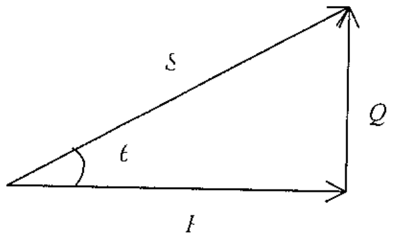


Figure 1 Power Triangle

$$PowerFactor = \frac{ActivePower, P}{ApparentPower, S} = \cos\theta = \frac{KW}{KVA}$$
$$ApparentPower, S = ActivePower, P + \mathrm{Re}\,activePower, Q$$

Reactive power is associated with power factor. Higher loss of reactive power leads to low power factor which is inefficient and expensive. Compensation [7][4] of reactive power means improvement of power factor and efficiency of the system.

There are generally many factors contribute to losses in distribution system. Among them are:

i. Long distribution distance which resulted in high line resistance and reactance, low voltage and high current that leads to high losses.
ii. Low power factor contributes towards high distribution losses.
iii. Location of distribution transformers – the farthest customers from the distribution transformers obtain an extremely low voltage even though a reasonably good voltage level is maintained at the transformer secondary.

The total power loss (P_L) in a distribution system having b number of branches is given by [7]:

$$P_L = \sum_{i=1}^{b} I_i^2 R_i \tag{2.1}$$

Here I_i and R_i are the current magnitude and resistance respectively, of the i-th branch. The branch current can be obtained from the load flow analysis. The branch current has two components; active (I_a) and reactive (I_r). The loss associated with the active and reactive components of branch currents can be written as:

$$P_{La} = \sum_{i=1}^{b} I_{ai}^2 R_i \tag{2.2}$$

$$P_{Lr} = \sum_{i=1}^{b} I_{ri}^2 R_i \qquad (2.3)$$

Note that, for a given configuration of a single source radial network, the loss P_{La} associated with the active component of branches cannot be minimized because all active power must be supplied by the source at the root bus. However, supplying a part of the reactive power demand locally by using capacitors of optimal size can minimize the loss P_{Lr} associated with the reactive component of branch currents.

2.2.1 Techniques to Reduce Reactive Losses

The most popular technique for compensating reactive power losses is using capacitors. Shunt capacitor compensation is the most popular method used since it is efficient and cost effective. Capacitors supply an amount of reactive power to the system at the point where they are connected [1]. Suitable capacitor banks at grid or main substation are desirable to compensate reactive power of lines [10].

According to *Salama*[4], there is a method of minimizing the lost of reactive power by placing optimal capacitors at proper location. The method first finds the location of the capacitor in sequential manner. Once the capacitor locations are identified, the size of optimal capacitor at each selected location is determined through optimizing the loss saving equation. According to the results, the busses as well as the corresponding optimal capacitors are determined in such a way that maximum loss reduction is achieved with minimum capacitor installment.

2.3 Load Flow Analysis [1]

Let us consider the IEEE 34-bus test system. In this method, the initial values of node voltages are assumed to be (1+j0) p.u. the load current at each node can be formed from the relation;

$$J_i = \frac{P_i - jQ_i}{V_i^*} + \frac{V_i}{Z_i} + Y_i V_i + I_{Li} \qquad (2.4)$$

$i = 1,2...nb$

Where nb → no. of nodes or buses

The branch currents can be written in terms of load currents of all nodes and simplified in matrix form as:

$$[I_b] = [C][J_L] \tag{2.5}$$

Where C ➔ branch to node matrix of k x k matrix

J_L ➔ Load current

The voltage drops across all branches can be computed from the relation:

$$[V_b] = [Z] \cdot [I_b] \tag{2.6}$$

Where I_b ➔ Branch current

The node voltages can be written in terms of branch voltages:

$$V_i = V_o - \sum_{j=1}^{b} C_{ji} V_j \tag{2.7}$$

i = 1,2,…n

Where b ➔ number of branches

The branch-to-node matrix, [C] is formed from the topology description of the given system (34-bus test system). The load currents, branch currents, branch voltages and node voltages are computed successively for a given set of load data and source node voltage, using previous equations, respectively by iteration process. The convergence is obtained when the difference between node voltages of two successive iterations is less than the specified values.

2.4 Loss Minimization by a Singly Located Capacitor [7][1]

Consider a single source radial distribution system with b branches and nb nodes. Let a capacitor C be placed at bus m and α be a set of branches connected between the source and the capacitor buses. If the capacitor is placed at bus 12 (m=12), the set α: consists of branches 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 and 11. The capacitor draws a reactive current I_c and for a radial network, it changes only the reactive component of current of branch set α.

The current of other branches ($\notin \alpha$) is unaffected by the capacitor. Thus the new reactive current I_{ri}^{new} of the *i*-th branch is given by:

$$I_{ri}^{new} = I_{ri} + D_i I_c \tag{2.8}$$

Where $D_i = 1$; if branch $I \propto \alpha$

= 0; otherwise

Here I^{ri} is the reactive current of the i^{th} branch in the original system obtained from the load flow solution. The loss $P_{Lr}{}^{Com}$ associated with the reactive component of branch current in the compensated system (when the capacitor is connected) can be written as:

$$P_{Lr}^{Com} = \sum_{i=1}^{b} (I_{ri} + D_i I_c)^2 R_i \tag{2.9}$$

The loss saving *S* is the difference between eqn. (2.3) and (2.9) is given by:

$$S = P_{Lr} - P_{Lr}^{Com} = -\sum_{i=1}^{b} (2D_i I_{ri} I_c + D_i I_c^2) R_i \tag{2.10}$$

The capacitor current I_c that provides the maximum loss saving can be obtained from:

$$\frac{\partial S}{\partial I_c} = -2\sum_{i=1}^{b} (D_i I_{ri} + D_i I_c) R_i = 0 \tag{2.11}$$

The capacitor current for the maximum loss saving is:

$$P_{Lr}^{Com} = \sum_{i=1}^{b} (I_{ri} + D_i I_c)^2 R_i$$

$$I_c = -\frac{\sum_{i=1}^{b} D_i I_{ri} R_i}{\sum_{i-1}^{b} D_i R_i} = -\frac{\sum_{i\in\alpha} I_{ri} R_i}{\sum_{i\in\alpha} R_i} \tag{2.12}$$

The corresponding capacitor size is:

$$Q_c = V_m I_c \tag{2.13}$$

Here V_m is the voltage magnitude of the capacitor bus m where this capacitor is to be connected.

2.5 Fuzzy Logic System

2.5.1 Fuzzy Sets

Fuzzy Logic starts with the concept of a fuzzy set [3]. A fuzzy set is a set without a crisp, clearly defined boundary. It can contain elements with only a partial degree of membership. The fuzzy set is essentially a generalization of the classical or ordinary set. The ordinary set is defined in such a way that individuals in some given universe of discourse are divided into two groups: members – those that certainly belong in the set and non-members – those that certainly do not.

A sharp ambiguous distinction exists between the members and non-members of the class or category represented by the ordinary set. However, many of the categories commonly employed to describe our perception of reality do not exhibit this sharp distinction. For example, there is no sharp distinction in classifying between a level of height of a student: TALL or SHORT. Most would agree that a height of 1.80 meters is TALL and 1.20 meters is short, but what if the height is 1.55 meters? It seems like it is a part of TALL, but somehow it appears like it should be excluded. Classical sets would not tolerate this kind of thing. It will interpret either TALL or SHORT only. The fuzzy sets introduce vagueness by eliminating the sharp boundaries dividing members of the class from non-members. In fuzzy logic, the truth of any statement becomes a matter of degree.

2.5.2 Fuzzy Membership Functions [4]

A membership function (MF) is a curve that defines how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. The input space is sometimes referred to as the universe of discourse.

Mathematically, a fuzzy set is defined by assigning to each individual in the universe of discourse a value in the interval [0, 1] representing its degree of membership in the fuzzy set, depending on its similarity to the concept represented by the fuzzy sets. Thus, an individual may reside in a fuzzy set of a certain degree (greater or lesser) membership functions from range of 0 to 1.

2.5.3 Fuzzy Logical Operations

The three basic operations [8] on fuzzy sets are: complement, union and intersection. The basic operations are defined as functions that satisfy certain axiomatic requirements and operate on membership grades of fuzzy sets. The results of these operations are membership functions of new fuzzy sets representing the concept of fuzzy complement, union and intersection.

1. *NOT (Complement)*

   NOT is the complement operator. The membership function NOT *Tall* is described by the equation:

   $$\mu_{NOTTall}(x) = 1 - \mu_{Tall}(x) \qquad (2.14)$$

   Complementation of fuzzy sets also has the property that

   $$\mu_{NOTNOTTall}(x) = 1 - \mu_{NOTTall}(x) = \mu_{Tall}(x) \qquad (2.15)$$

2. *AND (Intersection)*

   AND is the intersection operator. The AND operator requires at least two arguments. With fuzzy logic, those arguments are membership functions (MF). Using the intersection operator, the mathematical notation for the intersection of the *Tall* and *Short* fuzzy sets is:

   $$\mu_{Tall \cap Short}(x) = \min[\mu_{Tall}(x), \mu_{Short}(x)] \qquad (2.16)$$

   This equation describes the intersection of *Tall* and *Short* as the pointwise minimum of two fuzzy sets.

3. *OR (Union)*

   OR is the union operator. The OR operator also requires at least two arguments. Using the union operator, the mathematical notation for the union of the *Tall* and *Short* fuzzy sets is:

   $$\mu_{Tall \cup Short}(x) = \max[\mu_{Tall}(x), \mu_{Short}(x)] \qquad (2.17)$$

2.5.4 Fuzzy IF-THEN Rule

Fuzzy sets and fuzzy operators are the basic component of fuzzy logic. These IF-THEN rule statements are used to formulate the conditional statements that include Fuzzy Logic. A single fuzzy IF-THEN rule [3][8] assumes the form:

IF x is A THEN y is B

Where A and B are linguistic values defined by fuzzy sets on the ranges (universe of discourse) X and Y, respectively. The IF part of the rule "*x is A*" is called the *antecedent* or premise, while the THEN part of the rule "*y is B*" is called the *consequent* or conclusion.

Interpreting the IF-THEN rules is a three part process. The first part is the fuzzification of input. This part resolves all fuzzy statements in the antecedent to a degree of membership between 0 and 1. If there is only one part to the antecedent, this is the degree of support for the rule. The second part is to apply fuzzy operator to multiple part antecedents. If there are multiple parts to the antecedent, fuzzy logic operators are applied and the antecedent is resolved to a single number between zero and one. This is the degree of support for the rule.

The last part is to apply the implication method. The degree of support for the entire rule is used to shape the output fuzzy set. The consequent of a fuzzy rule assigns an entire fuzzy set to the output. This fuzzy set is represented by a membership function that is chosen to indicate the qualities of the consequent.

CHAPTER 3

METHODOLOGY

This chapter describes the methodology used in completing this project. It consists of the identification of procedures as well as tools required for the entire project.

3.1 Procedure Identification

Gantt chart in Appendix A an B shows the milestone in completing this project for the two-semesters final year project also the task completed by the author.

The research began with literature review of electrical power and basic distribution system. The study continued with theories on losses specifically on reactive losses in radial distribution system. Afterwards, techniques of compensating the losses of reactive power were reviewed and evaluated. The task done after that is the simulation/implementation of the techniques using appropriate software/simulation system.

For the project work, fuzzy logic technique is going to be evaluated. Through fuzzy logic, the best locations of busbars for capacitor placement will be decided. The sizes of the capacitors to be placed are then calculated. From the value obtained, shunt capacitors will be placed onto the selected busbars. The placement of the capacitors will be simulated using load flow analysis software. With the proposed method, the final result obtained would be compared to the project done previously using different technique. Figure 2 shows the flow of this project.

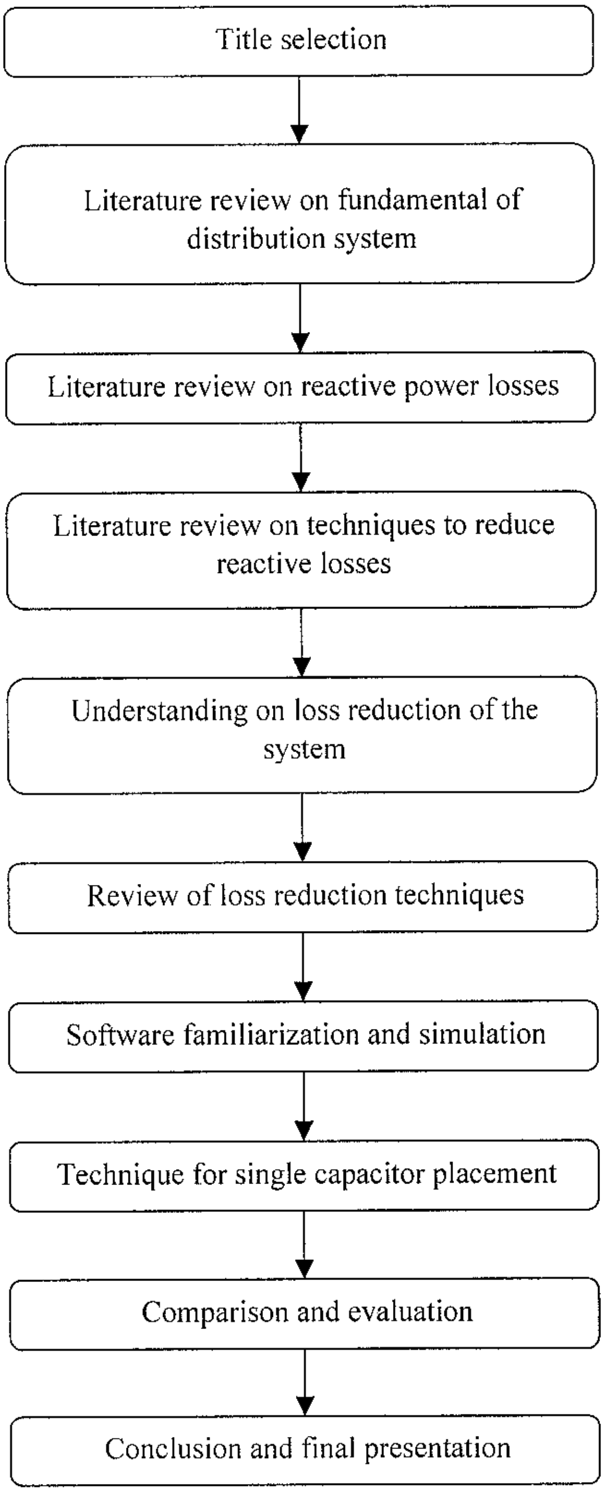


Figure 2 Methodology Flow Chart

3.2 Tools Required

The tools and software required for this project would be simulation software and test system for the simulation of the actual distribution system. The software is used for simulating and calculating the voltage and current of respective buses by means of load flow analysis.

3.2.1 MATLAB

For the calculation algorithm, MATLAB is to be used. MATLAB is an interactive software system for numerical computations and graphics. MATLAB is used as the calculation involves matrix computation for algorithm designing and simulations especially for fuzzy logic. Programming in MATLAB is more convenient compared to other similar programming software since declaration is not required and has its own module for fuzzy logic programming and simulation (Fuzzy Toolbox).

3.2.2 ERACS Power System Analysis Software

ERACS is a powerful and useful software used for power system analysis of the project. It has all the main elements that are available in a power system. This software is used for load flow analysis for simulation purpose.

3.2.3 IEEE 34-bus Test System

For simulation of the system, a standard test model is needed. This model should represent the actual radial distribution system. Simulation is done on this test system and from result of simulation, the new approach is determined whether suitable or not to be implemented on a real practical system. If there is no problem with simulation, there should be no problem in applying the system practically. The IEEE 34-bus standard test system will be used as the test model for this project.

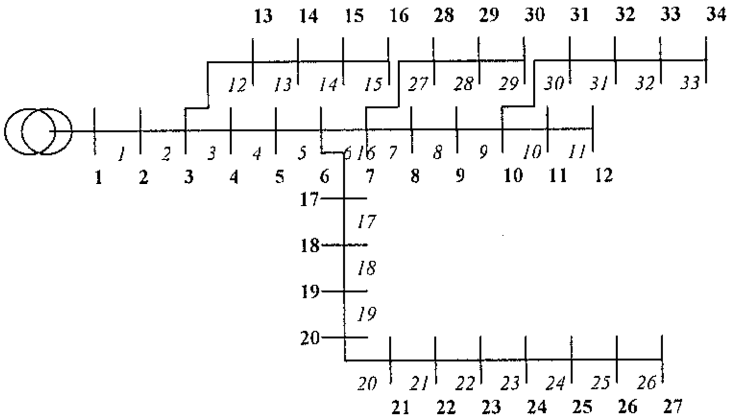


Figure 3 Single Line Equivalent of IEEE 34-bus Test System

CHAPTER 4

PROJECT WORK

Before applying fuzzy logic technique, a load flow analysis need to be done to calculate the distribution losses in the system. From the load analysis obtained, fuzzy logic is to be applied to locate the appropriate location for capacitor placement for optimum loss reduction. Some assumptions are made:

1. The load real and reactive power on the node of the feeders are known
2. The feeders are 3-phase and are balanced
3. Harmonic current are disregarded

4.1 Load Flow Analysis

From the load flow analysis using ERACS software on the IEEE 34-bus test system, parameters such as bus voltage and line current will be obtained. Line current is needed to calculate the losses (real and reactive loss). Losses exist in the line/branch since there resistance and voltage difference between the corresponding buses.

The network of 34-bus test system is constructed using ERACS. A diagram of network is attached in the Appendix E.

4.2 Proposed Method

For single capacitor placement method, a shunt capacitor is placed at the suitable busbar. Then the simulation is run once again with the first capacitor installed to find the next suitable candidate node for capacitor placement. The process is conducted several times until the loss saving is no longer significant (loss saving less than 1 kW). Flowchart below illustrates the entire process for single shunt capacitor placement.

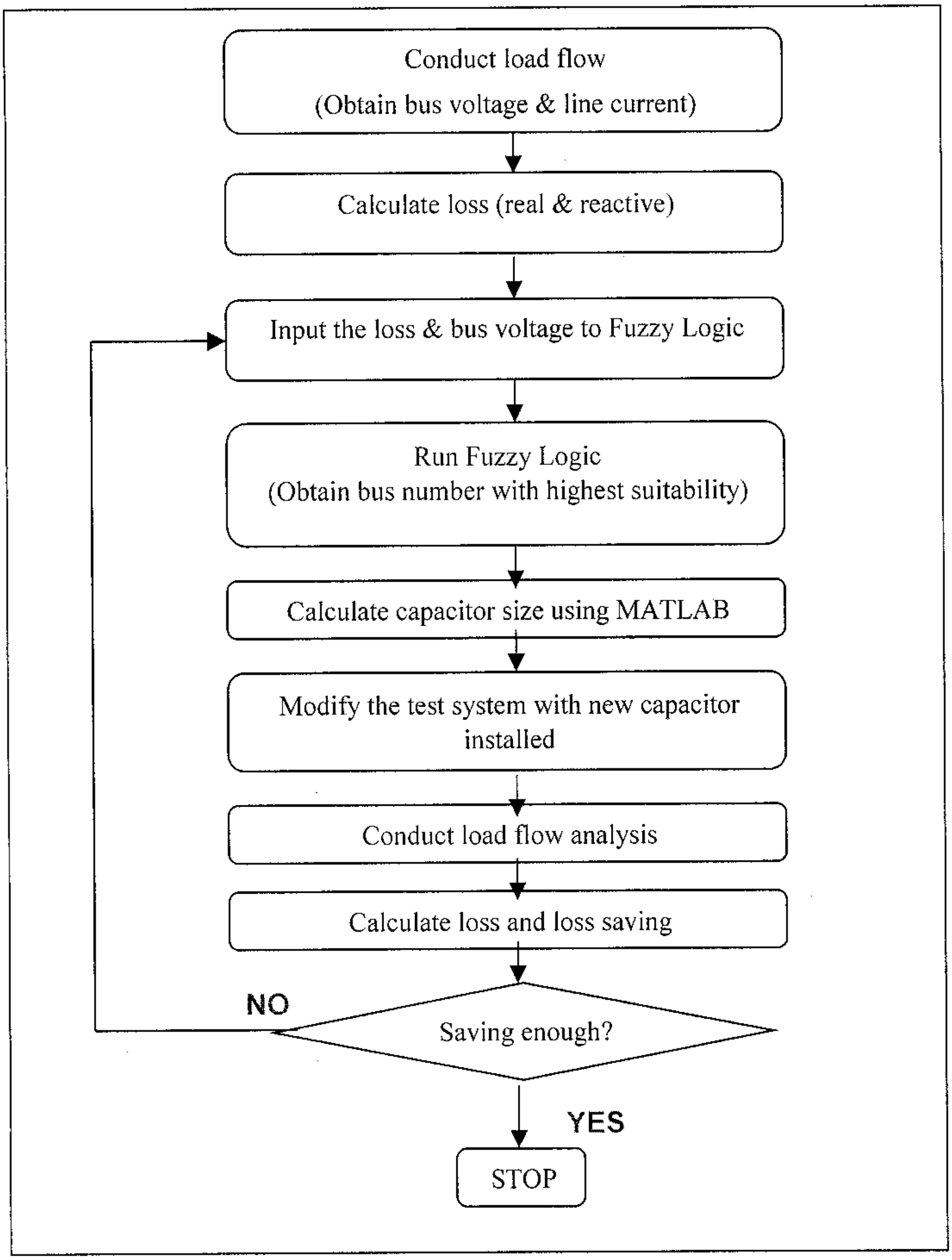


Figure 4 Flowchart of the proposed method

IEEE 34-bust test system is used as a test system for this project to represent the actual radial distribution line. All the line and load data of the test system will be put into ERACS (power analysis software) to be simulated. After all values have been inserted, load flow of the system is conducted, where the result will be used in the next step.

From the load-flow analysis result, data of voltage profile (V), line current (I) and current angle will be used. These data are then evaluated to obtain the current of reactive part (I_r) and the power losses of the reactive part (P_r). Fuzzy Logic will be used based on these set of data.

A MATLAB program is designed to take the inputs of loss of the reactive part (P_r), voltage (V_{pu}) and reactive current (I_r). These inputs will be triggered into the Fuzzy Logic system that has been developed previously and integrated into the program. Once the program is loaded, it will immediately give the output of bus number with the highest suitability and at same time calculate the capacitor size to be compensated. Both the bus number and the capacitor size will be displayed.

Using the bus number and capacitor size obtained, the 34-bus test system data (using ERACS) for the load flow analysis is modified by placing the shunt capacitor. Then, load flow analysis is run once again with the shunt capacitor installed. From the result of the load flow, a new set of voltage profile, reactive power loss and total power loss will be obtained. The result will be tabulated and compared to the values before compensation and the power loss saving will be noted.

Using the new values of P_r, V_{pu} and I_r, the program is run again to obtain the next suitable busbar for capacitor placement also the new capacitor size.

The above steps are repeated several times until the lost saving obtained is not less than 1 kW. The final result will be tabulated and the total loss saving is noted. Finally graphs will be plotted to visually see the difference of the losses and also the voltage profile, before and after the capacitors placement.

4.2.1 Fuzzy Logic System

Fuzzy Logic is used as a method to find the suitable busbar for shunt capacitor placement. For the fuzzy logic part, the Fuzzy Logic toolbox inside MATLAB is used. Fuzzy Logic Toolbox is selected instead of FuzzyTech software because it is more convenient to be integrated with calculation part with MATLAB. Flowchart below illustrates the steps in creating the fuzzy logic system for finding the suitable busbar for compensation.

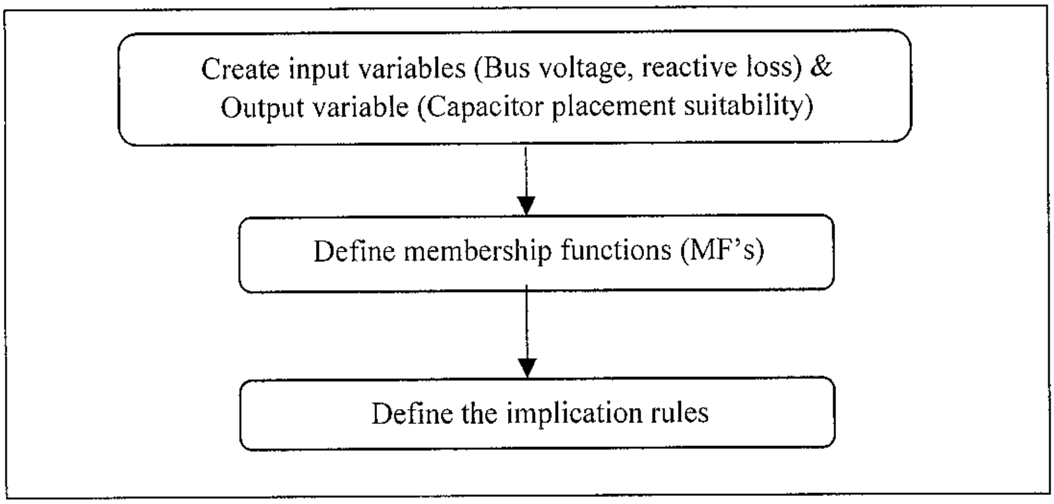


Figure 5 Steps for creating fuzzy logic system

A concern for the development of fuzzy systems is the assignment of appropriate membership functions. Constructions of membership functions can be based on intuition, rank ordering or probabilistic method. The most commonly used membership functions is the triangular shaped.

There Fuzzy Logic system basically consists of 3 parts, which are the inputs, inference rules and output. Figure below shows the relationship between the *antecedents* (inputs) and *consequence* (output)

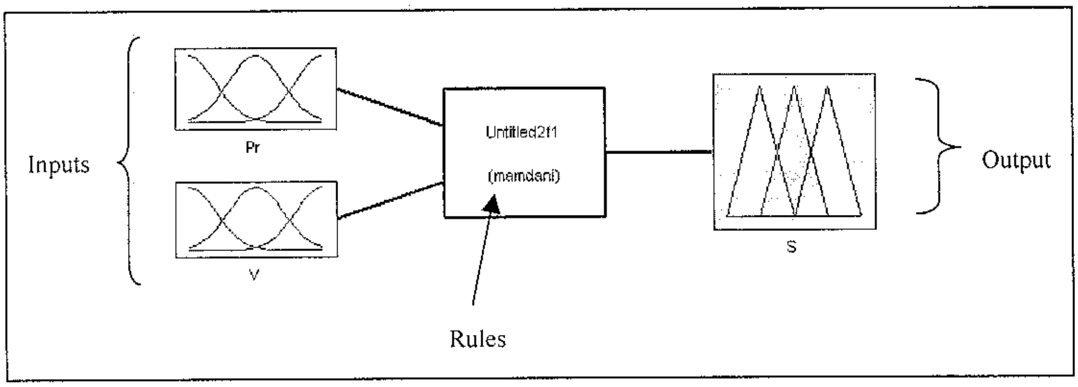


Figure 6 Fuzzy Logic System

Inputs:

The variables to the Fuzzy Logic system are Loss of Reactive Part (P_r) and Voltage (V_{pu}), whereby these values are to be compensated later. These values are taken from the evaluation of result from the load flow analysis.

From the result of the load flow, the membership function of the input variables is defined. For $\boldsymbol{P_r}$, five membership functions are formed, namely *low*, *lowmed, med, himed and high*. Triangular membership functions are commonly used. The width of each membership functions depends on how it is defined based on the P_r data from load flow analysis. Note from the figure below that reactive part loss, P_r from 6 to 10 kVAR is considered high, 3 to 6 is considered medium and 0 to 2 is considered low in losses.

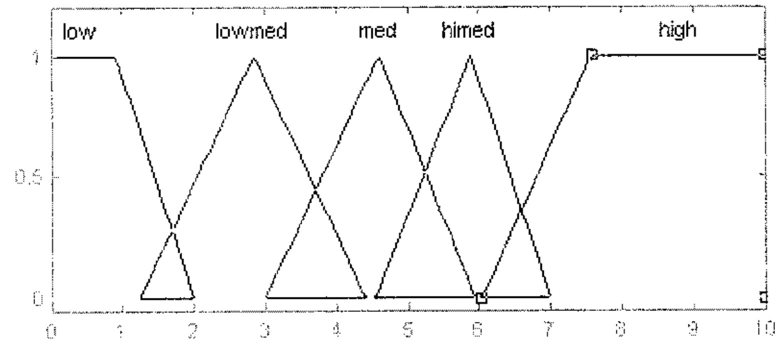


Figure 7 MF of input variable, Pr

Another **input** variable of the fuzzy logic system is the voltage, V. This information is also taken from the load flow analysis data of voltage in pu (V_{pu}). And the width of each membership functions is also defined according to the author's logical decision based on tabulation of the data. Voltage from 0.99 to 1 V p.u is considered high; where else other membership functions of hinorm, normal, lonorm and low can be viewed in figure below.

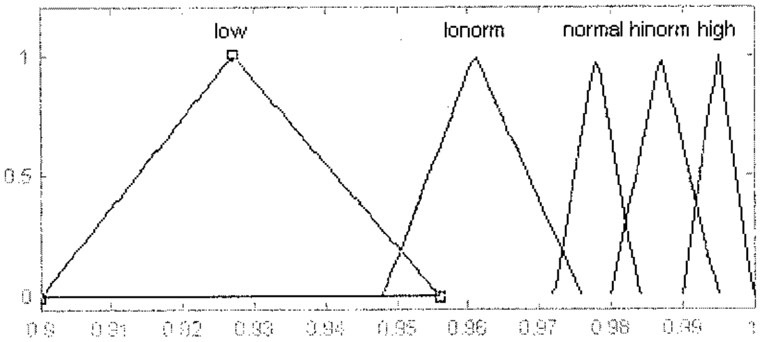


Figure 8 MF of input variable, V

Output:

Next step is to define the output variable which is the capacitor placement suitability, *S*. The capacitor placement suitability is normalized from 0 to 1, where the busbar with highest suitability will be selected to be compensated with shunt capacitor. The output variable, *S* consists of 3 membership functions namely low, med and high. The membership functions are uniformly distributed. Less membership functions are used for the purpose of reducing the processing time while obtaining similar result (*See figure below*).

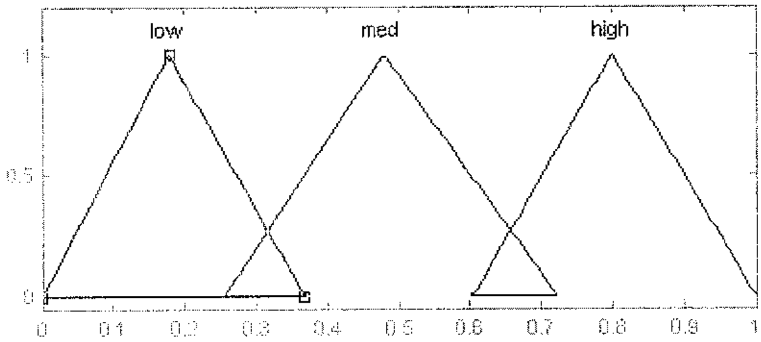


Figure 9 MF of output variable, S

Inference rules:

When losses and voltage level of a distribution system are studied, an experienced engineer can choose locations for capacitor placement which are probably highly suitable. For example, it is intuitive that a section with high losses and low voltage is highly ideal for placements of capacitors; whereas a low loss section with good voltage is not.

This part is to define the relationship between inputs and output and how the inputs will influence the output. The rules are defined based on condition – IF reactive part loss HIGH and voltage LOW, THEN capacitor placement suitability is HIGH. From there, a set of inference rules is developed with the help of the writer's logical decision making process. The rule base can be summarized in the table below. The full set of inference rules obtained from the table is attached in the Appendix C. Those rules are inserted one by one into the rule block of the fuzzy logic system.

Table 1 Rules for capacitor placement suitability output

AND		Voltage				
		Low	Low-Normal	Normal	High-normal	High
Reactive Power Loss	Low	Low	Low	Low	Low	Low
	Low-Med	Low	Low	Low	Low	Low
	Med	Med	Med	Med	Low	Low
	High-Med	High	Med	Med	Med	Low
	High	High	High	Med	Med	Med

CHAPTER 5

RESULT AND DISCUSSION

5.1 Load Flow Analysis Data

Load flow analysis is the first step in determining the loss of the system. Then the fuzzy logic method can be applied to find the suitable bus for loss compensation. From load flow analysis, the voltage profile (in kV and p.u.) and the line current (in kA) is obtained. The voltage profile and the corresponding bus numbers are tabulated in Table 2.

The line current has two components, which are the active and reactive components. This component has already been discussed earlier in the theory part. Basically, the loss associated with the active component can only be minimized by the source at the generator bus. The loss associated with reactive component however, can be reduced by supplying part of the reactive power locally by means of shunt capacitors.

Table 3 shows the active current and angle, also the calculation for the reactive current. The loss due to active and reactive part is also calculated and the sum of these two losses gives the total real losses.

Table 2 Voltage profile

Busbar	Voltage (pu)	Voltage (kV)
1	1.00000	11.000
2	0.99414	10.936
3	0.98902	10.879
4	0.98205	10.803
5	0.97606	10.737
6	0.97041	10.675
7	0.96659	10.632
8	0.96448	10.609
9	0.96202	10.582
10	0.96083	10.569
11	0.96037	10.564
12	0.96024	10.563
13	0.98869	10.876
14	0.98838	10.872
15	0.98830	10.871
16	0.98829	10.871
17	0.96595	10.625
18	0.96225	10.585
19	0.95815	10.540
20	0.95486	10.503
21	0.95199	10.472
22	0.94872	10.436
23	0.94604	10.406
24	0.94351	10.379
25	0.94230	10.365
26	0.94183	10.360
27	0.94169	10.359
28	0.96625	10.629
29	0.96603	10.626
30	0.96591	10.625
31	0.96049	10.565
32	0.96015	10.562
33	0.95998	10.560
34	0.95992	10.559

Table 3 Calculation of losses from load flow data

Line	I (kA)	Angle	Ir (kA)	R (Ω)	Pr Loss (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.2980	-31.17	-0.15423	0.11700	8.34945	0.25498	22.82075	31.17020
2	0.2837	-31.14	-0.14671	0.10725	6.92546	0.24282	18.97081	25.89627
3	0.2694	-31.11	-0.13919	0.16445	9.55836	0.23066	26.24719	35.80555
4	0.2549	-31.08	-0.13160	0.14950	7.76750	0.21830	21.37334	29.14084
5	0.2404	-31.06	-0.12403	0.14950	6.89961	0.20593	19.02017	25.91978
6	0.0821	-31.20	-0.04252	0.31440	1.70564	0.07023	4.65192	6.35755
7	0.0676	-31.00	-0.03482	0.20960	0.76223	0.05794	2.11124	2.87347
8	0.0529	-30.94	-0.02719	0.31440	0.69752	0.04537	1.94194	2.63946
9	0.0381	-30.84	-0.01953	0.20960	0.23992	0.03271	0.67285	0.91277
10	0.0236	-31.03	-0.01217	0.13100	0.05818	0.02022	0.16071	0.21889
11	0.0088	-30.86	-0.00451	0.10480	0.00641	0.00755	0.01794	0.02435
12	0.0143	-31.72	-0.00752	0.15720	0.02666	0.01216	0.06977	0.09644
13	0.0098	-31.64	-0.00514	0.20960	0.01662	0.00834	0.04377	0.06039
14	0.0053	-31.44	-0.00276	0.10480	0.00240	0.00452	0.00643	0.00883
15	0.0008	-28.94	-0.00039	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.1582	-30.99	-0.08145	0.17940	3.57088	0.13562	9.89878	13.46966
17	0.1435	-30.96	-0.07382	0.16445	2.68831	0.12306	7.47088	10.15919
18	0.1288	-30.93	-0.06619	0.20790	2.73290	0.11049	7.61393	10.34683
19	0.1140	-30.90	-0.05854	0.18900	1.94296	0.09782	5.42577	7.36873
20	0.0991	-30.87	-0.05085	0.18900	1.46584	0.08506	4.10256	5.56840
21	0.0842	-30.84	-0.04317	0.26200	1.46450	0.07229	4.10796	5.57246
22	0.0692	-30.82	-0.03545	0.26200	0.98784	0.05943	2.77603	3.76387
23	0.0542	-30.80	-0.02775	0.31440	0.72644	0.04656	2.04435	2.77078
24	0.0391	-30.79	-0.02002	0.20960	0.25192	0.03359	0.70940	0.96132
25	0.0241	-30.79	-0.01234	0.13100	0.05982	0.02070	0.16844	0.22826
26	0.0090	-30.81	-0.00461	0.10480	0.00668	0.00773	0.01878	0.02547
27	0.0145	-32.11	-0.00771	0.15720	0.02801	0.01228	0.07114	0.09915
28	0.0097	-32.11	-0.00516	0.15720	0.01253	0.00822	0.03184	0.04437
29	0.0048	-32.10	-0.00255	0.15720	0.00307	0.00407	0.00780	0.01087
30	0.0146	-30.53	-0.00742	0.15720	0.02595	0.01258	0.07458	0.10053
31	0.0109	-30.53	-0.00554	0.20960	0.01928	0.00939	0.05543	0.07471
32	0.0073	-30.53	-0.00371	0.15720	0.00648	0.00629	0.01865	0.02513
33	0.0036	-30.53	-0.00183	0.10480	0.00105	0.00310	0.00302	0.00407
				TOTAL	**59.01045**		**162.70824**	**221.71869**

5.2 Single Capacitor Placement

From the data of load flow analysis in Table 3, the loss of reactive part (P_r), bus voltages (V_{pu}) and current of reactive part (I_r) are inserted into the MATLAB program (which integrates the Fuzzy Logic and an algorithm to calculate the capacitor size) to obtain the capacitor placement suitability (refer to Appendix D). The MATLAB program is run and immediately the bus number with highest suitability will be obtained, together with the capacitor size to be compensated.

For the first iteration, **Bus 6** is found to be the suitable node for placement with capacitor size of **1148.60 kVAR**.

```
The most suitable bus for capacitor placement is bus  6
and the capacitor size is  1148.6 kVAR
```

Figure 10 Output of MATLAB for 1st iteration

Once the bus number and capacitor size is obtained, the corresponding bus data in the 34-bust test network is updated. Then ERACS is run one more time to obtain the load flow of the new system with one capacitor installed. The same procedure as above, where the new P_r, V_{pu} and I_r in inserted into the MATLAB program to obtain the next suitable bus number for capacitor placement. These procedures are repeated several times until 5 capacitors are placed onto the network to compensate the losses.

After 5 iterations, 5 capacitors are installed onto the network on bus 6, 17, 18, 19 and 21. Table 4 below summarized the bus numbers and their respective capacitor size.

Table 4 Bus number and capacitor size

Iteration	Bus	Capacitor Size
1	6	1148.60
2	17	823.45
3	18	481.41
4	19	306.85
5	21	239.72

After all the capacitors are placed on the designated buses, the load flow analysis is run once again to obtain the new load flow and the loss saving of the system. Table 5 summarized the load flow data after all capacitors are in place.

Table 5 Result after 5th iteration

Line	I (kA)	Angle (deg)	Ir (kA)	R	Pr Loss (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.252	0.93	0.00407	0.11700	0.00583	0.25227	22.33718	22.34301
2	0.241	2.77	0.01161	0.10725	0.04340	0.24022	18.56670	18.61010
3	0.229	4.81	0.01921	0.16445	0.18204	0.22809	25.66714	25.84918
4	0.218	7.10	0.02687	0.14950	0.32371	0.21583	20.89314	21.21685
5	0.207	9.64	0.03459	0.14950	0.53662	0.20358	18.58843	19.12505
6	0.082	-32.20	-0.04349	0.31440	1.78357	0.06905	4.49679	6.28035
7	0.067	-32.01	-0.03562	0.20960	0.79769	0.05698	2.04187	2.83956
8	0.053	-31.94	-0.02783	0.31440	0.73045	0.04464	1.87916	2.60961
9	0.038	-31.85	-0.02000	0.20960	0.25151	0.03219	0.65170	0.90321
10	0.023	-32.04	-0.01241	0.13100	0.06057	0.01984	0.15462	0.21519
11	0.009	-31.87	-0.00459	0.10480	0.00663	0.00739	0.01716	0.02380
12	0.014	-32.05	-0.00759	0.15720	0.02715	0.01212	0.06929	0.09644
13	0.010	-31.97	-0.00519	0.20960	0.01693	0.00831	0.04346	0.06039
14	0.005	-31.76	-0.00279	0.10480	0.00245	0.00451	0.00639	0.00883
15	0.001	-29.26	-0.00039	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.135	6.96	0.01635	0.17940	0.14391	0.13391	9.65026	9.79417
17	0.123	-9.50	-0.02025	0.16445	0.20220	0.12102	7.22532	7.42753
18	0.115	-19.53	-0.03845	0.20790	0.92225	0.10838	7.32618	8.24843
19	0.107	-26.26	-0.04725	0.18900	1.26571	0.09578	5.20163	6.46734
20	0.092	-25.27	-0.03932	0.18900	0.87643	0.08329	3.93310	4.80953
21	0.084	-32.21	-0.04450	0.26200	1.55675	0.07065	3.92344	5.48019
22	0.069	-32.18	-0.03654	0.26200	1.04941	0.05806	2.64947	3.69888
23	0.054	-32.17	-0.02864	0.31440	0.77378	0.04554	1.95626	2.73004
24	0.039	-32.16	-0.02065	0.20960	0.26818	0.03285	0.67844	0.94662
25	0.024	-32.16	-0.01272	0.13100	0.06360	0.02023	0.16089	0.22449
26	0.009	-32.18	-0.00474	0.10480	0.00706	0.00753	0.01784	0.02490
27	0.014	-33.11	-0.00787	0.15720	0.02918	0.01206	0.06861	0.09779
28	0.010	-33.11	-0.00524	0.15720	0.01297	0.00804	0.03049	0.04346
29	0.005	-33.11	-0.00262	0.15720	0.00324	0.00402	0.00762	0.01087
30	0.015	-31.54	-0.00758	0.15720	0.02713	0.01236	0.07202	0.09915
31	0.011	-31.54	-0.00570	0.20960	0.02044	0.00929	0.05427	0.07471
32	0.007	-31.54	-0.00377	0.15720	0.00669	0.00614	0.01776	0.02445
33	0.004	-31.54	-0.00188	0.10480	0.00111	0.00307	0.00296	0.00407
				TOTAL	**11.99863**		**158.38965**	**170.38829**

From the load flow analysis of the 5th iteration, the total power loss can be calculated and power saving of the system can be found. The total power loss and total saving is tabulated below.

Table 6 Losses and savings

No. of Capacitors	Total Real Power Loss	Power Loss Saving	Total Saving
0	221.72		
1	193.08	28.64	28.64
2	179.28	13.80	42.44
3	174.37	4.91	47.35
4	172.21	2.16	49.51
5	170.39	1.82	51.33

From the tabulated result, it can be observed that the total power loss is reduced after compensation and the total power saving is **51.33 kW.**

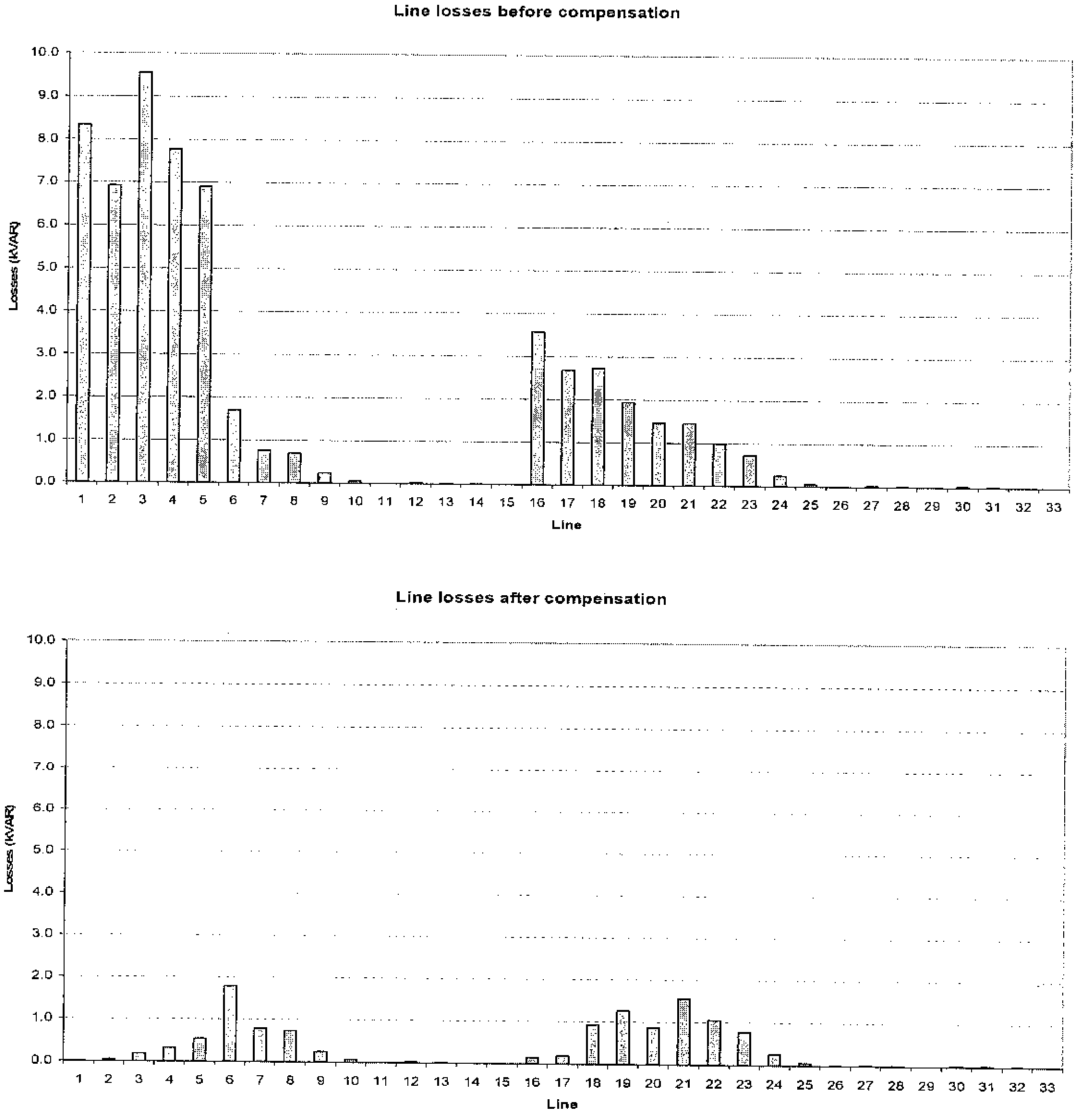
By placing shunt capacitors, the voltage profile of the network will also be improved. This is because the current flowing in the line is decreasing due to flow of less reactive component branch current that reduces the voltage drop, hence improve the voltage profile. Table 7 below shows the comparison between voltage profile before and after the capacitor placement. Note that voltage profile at every bus is improved.

Table 7 Voltage profile before and after capacitor placement

Busbar	Voltage	
	Before	After
1	11.000	11.000
2	10.936	10.949
3	10.879	10.906
4	10.803	10.842
5	10.737	10.788
6	10.675	10.738
7	10.632	10.697
8	10.609	10.674
9	10.582	10.647
10	10.569	10.634
11	10.564	10.629
12	10.563	10.627
13	10.876	10.902
14	10.872	10.899
15	10.871	10.898
16	10.871	10.898
17	10.625	10.698
18	10.585	10.662
19	10.540	10.620
20	10.503	10.585
21	10.472	10.555
22	10.436	10.519
23	10.406	10.490
24	10.379	10.462
25	10.365	10.449
26	10.360	10.444
27	10.359	10.443
28	10.629	10.693
29	10.626	10.690
30	10.625	10.689
31	10.565	10.630
32	10.562	10.626
33	10.560	10.624
34	10.559	10.624

For comparison, Figure 11 below shows the comparison of power losses of reactive part in the system before and after the capacitors placements. The fuzzy logic system considers the loss reduction and the voltage profile simultaneously when deciding which nodes are most ideal for capacitor placement. Hence, a good compromise of loss reduction and voltage profile improvement is achieved. In Figure 12, the improvement of the voltage profile before and after compensation of capacitors can be observed.

Figure 11 Line losses before and after compensation

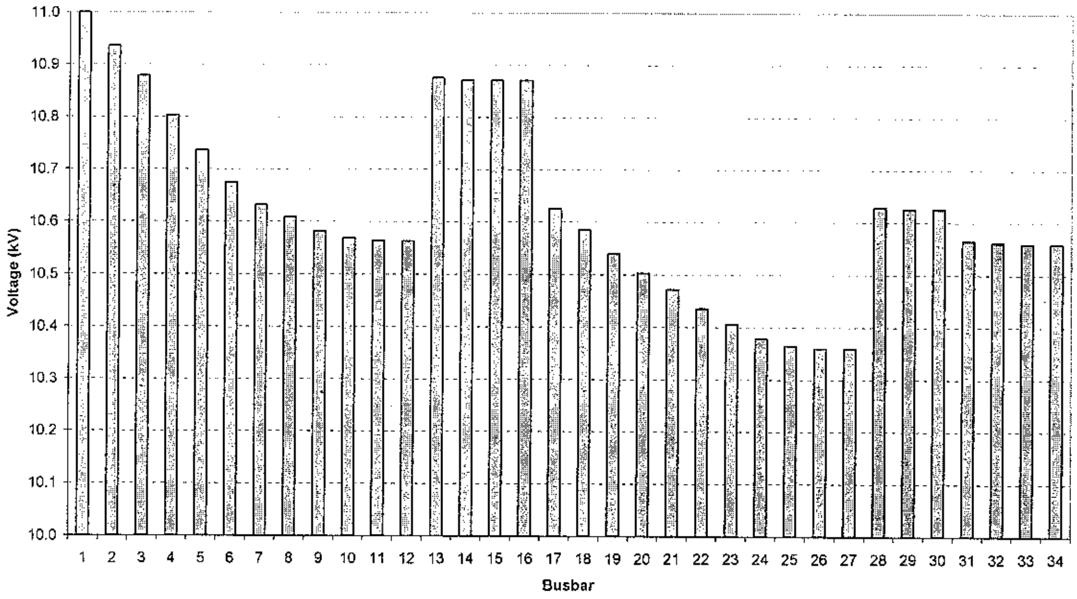


Line losses before compensation

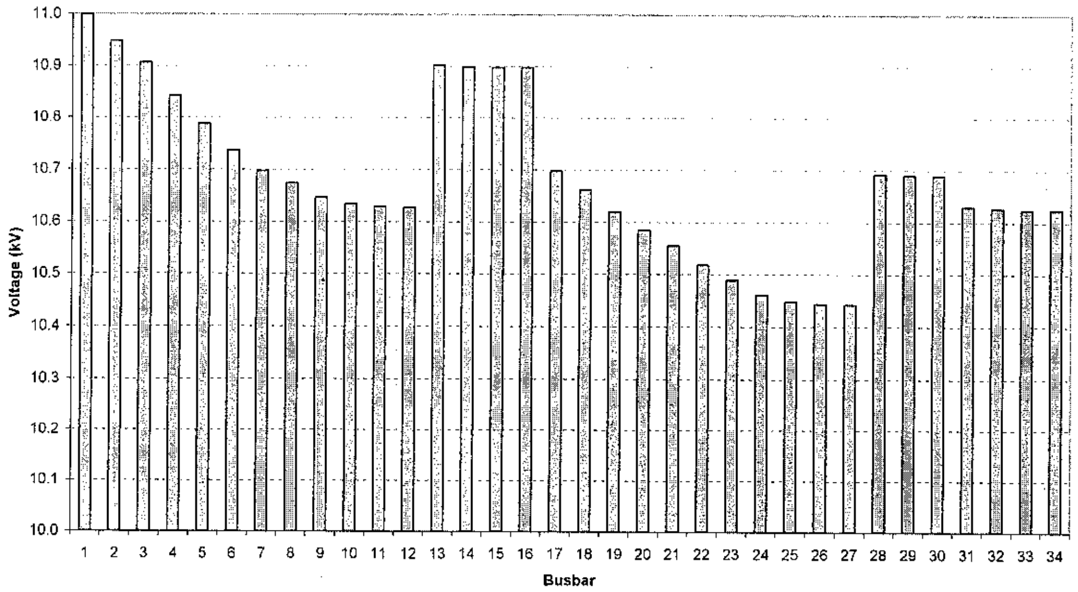
Line losses after compensation

Figure 12 Voltage profile before and after compensation

Voltage Profile Before Compensation



Voltage Profile after Compensation



5.3 Comparison with Existing Method

Results obtained from the simulation would be compared to an existing method using heuristic search strategies by M Chis, M.M.A Salama and Jayaram[6]. Table below shows the comparison between the results of two methods. As seen from the table, the proposed method using fuzzy logic compensates losses up to 51.33 kW with 3000.08 kVAR capacitors bank while the existing method compensates 53.69 kW with 2700 kVAR capacitors bank.

Table 8 Result Comparison

Iteration	Bus No.		Capacitor size (kVAR)		Saving (kW)	
No.	Proposed Method	Method (1)	Proposed Method	Method (1)	Proposed Method	Method (1)
1	2	26	1148.6	1400	28.64	41.07
2	4	11	823.45	750	13.8	10.64
3	6	17	481.41	300	4.91	1.17
4	7	4	306.85	250	2.16	0.81
5	8		239.77		1.82	
		TOTAL	3000.08	2700	51.33	53.69

Although the saving offered by the proposed system is less, it is more realistic to be applied in actual system, since the losses used by this system are not calculated based on appropriate formulas, but from the load flow. Thus this fuzzy system approach will choose a more reliable location for capacitor placements. In addition to the above advantage, the simplicity and the flexibility of using the fuzzy system are apparent. The system requires only the losses and voltages of the feeder sections to determine the suitable locations for capacitor placement.

CHAPTER 6

CONCLUSION

As for the conclusion, loss reduction for radial distribution network using fuzzy logic is implemented in this project. Fuzzy Logic is used as a tool to find the suitable bus for capacitor placement. ERACS power system analysis software is used as simulation tool for load flow analysis. For the purpose of calculating the capacitor size and integrating with fuzzy logic, MATLAB is used whereby it has its own Fuzzy Toolbox to ease the process.

The main advantage of using Fuzzy Logic is simplicity and time efficient. Fuzzy Logic uses less processing time compared to other methods (i.e. calculation of loss saving at each bus one by one). Therefore it is possible to make more iteration and obtain more loss reduction with less processing time compared to normal method.

For this method, the load distribution of the system is assumed to be uniform. This fuzzy logic method can be applied to any radial distribution system with any number of buses with only minor adjustments.

As recommendation for future works, the fuzzy logic system can be integrated with neural network to obtain a more efficient result. Neural network can be used to replace the author's logical decision in determining the membership functions by its self-learning ability.

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APPENDICES

APPENDIX A

GANTT CHART OF THE FIRST SEMESTER

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Topic	▨													
		→													
2	Preliminary Research Work		▨	▨											
			→	→											
3	Submission of Preliminary Report				●										
4	Project work				▨	▨	▨	▨							
	• Reference/Literature				→	→	→	→							
5	Submission of Progress Report								●						
6	Project work (cont.)								▨	▨	▨	▨			
	• Analyze research finding								→	→					
	• Evaluation of finding										→	→			
7	Prepare Interim Report												▨	▨	
													→	→	
8	Submission of Interim Report final draft												●		
9	Oral presentation													▨	
10	Submission of Interim Report														●

● Suggested milestone → Actual

▨ Process

APPENDIX B

GANTT CHART OF THE SECOND SEMESTER

No	Detail/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Selection of Topic	▨													
		→													
2	Project work continue		▨	▨											
			→	→											
3	Submission of Progress Report 1				●										
4	Project work continue				▨	▨	▨	▨							
	• Refine the technique for Single Capacitor Placement				→	→	→	→							
5	Submission of Progress Report 2								●						
6	Project work continue								▨	▨	▨	▨			
	• Refine the technique for Multiple Capacitor Placement							→	→	→					
	• Evaluation and validation of result										→	→			
7	Prepare Interim Report										▨	▨			
8	Exhibition												●		
9	Submission of project dissertation													●	
10	Oral presentation														●

● Suggested milestone → Actual

▨ Process

APPENDIX C

INFERENCE RULES

1 **If** (Pr is low) **and** (V is low) **then** (S is low)(1)
2 **If** (Pr is low) **and** (V is lonorm) **then** (S is low)(1)
3 **If** (Pr is low) **and** (V is normal) **then** (S is low)(1)
4 **If** (Pr is low) **and** (V is low) **then** (S is low)(1)
5 **If** (Pr is low) **and** (V is high) **then** (S is low)(1)
6 **If** (Pr is lowmed) **and** (V is low) **then** (S is low)(1)
7 **If** (Pr is lowmed) **and** (V is lonorm) **then** (S is low)(1)
8 **If** (Pr is lowmed) **and** (V is normal) **then** (S is low)(1)
9 **If** (Pr is lowmed) **and** (V is hinorm) **then** (S is low)(1)
10 **If** (Pr is lowmed) **and** (V is high) **then** (S is low)(1)
11 **If** (Pr is med) **and** (V is low) **then** (S is med)(1)
12 **If** (Pr is med) **and** (V is lonorm) **then** (S is med)(1)
13 **If** (Pr is med) **and** (V is normal) **then** (S is med)(1)
14 **If** (Pr is med) **and** (V is hinorm) **then** (S is low)(1)
15 **If** (Pr is himed) **and** (V is low) **then** (S is high)(1)
16 **If** (Pr is himed) **and** (V is lonorm) **then** (S is med)(1)
17 **If** (Pr is himed) **and** (V is normal) **then** (S is med)(1)
18 **If** (Pr is himed) **and** (V is hinorm) **then** (S is med)(1)
19 **If** (Pr is himed) **and** (V is high) **then** (S is low)(1)
20 **If** (Pr is high) **and** (V is low) **then** (S is high)(1)
21 **If** (Pr is high) **and** (V is lonorm) **then** (S is high)(1)
22 **If** (Pr is high) **and** (V is normal) **then** (S is med)(1)
23 **If** (Pr is high) **and** (V is hinorm) **then** (S is med)(1)
24 **If** (Pr is high) **and** (V is high) **then** (S is med)(1)
25 **If** (Pr is med) **and** (V is high) **then** (S is low)(1)

APPENDIX D

MATLAB PROGRAM FOR SINGLE CAPACITOR PLACEMENT

```
%Define Pr, V, Ir, R and D

Pr=[     8.34945; 6.92546; 9.55836; 7.76750; 6.89961;...
         1.70564; 0.76223; 0.69752; 0.23992; 0.05818;...
         0.00641; 0.02666; 0.01662; 0.00240; 0.00002;...
         3.57088; 2.68831; 2.73290; 1.94296; 1.46584;...
         1.46450; 0.98784; 0.72644; 0.25192; 0.05982;...
         0.00668; 0.02801; 0.01253; 0.00307; 0.02595;...
         0.01928; 0.00648; 0.00105];

V=[      0.99414; 0.98902; 0.98205; 0.97606; 0.97041;
         0.96659; 0.96448; 0.96202; 0.96083; 0.96037;
         0.96024; 0.98869; 0.98838; 0.98830; 0.98829;
         0.96595; 0.96224; 0.95815; 0.95486; 0.95199;
         0.94872; 0.94604; 0.94351; 0.94230; 0.94183;
         0.94169; 0.96625; 0.96603; 0.96591; 0.96049;
         0.96015; 0.95998; 0.95992];

Ir=[     -0.15423,-0.14671,-0.13919,-0.13160,-0.12403,...
         -0.04252,-0.03482,-0.02719,-0.01953,-0.01217,...
         -0.00451,-0.00752,-0.00514,-0.00276,-0.00039,...
         -0.08145,-0.07382,-0.06619,-0.05854,-0.05085,...
         -0.04317,-0.03545,-0.02775,-0.02002,-0.01234,...
         -0.00461,-0.00771,-0.00516,-0.00255,-0.00742,...
         -0.00554,-0.00371,-0.00183];

R=[      0.11700,0.10725,0.16445,0.14950,0.14950,...
         0.31440,0.20960,0.31440,0.20960,0.13100,...
         0.10480,0.15720,0.20960,0.10480,0.05240,...
         0.17940,0.16445,0.20790,0.18900,0.18900,...
         0.26200,0.26200,0.31440,0.20960,0.13100,...
         0.10480,0.15720,0.15720,0.15720,0.15720,...
         0.20960,0.15720,0.10480];

D=[ 1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0;
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```

```
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    1,1,1,1,1,1,1,1,1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1,1,1,1];


%Load data from Fuzzy Logic Toolbox

a=readfis('Untitled2fl.fis');


%Evaluate the data with inputs of P and V
%Triggers the Fuzzy Logic

S=evalfis([Pr V],a);


%Calculate capacitor current, Ic

for m=1:33;
    num=0;denum=0;

    for n=1:33;
        num1=(D(m,n)*Ir(n)*R(n));
        denum1=(D(m,n)*R(n));
        num=num+num1;
        denum=denum+denum1;
    end

    Ic(m)=-num/denum;
end

%Calculate the bus number with highest suitability
%Calculate capacitor size
```
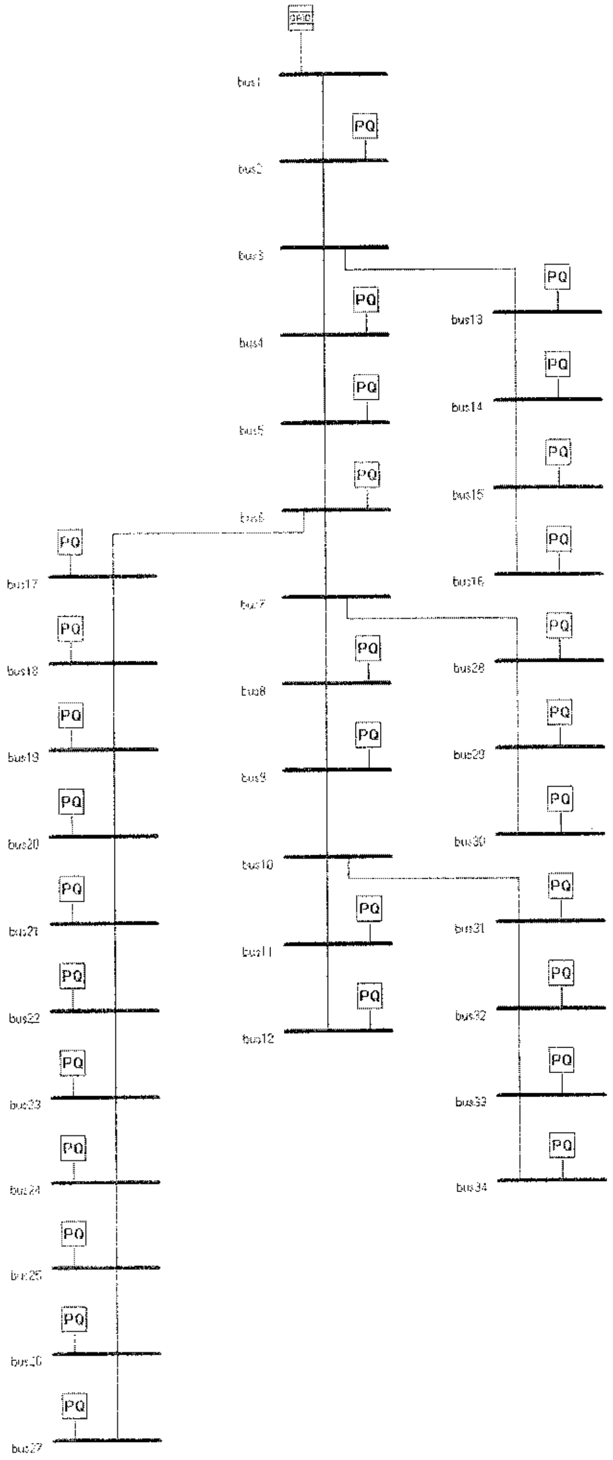

```
max=0;
for p=1:33;
    if (max<S(p))
        max=S(p);
        no=p+1;

        Qc=V(no)*11*Ic(no)*1000;  %From p.u voltage to normal voltage
    end
end


%Display the most suitable bus for capacitor placement and
%corresponding capacitor size

fprintf('\n\nThe most suitable bus for capacitor placement is bus %2d',no)
fprintf('\nand the capacitor size is %8.2f kVAR', Qc);
```

APPENDIX E

34-BUS TEST DIAGRAM OF ERACS



APPENDIX F

LINE DATA FOR IEEE 34-BUS TEST SYSTEM

No. of Nodes: 34	Base Voltage: 11kV
No. of Branches: 33	Base Load: 5MVA

Line	Sending End Node	Receiving End Node	Resistance (Ω)	Reactance (Ω)
1	1	2	0.1170	0.04800
2	2	3	0.10725	0.04400
3	3	4	0.16445	0.04565
4	4	5	0.14950	0.04150
5	5	6	0.14950	0.04150
6	6	7	0.31440	0.05400
7	7	8	0.20960	0.03600
8	8	9	0.31440	0.05400
9	9	10	0.20960	0.03600
10	10	11	0.13100	0.02250
11	11	12	0.10480	0.01800
12	3	13	0.15720	0.02700
13	13	14	0.20960	0.03600
14	14	15	0.10480	0.01800
15	15	16	0.05240	0.00900
16	6	17	0.17940	0.04980
17	17	18	0.16445	0.04565
18	18	19	0.20790	0.04730
19	19	20	0.18900	0.04300
20	20	21	0.18900	0.04300
21	21	22	0.26200	0.04500
22	22	23	0.26200	0.04500
23	23	24	0.31440	0.05400
24	24	25	0.20960	0.03600
25	25	26	0.13100	0.02250
26	26	27	0.10480	0.01800
27	7	28	0.15720	0.02700
28	28	29	0.15720	0.02700
29	29	30	0.15720	0.02700
30	10	31	0.15720	0.02700
31	31	32	0.20960	0.03600
32	32	33	0.15720	0.02700
33	33	34	0.10480	0.01800

APPENDIX G

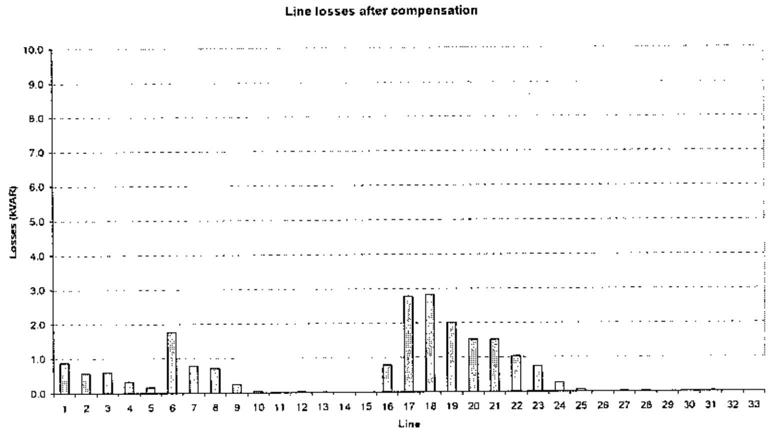
LOAD DATA FOR IEEE 34-BUS TEST SYSTEM

Busbar	PL (kW)	QL (kVAR)
2	230	142.5
3	0	0
4	230	142.5
5	230	142.5
6	0	0
7	0	0
8	230	142.5
9	230	142.5
10	0	0
11	230	142.5
12	137	84
13	72	45
14	72	45
15	72	45
16	13.5	7.5
17	230	142.5
18	230	142.5
19	230	142.5
20	230	142.5
21	230	142.5
22	230	142.5
23	230	142.5
24	230	142.5
25	230	142.5
26	230	142.5
27	137	85
28	75	48
29	75	48
30	75	48
31	57	34.5
32	57	34.5
33	57	34.5
34	57	34.5

APPENDIX H

RESULTS

Iteration: 2; Bus Location: 17; Capacitor Size: 823.45 kVAR


Line losses after compensation

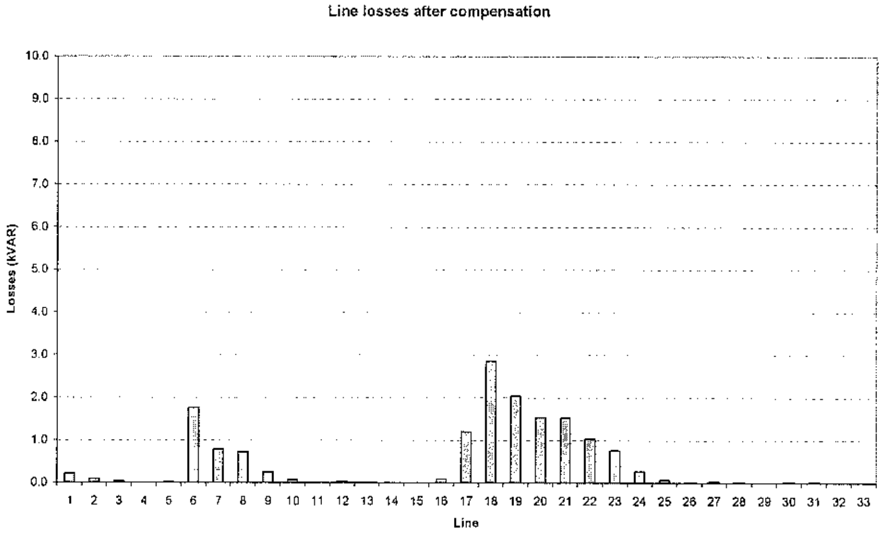
Voltage Profile

Bus	pV (pu)	V (kV)
1	1.00000	11.000
2	0.99497	10.945
3	0.99061	10.897
4	0.98444	10.829
5	0.97918	10.771
6	0.97425	10.717
7	0.97044	10.675
8	0.96835	10.652
9	0.96589	10.625
10	0.96471	10.612
11	0.96425	10.607
12	0.96411	10.605
13	0.99028	10.893
14	0.98997	10.890
15	0.98989	10.889
16	0.98988	10.889
17	0.97016	10.672
18	0.96647	10.631
19	0.96239	10.586
20	0.95911	10.550
21	0.95626	10.519
22	0.95301	10.483
23	0.95034	10.454
24	0.94782	10.426
25	0.94661	10.413
26	0.94615	10.408
27	0.94601	10.406
28	0.97011	10.671
29	0.96988	10.669
30	0.96977	10.667
31	0.96437	10.608
32	0.96403	10.604
33	0.96386	10.602
34	0.96380	10.602

Calculation of losses

Line	I (kA)	Angle (deg)	Ir	Resistance	Pr Losses (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.258	-11.19	-0.0500	0.11700	0.87821	0.25280	22.43145	23.30966
2	0.244	-10.01	-0.0425	0.10725	0.58092	0.24068	18.63764	19.21857
3	0.231	-8.69	-0.0349	0.16445	0.60102	0.22845	25.74743	26.34845
4	0.218	-7.19	-0.0273	0.14950	0.33386	0.21629	20.98066	21.31451
5	0.205	-5.49	-0.0196	0.14950	0.17226	0.20396	18.65757	18.82983
6	0.082	-31.86	-0.0432	0.31440	1.75830	0.06948	4.55288	6.31118
7	0.067	-31.66	-0.0354	0.20960	0.78709	0.05737	2.06939	2.85649
8	0.053	-31.60	-0.0276	0.31440	0.71917	0.04489	1.90037	2.61954
9	0.038	-31.51	-0.0199	0.20960	0.24797	0.03240	0.66001	0.90799
10	0.024	-31.70	-0.0123	0.13100	0.05992	0.01999	0.15712	0.21703
11	0.009	-31.53	-0.0045	0.10480	0.00651	0.00742	0.01729	0.02380
12	0.014	-31.94	-0.0076	0.15720	0.02698	0.01214	0.06945	0.09644
13	0.010	-31.86	-0.0052	0.20960	0.01682	0.00832	0.04357	0.06039
14	0.005	-31.65	-0.0028	0.10480	0.00243	0.00451	0.00640	0.00883
15	0.001	-29.15	-0.0004	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.140	-15.93	-0.0383	0.17940	0.78880	0.13414	9.68470	10.47351
17	0.143	-31.70	-0.0751	0.16445	2.78131	0.12158	7.29310	10.07441
18	0.128	-31.67	-0.0673	0.20790	2.82495	0.10911	7.42571	10.25066
19	0.113	-31.64	-0.0595	0.18900	2.00609	0.09655	5.28528	7.29137
20	0.099	-31.61	-0.0517	0.18900	1.51422	0.08397	3.99813	5.51235
21	0.084	-31.58	-0.0439	0.26200	1.51383	0.07139	4.00581	5.51964
22	0.069	-31.56	-0.0361	0.26200	1.02202	0.05871	2.70929	3.73131
23	0.054	-31.54	-0.0282	0.31440	0.74979	0.04594	1.99041	2.74019
24	0.039	-31.53	-0.0204	0.20960	0.26158	0.03324	0.69483	0.95640
25	0.024	-31.53	-0.0126	0.13100	0.06191	0.02046	0.16446	0.22637
26	0.009	-31.55	-0.0047	0.10480	0.00682	0.00758	0.01808	0.02490
27	0.015	-32.77	-0.0078	0.15720	0.02905	0.01219	0.07010	0.09915
28	0.010	-32.77	-0.0052	0.15720	0.01273	0.00807	0.03073	0.04346
29	0.005	-32.77	-0.0026	0.15720	0.00318	0.00404	0.00768	0.01087
30	0.015	-31.20	-0.0075	0.15720	0.02660	0.01240	0.07255	0.09915
31	0.011	-31.19	-0.0056	0.20960	0.02004	0.00932	0.05467	0.07471
32	0.007	-31.19	-0.0038	0.15720	0.00674	0.00624	0.01839	0.02513
33	0.004	-31.19	-0.0019	0.10480	0.00109	0.00308	0.00298	0.00407
				TOTAL	**19.82224**		**159.45822**	**179.28046**

Iteration: 3; Bus Location: 18; Capacitor Size: 481.41 kVAR



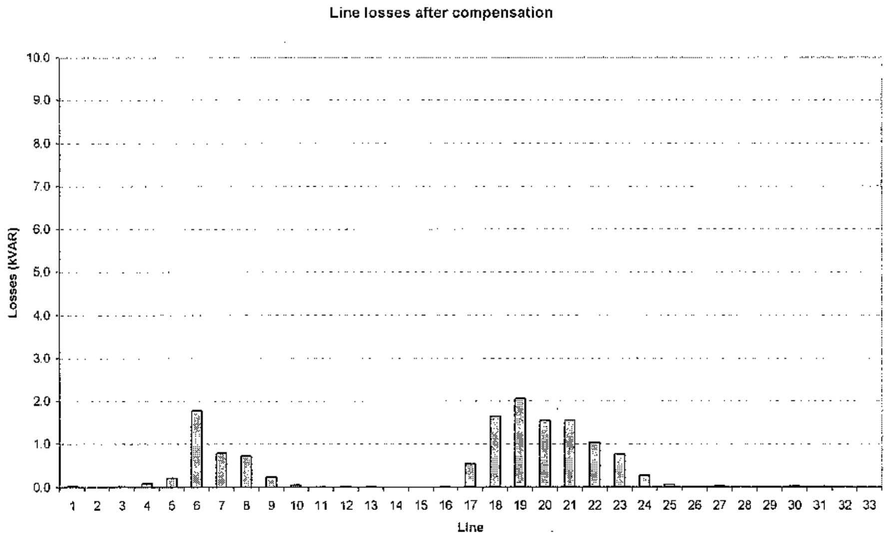
Voltage Profile

Bus	pV (pu)	V (kV)
1	1.00000	11.000
2	0.99516	10.947
3	0.99099	10.901
4	0.98501	10.835
5	0.97992	10.779
6	0.97517	10.727
7	0.97137	10.685
8	0.96927	10.662
9	0.96682	10.635
10	0.96564	10.622
11	0.96518	10.617
12	0.96505	10.616
13	0.99065	10.897
14	0.99035	10.894
15	0.99027	10.893
16	0.99026	10.893
17	0.97130	10.684
18	0.96780	10.646
19	0.96373	10.601
20	0.96045	10.565
21	0.95761	10.534
22	0.95436	10.498
23	0.95169	10.469
24	0.94918	10.441
25	0.94797	10.428
26	0.94751	10.423
27	0.94737	10.421
28	0.97103	10.681
29	0.97081	10.679
30	0.97070	10.678
31	0.96530	10.618
32	0.96496	10.615
33	0.96479	10.613
34	0.96473	10.612

Calculation of losses

Line	I (kA)	Angle (deg)	Ir	Resistance	Pr Losses (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.254	-5.58	-0.0247	0.11700	0.21354	0.25250	22.37811	22.59166
2	0.241	-4.08	-0.0171	0.10725	0.09445	0.24039	18.59311	18.68756
3	0.228	-2.40	-0.0095	0.16445	0.04497	0.22820	25.69140	25.73637
4	0.216	-0.51	-0.0019	0.14950	0.00163	0.21599	20.92359	20.92522
5	0.204	1.63	0.0058	0.14950	0.01508	0.20372	18.61312	18.62820
6	0.082	-32.02	-0.0433	0.31440	1.76989	0.06927	4.52586	6.29576
7	0.067	-31.82	-0.0355	0.20960	0.79192	0.05718	2.05610	2.84802
8	0.053	-31.76	-0.0277	0.31440	0.72300	0.04472	1.88661	2.60961
9	0.038	-31.67	-0.0199	0.20960	0.24894	0.03226	0.65428	0.90321
10	0.024	-31.86	-0.0124	0.13100	0.06047	0.01996	0.15657	0.21703
11	0.009	-31.69	-0.0046	0.10480	0.00657	0.00740	0.01723	0.02380
12	0.014	-31.99	-0.0076	0.15720	0.02706	0.01213	0.06938	0.09644
13	0.010	-31.91	-0.0052	0.20960	0.01687	0.00832	0.04352	0.06039
14	0.005	-31.70	-0.0028	0.10480	0.00244	0.00451	0.00639	0.00883
15	0.001	-29.20	-0.0004	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.135	-5.41	-0.0127	0.17940	0.08662	0.13400	9.66404	9.75066
17	0.131	-22.16	-0.0494	0.16445	1.20405	0.12133	7.26233	8.46638
18	0.128	-31.91	-0.0677	0.20790	2.85522	0.10866	7.36348	10.21870
19	0.113	-31.88	-0.0598	0.18900	2.03040	0.09621	5.24812	7.27852
20	0.099	-31.85	-0.0520	0.18900	1.53218	0.08367	3.96899	5.50118
21	0.084	-31.83	-0.0441	0.26200	1.53127	0.07112	3.97520	5.50647
22	0.069	-31.80	-0.0363	0.26200	1.03328	0.05847	2.68721	3.72048
23	0.054	-31.79	-0.0284	0.31440	0.76027	0.04582	1.97993	2.74019
24	0.039	-31.78	-0.0205	0.20960	0.26387	0.03307	0.68763	0.95151
25	0.024	-31.78	-0.0126	0.13100	0.06226	0.02032	0.16223	0.22449
26	0.009	-31.80	-0.0047	0.10480	0.00691	0.00756	0.01799	0.02490
27	0.014	-32.93	-0.0078	0.15720	0.02890	0.01209	0.06889	0.09779
28	0.010	-32.93	-0.0052	0.15720	0.01284	0.00806	0.03062	0.04346
29	0.005	-32.93	-0.0026	0.15720	0.00321	0.00403	0.00766	0.01087
30	0.015	-31.36	-0.0075	0.15720	0.02685	0.01238	0.07230	0.09915
31	0.011	-31.36	-0.0057	0.20960	0.02023	0.00931	0.05448	0.07471
32	0.007	-31.35	-0.0037	0.15720	0.00662	0.00615	0.01783	0.02445
33	0.004	-31.35	-0.0019	0.10480	0.00110	0.00307	0.00297	0.00407
				TOTAL	**15.48294**		**158.88723**	**174.37017**

Iteration: 4; Bus Location: 19; Capacitor Size: 306.85 kVAR



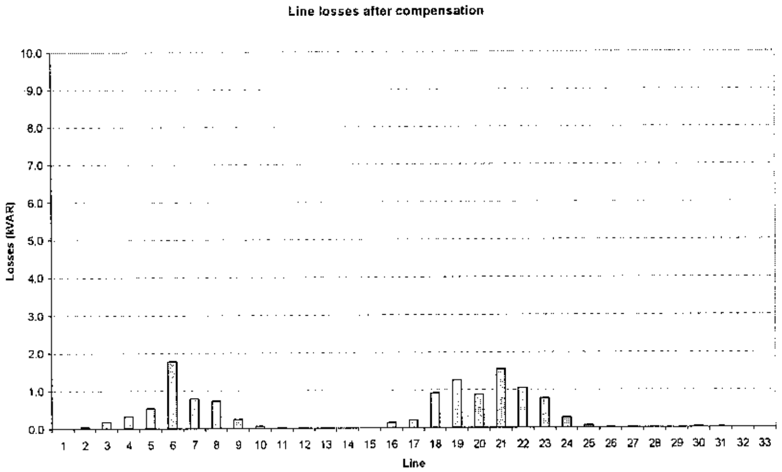
Voltage Profile

Bus	pV (pu)	V (kV)
1	1.00000	11.000
2	0.99529	10.948
3	0.99123	10.903
4	0.98538	10.839
5	0.98040	10.784
6	0.97576	10.733
7	0.97195	10.691
8	0.96986	10.668
9	0.96741	10.641
10	0.96623	10.629
11	0.96577	10.624
12	0.96564	10.622
13	0.99089	10.900
14	0.99059	10.896
15	0.99051	10.896
16	0.99050	10.896
17	0.97202	10.692
18	0.96864	10.655
19	0.96470	10.612
20	0.96143	10.576
21	0.95859	10.544
22	0.95534	10.509
23	0.95267	10.479
24	0.95017	10.452
25	0.94896	10.439
26	0.94850	10.433
27	0.94836	10.432
28	0.97162	10.688
29	0.97140	10.685
30	0.97129	10.684
31	0.96589	10.625
32	0.96555	10.621
33	0.96538	10.619
34	0.96533	10.619

Calculation of losses

Line	I (kA)	Angle (deg)	Ir	Resistance	Pr Losses (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.253	-1.94	-0.0085	0.11700	0.02554	0.25236	22.35291	22.37844
2	0.240	-0.24	-0.0010	0.10725	0.00032	0.24030	18.57884	18.57916
3	0.228	1.66	0.0066	0.16445	0.02145	0.22810	25.66987	25.69132
4	0.216	3.78	0.0142	0.14950	0.09107	0.21593	20.91172	21.00279
5	0.205	6.16	0.0220	0.14950	0.21649	0.20372	18.61334	18.82983
6	0.082	-32.12	-0.0434	0.31440	1.78002	0.06919	4.51574	6.29576
7	0.067	-31.93	-0.0355	0.20960	0.79413	0.05703	2.04543	2.83956
8	0.053	-31.86	-0.0278	0.31440	0.72718	0.04467	1.88243	2.60961
9	0.038	-31.77	-0.0200	0.20960	0.25038	0.03222	0.65283	0.90321
10	0.023	-31.96	-0.0124	0.13100	0.06030	0.01985	0.15489	0.21519
11	0.009	-31.79	-0.0046	0.10480	0.00660	0.00739	0.01719	0.02380
12	0.014	-32.02	-0.0076	0.15720	0.02711	0.01212	0.06933	0.09644
13	0.010	-31.94	-0.0052	0.20960	0.01690	0.00832	0.04349	0.06039
14	0.005	-31.73	-0.0028	0.10480	0.00244	0.00451	0.00639	0.00883
15	0.001	-29.23	-0.0004	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.134	1.55	0.0036	0.17940	0.00704	0.13395	9.65688	9.66392
17	0.126	-15.25	-0.0330	0.16445	0.53839	0.12118	7.24438	7.78277
18	0.120	-25.29	-0.0513	0.20790	1.63905	0.10850	7.34223	8.98128
19	0.113	-32.07	-0.0601	0.18900	2.04823	0.09593	5.21744	7.26567
20	0.098	-32.04	-0.0522	0.18900	1.54526	0.08341	3.94475	5.49001
21	0.084	-32.01	-0.0443	0.26200	1.54380	0.07089	3.94952	5.49332
22	0.069	-31.99	-0.0364	0.26200	1.04121	0.05827	2.66846	3.70968
23	0.054	-31.97	-0.0285	0.31440	0.76549	0.04564	1.96455	2.73004
24	0.039	-31.97	-0.0206	0.20960	0.26668	0.03300	0.68483	0.95151
25	0.024	-31.97	-0.0127	0.13100	0.06292	0.02028	0.16157	0.22449
26	0.009	-31.99	-0.0047	0.10480	0.00699	0.00755	0.01792	0.02490
27	0.014	-33.03	-0.0078	0.15720	0.02906	0.01207	0.06873	0.09779
28	0.010	-33.03	-0.0052	0.15720	0.01291	0.00805	0.03055	0.04346
29	0.005	-33.03	-0.0026	0.15720	0.00323	0.00402	0.00764	0.01087
30	0.015	-31.46	-0.0076	0.15720	0.02701	0.01237	0.07215	0.09915
31	0.011	-31.46	-0.0057	0.20960	0.02035	0.00930	0.05436	0.07471
32	0.007	-31.46	-0.0038	0.15720	0.00666	0.00614	0.01779	0.02445
33	0.004	-31.46	-0.0019	0.10480	0.00111	0.00307	0.00297	0.00407
				TOTAL	**13.58533**		**158.62119**	**172.20652**

Iteration: 5; Bus Location: 21; Capacitor Size: 239.77 kVAR



Voltage Profile

Bus	pV (pu)	V (kV)
1	1.00000	11.000
2	0.99539	10.949
3	0.99142	10.906
4	0.98566	10.842
5	0.98077	10.788
6	0.97622	10.738
7	0.97242	10.697
8	0.97033	10.674
9	0.96787	10.647
10	0.96669	10.634
11	0.96624	10.629
12	0.96610	10.627
13	0.99108	10.902
14	0.99078	10.899
15	0.99069	10.898
16	0.99069	10.898
17	0.97258	10.698
18	0.96931	10.662
19	0.96547	10.620
20	0.96229	10.585
21	0.95954	10.555
22	0.95630	10.519
23	0.95363	10.490
24	0.95113	10.462
25	0.94993	10.449
26	0.94946	10.444
27	0.94932	10.443
28	0.97208	10.693
29	0.97186	10.690
30	0.97175	10.689
31	0.96636	10.630
32	0.96602	10.626
33	0.96585	10.624
34	0.96579	10.624

Calculation of losses

Line	I (kA)	Angle (deg)	Ir (kA)	Resistance	Pr Losses (kvar)	Ia (kA)	Pa Loss (kW)	Total Real Losses
1	0.252	0.93	0.0041	0.11700	0.00583	0.25227	22.33718	22.34301
2	0.241	2.77	0.0116	0.10725	0.04340	0.24022	18.56670	18.61010
3	0.229	4.81	0.0192	0.16445	0.18204	0.22809	25.66714	25.84918
4	0.218	7.10	0.0269	0.14950	0.32371	0.21583	20.89314	21.21685
5	0.207	9.64	0.0346	0.14950	0.53662	0.20358	18.58843	19.12505
6	0.082	-32.20	-0.0435	0.31440	1.78357	0.06905	4.49679	6.28035
7	0.067	-32.01	-0.0356	0.20960	0.79769	0.05698	2.04187	2.83956
8	0.053	-31.94	-0.0278	0.31440	0.73045	0.04464	1.87916	2.60961
9	0.038	-31.85	-0.0200	0.20960	0.25151	0.03219	0.65170	0.90321
10	0.023	-32.04	-0.0124	0.13100	0.06057	0.01984	0.15462	0.21519
11	0.009	-31.87	-0.0046	0.10480	0.00663	0.00739	0.01716	0.02380
12	0.014	-32.05	-0.0076	0.15720	0.02715	0.01212	0.06929	0.09644
13	0.010	-31.97	-0.0052	0.20960	0.01693	0.00831	0.04346	0.06039
14	0.005	-31.76	-0.0028	0.10480	0.00245	0.00451	0.00639	0.00883
15	0.001	-29.26	-0.0004	0.05240	0.00002	0.00070	0.00008	0.00010
16	0.135	6.96	0.0164	0.17940	0.14391	0.13391	9.65026	9.79417
17	0.123	-9.50	-0.0202	0.16445	0.20220	0.12102	7.22532	7.42753
18	0.115	-19.53	-0.0385	0.20790	0.92225	0.10838	7.32618	8.24843
19	0.107	-26.26	-0.0472	0.18900	1.26571	0.09578	5.20163	6.46734
20	0.092	-25.27	-0.0393	0.18900	0.87643	0.08329	3.93310	4.80953
21	0.084	-32.21	-0.0445	0.26200	1.55675	0.07065	3.92344	5.48019
22	0.069	-32.18	-0.0365	0.26200	1.04941	0.05806	2.64947	3.69888
23	0.054	-32.17	-0.0286	0.31440	0.77378	0.04554	1.95626	2.73004
24	0.039	-32.16	-0.0207	0.20960	0.26818	0.03285	0.67844	0.94662
25	0.024	-32.16	-0.0127	0.13100	0.06360	0.02023	0.16089	0.22449
26	0.009	-32.18	-0.0047	0.10480	0.00706	0.00753	0.01784	0.02490
27	0.014	-33.11	-0.0079	0.15720	0.02918	0.01206	0.06861	0.09779
28	0.010	-33.11	-0.0052	0.15720	0.01297	0.00804	0.03049	0.04346
29	0.005	-33.11	-0.0026	0.15720	0.00324	0.00402	0.00762	0.01087
30	0.015	-31.54	-0.0076	0.15720	0.02713	0.01236	0.07202	0.09915
31	0.011	-31.54	-0.0057	0.20960	0.02044	0.00929	0.05427	0.07471
32	0.007	-31.54	-0.0038	0.15720	0.00669	0.00614	0.01776	0.02445
33	0.004	-31.54	-0.0019	0.10480	0.00111	0.00307	0.00296	0.00407
				TOTAL	**11.99863**		**158.38965**	**170.38829**