بِسۡمِ ٱللَّهِ ٱلرَّحۡمَٰنِ ٱلرَّحِيمِ

Sudan University of Science and Technology

College of Graduate Studies

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An Intelligent Load Shedding System Application in Sudan National Grid

تطبيق خفض الأحمال الذكي في شبكة الكهرباء السودانية القومية

A Thesis submitted in partial fulfillment for the requirement of the

Degree of M.Sc. in Electrical Engineering (Power)

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February 2018

الآيـة

(اللَّهُ نُورُ السَّمَاوَاتِ وَالأَرْضِ مَثَلُ نُورِهِ كَمِشْكَاةٍ فِيهَا مِصْبَاحٌ الْمِصْبَاحُ فِي زُجَاجَةٍ الزُّجَاجَةُ كَأَنَّهَا كَوْكَبٌ دُرِّيٌّ يُوقَدُ مِن شَجَرَةٍ مُّبَارَكَةٍ زَيْتُونَةٍ لّا شَرْقِيَّةٍ وَلا غَرْبِيَّةٍ يَكَادُ زَيْتُهَا يُضِيءُ وَلَوْ لَمْ تَمْسَسْهُ نَارٌ نُّورٌ عَلَى نُورٍ يَهْدِى اللَّهُ لِنُورِهِ مَن يَشَاء وَيَضْرِبُ اللَّهُ الأَمْثَالَ لِلنَّاسِ وَاللَّهُ بِكُلِّ شَيْءٍ عَلِيمٌ)

سورة النور

آية رقم (35)

Dedication

To whom she dressed me the life, Mother.

To whom always support me, my family.

The suns that burn to light for us, Teachers.

To whom I share with them the sorrow and sweet, Friends.

Acknowledgments

Thanks to Allah the compassionate the merciful for giving me patience and strength to accomplish this thesis

All thanks and appreciations go to Allah for his unlimited blessings and for giving me the strength to complete this study.

Special thanks are extended to my supervisor **Dr. Mohamed Osman Hassan** for his considerable effort, great help and continuous scientific directing along this study.

My appreciation is also extended to the Sudan University of Science & Technology for giving me the opportunity to carry out this study.

Furthermore, great thanks are also to my colleagues and lecturers in the Engineering Faculty and the Electrical Engineering Department in particular for their continual encouragement and support.

Thanks go to Sudan National Dispatch Centre, for providing me all the necessary information that was helpful in accomplishing this work.

Also special thanks to my friend Eng. Hassam Algemmar and my colleagues in STPG Department of Protection and Control for their support.

Finally, my most appreciations are to my parents, brother and sisters

For their full support, encouragement and patience that give me the power all life.

Abstract

Conventional methods of system load shedding are too slow and do not effectively calculate the correct amount of load to be shed. This results in either excessive or insufficient load reduction. In recent years, load shedding systems have been repackaged using conventional under-frequency relay and/or breaker interlocks schemes integrated with Programmable Logic Controllers to give a new look to an antiquated load preservation methodology. A truly modern and intelligent load shedding system with a computerized power management system should provide fast and optimal load management by utilizing system topology and actual operating conditions tempered with knowledge of past system disturbances. This thesis demonstrates the need for a modern load shedding scheme and introduces the new technology of intelligent load shedding. Comparisons of intelligent load shedding with conventional load shedding methods are made from perspectives of system design, system engineering, project implementation, and system operation. A case study of the application of an intelligent load shedding scheme is Sudan Power Network is provided by using ETAP program and the results of simulation have showed.

المستخلص

الطرق التقليدية لخفض أحمال النظام بطيئة جدا وغير فعاله في حساب الكمية الجديدة خفض احمل التي يجب تخفيضها. وقد أدي ذلك إلى تخفيض الاحمل بشكل مفرط أو غير كاف. في السنوات الأخيرة، تم إعادة تجميع أنظمة تخفيض الحمولة باستخدام أنظمة مرحلات التردد وأنظمة تقاطع القواطع المدمجة مع وحدات التحكم المنطقية القابلة للبرمجة لإعطاء نظرة جديدة لمنهجية الحفاظ على الأحمال. إن توفر نظام خفض أحمال حديث وذكي مع نظام إدارة القدرة عن طريق الحواسب الآلية يزود منظومة القدرة بإدارة خفض أحمال بصورة سريعة ومثلى من خلال الاستفادة من طوبولوجيا النظام وظروف التشغيل الفعلية الت ي تم حسابها بمعرفة اضطرابات النظام السابقة. هذا البحث برهن على الحاجة إلى مخطط خفض الأحمال حديث وناقش التكنولوجيا الجديدة خفض الأحمال الذكي.

مقارنة بين خفض الأحمال الذكي مع الطرق التقليدية لخفض الأحمال نوقشت من وجهات نظر تصميم النظام، هندسة النظام، تنفيذ المشروع، وتشغيل النظام. وكان دراسة الحالة لتطبيق مخطط خفض الأحمال شبكة كهرباء السودان باستخدام برنامج ETAP وعرضت نتائج المحاكاة.

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LIST OF SYMBOLS

Σ	-	Summation
α	-	Value of fuzziness
W	-	Weight
KV	-	Kilovolt
Hz	-	Hertz
MVAR	-	Megavolt ampere reactive
MW	-	Megawatt
MVA	-	Megavolt ampere
S	-	Apparent power

LIST OF ABBREVIATIONS

Et al.	-	And others
Mi	-	Medium
Li	-	Lower limit
Ui	-	Upper limit
AHP	-	Analytic Hierarchy Process
AP	-	Area power
CI	-	Consistency Index
CR	-	Consistency ratio
DCS	-	Distributed Control System
ETAP	-	Electrical Transient Analysis Program
GIS	-	Gas Isolated Substation
HV	-	High voltage
ILS	-	Intelligent load shedding
IEEE	-	Institute of Electrical and Electronic Engineers
IMS	-	Information Management System
LP	-	Load power
LS	-	Load Shedding
LV	-	Low voltage
MCDM	-	Multi Criteria Decision Making
OP.	-	Operating
PS	-	Power Supply
RI	-	Random Index
SCADA	-	Supervisory Control and Data Acquisition

SD	-	System Dynamics
SEM	-	Structural Equation Modelling
SNG	-	Sudan National Grid
TG	-	Turbine Generator
TP	-	Total Power
UFLS	-	Under frequency load shedding
GWh	-	Giga watt hour

CHAPTER 1

INTRODUCTION

1.1 Thesis Background

Load shedding applies in power system where the total electrical power demand greatly exceeds the amount of power generated. If the load shedding was not done, the generator's overload breakers would automatically shut down the whole power station to protect its alternators from very severe damage. Such damage would be extremely expensive to repair and would take a lot of time to do it.

In general, load shedding can also be the number of loads that must almost instantly be removed from a power system to keep the remaining portion of the system operational. This load reduction is in response to a system disturbance and consequent possible additional disturbances that result in a generation deficiency condition. Common disturbances that can cause this condition to occur include faults, loss of generation, switching errors, lighting strikes, etc. [1].

In the modern large interconnected power system, there exists the possibility that under the certain condition, the whole system will be suddenly separated into several islands [2]. A sudden loss of generation due to abnormal conditions such as a generator fault or line tripping could disturb the balance between generations and loads resulting in the system frequency decline. The system power deficit could lead dangerously to the low speed of the generating set and might cause failure in turbines' blades [3].

Notifying that several power system blackouts have occurred recently over the world, frequency stability has become a major concern of power system operators.

Frequency stability refers to the ability of a power system to maintain steady frequency in the system after being subjected to a disturbance from a given initial condition [4]. System blackout is the state when the system or large areas of it may completely collapse. This state is usually preceded by a sequence of cascading failure events that knock out transmission lines and generating units [5].

Frequency instability, in particular, results from the inability of the combined transmission and generation system to deliver the power requested by loads. It is a dynamic phenomenon largely drove by the load response to frequency and voltage change. Load shedding is well known to be an effective countermeasure against frequency instability, especially when the system undergoes an initial frequency drop that is too pronounced to be corrected by generator governors [6].

1.2 Problem statement

Sudan national power grid has been subjected to four blackouts last eight years, due to defect in grid system configuration and operation for disturbances that have happened in network. The first black out was on 4.10.2009 due to the failure of feeding units at the Merowe dam which represent the slack bus of the Sudan power grid. Then the second blackout was on 23.5.2014 because of introduction of new infrastructure aimed in switchgear ties with Merowe bus bar. While the third blackout was caused by huge fire at electricity transformer in Merowe dam on 4.5.2015. And for the same reason of the first blackout, the last blackout occurred on 27.2.2017. Now it is clear that all blackouts happened because of trip sequences of generation bus bars without under frequency load shedding has operated correctly. Therefore, intelligent load shedding is important in reducing the incidence of tripping.

According to the statistics provided by national local dispatch center [7], the demand of the electric power was increasing rapidly year by year which needs for more generation projects and modern configuration of system grid operation to meet the expected new and more disturbances in the grid.

There are various causes of the electricity supply interruptions such as natural disasters, equipment failures, overload, damaged by third parties, maintenance works, unknown, trees and others. If the interruptions occurred, the electricity Supply Company should take actions to maintain the distribution of the electricity supply of the unaffected area. The company should reduce the interruptions as minimum as possible.

As consumers, people are desired to have continuously distributed electricity supplies without any interruption. For example, the industry will lose a lot of income if there are shortages in the electricity supplies.

This thesis will present a system with intelligent load shedding scheme for Sudan power grid to overcome the problem during electricity interruptions.

1.3 Thesis Objectives

There are three objectives for this thesis:

(I) To justify an intelligent load shedding scheme for Sudan power grid.

(ii) To implement criteria decision-making method AHP in the load shedding scheme.

(iii) To compare the effectiveness of the intelligent load shedding (ILS) scheme and under frequency load shedding (UFLS) scheme which is used in Sudan power grid.

1.4 Thesis Scope

The purpose of this thesis is to identify the intelligent load shedding scheme in Sudan national power grid. A systematic approach is developed to identify the priority based on the impact of the power system state. Therefore, this thesis will focus on the analysis of power system outages.

The criteria for the determination of "worst case" will be the total load shedding in the post-fault system. The contingencies will cover all possible scenarios, including those which will lead to the islanding of the power system.

1.5 Contribution And Claims Of Originality

The research has proposed and developed a systematic approach by identifying the power system dynamic vulnerability under extreme conditions, for example, with the loss of one or two power plant. The proposed methods have the following unique features:

1.5.1 New Method

The Analytical Hierarchy Process (AHP) method is the newly method that has been used in the intelligent load shedding scheme for a utility power system.

1.5.2 Simplified

The method that has been applied (AHP) is simpler in concept as the load shedding decision is determined based on the information such as criteria and alternatives.

1.5.3 Easy

The method proposed is easily been applied to the load shedding scheme. The calculation from the analysis is quite simple with a few steps only.

1.6 Thesis Outline

Chapter 2 is the literature review of this project. This chapter will give details about the theory of the application in load shedding problems in the electrical power system. Some previous researches are shown in this chapter.

Chapter 3 discusses about the project procedure and also approach used to implement the project is explained. Chapter 4 shows the results, data analysis and discussion. The intelligent load shedding in the electrical power system by using the Analytic Hierarchy Process (AHP) is discussed in this chapter.

Chapter 5 presents the project conclusions and recommendations. This chapter will discuss about the conclusions of the project and also some future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Conventional Load Shedding Approach

This section is a review of load shedding techniques that have been devised over a number of years each having its own set of applications and drawbacks .

2.1.1 Breaker Interlock Load Shedding

This is the simplest method of carrying out load shedding. For this scheme, the circuit breaker interdependencies are arranged to operate based on hardwired trip signals from an intertie circuit breaker or a generator trip. This method is often used when the speed of the load shedding is critical. Even though ,the execution of this scheme is fast, breaker interlock load shedding possesses a number of inherent drawbacks :

- Load shedding based on worst-case scenario
- Only one stage of load shedding
- Almost always, more load is shed than required
- Modifications to the system are costly

2.1.2 Under Frequency Load Shedding

Load shedding by frequency relays is the most commonly used method for controlling the frequency of power networks within set limits and maintaining network stability under critical conditions. In the conventional load-shedding methods, when frequency drops below the operational plan's set point, the frequency relays of the system issue commands to disconnect parts of the electrical power load in a stepwise manner, thereby preventing further frequency drop and its consequential effects [8].

The reason that frequency is the main criterion of system quality and security is as follows:

• A global variable of interconnected networks that has the same value in all parts of the network

• An indicator of the balance between supply and demand

• A critically important factor for the smooth operation of all users and particularly manufacturing and industries

One of the main problems of all interconnected networks is a total blackout because of frequency drop as a consequence of some power station failure or transmission line breakage. Presently, in the power generation and transmission systems of the world, the most appropriate way of preventing a total or partial blackout that is triggered by frequency drop is quick and automatic load shedding.

To study situations of imbalance between power supply and demand, and the resulting frequency variations under the circumstances of severe and major disorders, a simplified model of the steady state for systems that consist mainly of thermal units is used [8 – 10], which is shown in Figure 2.1. The expression of the model is as follows:

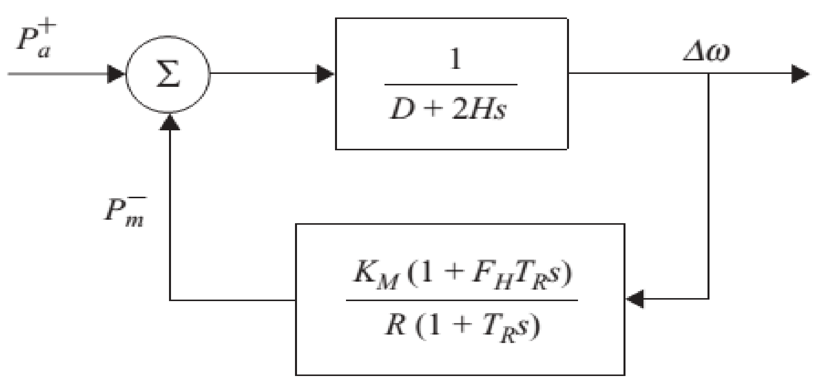

Figure 2.1 Steady - state frequency - response model

$$\Delta\omega = \frac{P_a}{D}\left(1 - e^{-\frac{D}{2H}t}\right) \tag{2.1}$$

Where

H: System's inertial constant

D: Load damping coefficient

K_m: Frequency control loop gain

F_H: High-pressure re-warmed turbines' power portion

T_R: Re-warming time constant

P_m: Mechanical power of the turbine (per unit)

Pa: Accelerator's power

$\Delta\omega$: Speed change (per unit)

Equation (2.1) models the system at the initial conditions of major disorders when the governor' s effect is lifted off because during the first seconds of the disorder, due to governor' s response delay and its operating time constant, it cannot play a role in prevention of the frequency drop [9].

The load damping coefficient (D) is an effective parameter that represents the relation between the load and the frequency. It cannot be ignored in planning for load - shedding schemes. In planning for load shedding, the load damping coefficient is normally expressed per unit as shown in the following formula:

According to equation (2.2), the main factors and parameters that control the behavior of frequency and overloading are the amount of overloading and the D and H parameters. The effect of these two parameters should be definitely considered in any load - shedding scheme.

$$D = \frac{F}{P}\frac{\Delta P}{\Delta F} \tag{2.2}$$

The value of D varies from 0 to 7 and is to be determined once for each system and used in all cases of planning. The latest studies have shown D = 3.3 for the sample network [8].

The effect of D on the frequency drop gradient is quite visible as an increase in D causes a decrease in the frequency drop gradient. For any specified overloading, systems with a higher value of D will have a higher stability and the final system frequency will be stabilized at a higher level. Figure 2.2 clearly shows the effect of Don the frequency drop curve.

In commonly used stepwise methods, the load - shedding scheme has little relation to the degree of overload. Any overload triggers the same strategy of load shedding, as the degree of overload does not determine the number or quantity of the load shedding.

This kind of scheme greatly simplifies the task of harmonizing the relays and the steps of load shedding, as simple calculations and a process of trial and error would suffice. It is one of the obvious advantages of this kind of scheme. Once the steps of load shedding are specified, if at any step the frequency continues to drop (with regard to the specified delay times), then the next step will be automatically activated until the frequency stops dropping. In such strategies, increasing the number of steps can increase the costs and allow a more precise harmony and a minimized blackout area. Nevertheless, in almost all countries, only three to five steps are planned, with rare cases of more steps.

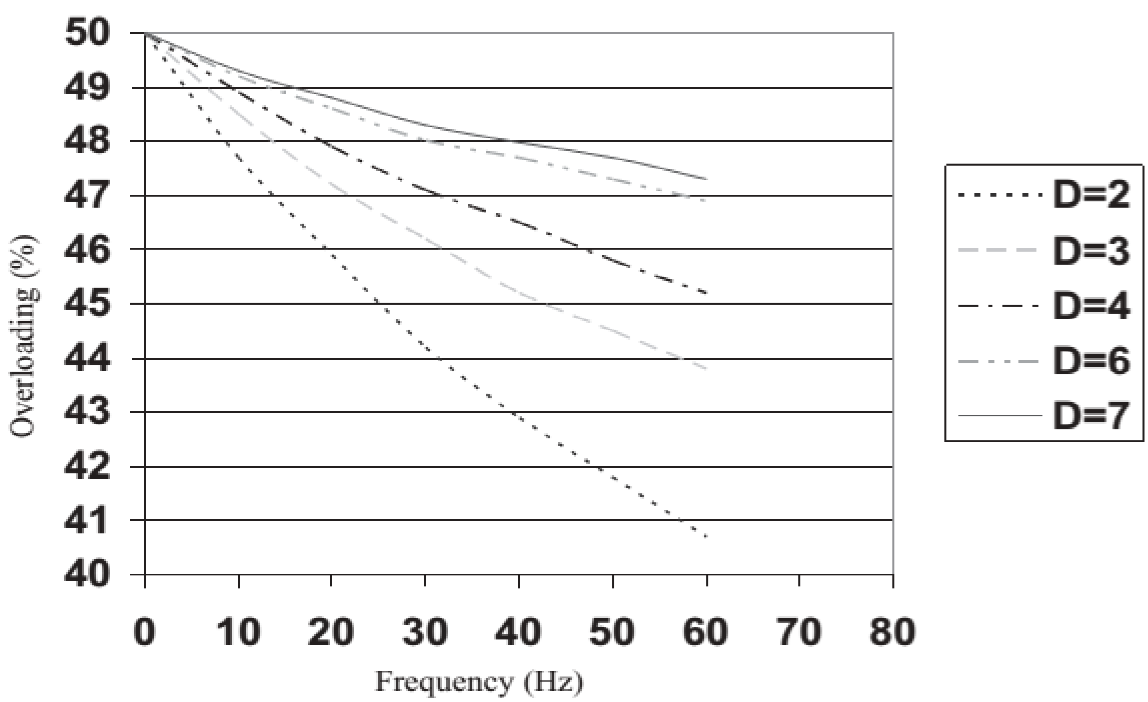

Figure 2.2 The effect of load damping coefficient on the frequency drop curve (system stability curves for various overloading)

In such strategies or plans, the first step of load shedding is regulated in such a way that with any frequency drop below the set point, this step is activated to operate within its specific time delay. The time duration for frequency to drop from normal to below the set point is not taken into consideration, despite the fact that we know that the gradient of frequency drop is directly proportional to the amount of overload and severity of the case; therefore, it can be a basis to decide on whether only one step is adequate.

Guidelines for setting up a frequency load shedding are common to both large and small systems. The design methodology considers fixed load reduction at fixed system frequency levels. Upon reaching the frequency set point and expiration of pre-specified time delay, the frequency relay trips one or more load breakers. This cycle is repeated until the system frequency is recovered, e.g., 10% load reduction for every 0.5% frequency reduction. Since this method of load shedding can be totally independent of the system dynamics, total loss of the system is an assumed possibility. Additional drawbacks of this scheme are described below .

2.1.2.1 Slow Response Time

In addition to the time it takes for the frequency to reach the pre-defined settings, there is an intentional time delay setting to prevent nuisance tripping during frequency spikes. Time delay may be further prolonged due to the over-frequency condition that can occur during the fault .

Upon detection of frequency decay and expiration of set time delay, the frequency relay initiates the first stage of load shedding. If the amount of load shed was insufficient, the frequency continues to decay ,activating the next stage of load shedding. Each additional stage introduces further delays in the load shedding process .

2.1.2.2 Incorrect / Excessive Load Shedding

The setting of each frequency relay is usually determined based on the most severe disturbance conditions, and most conservative generation and loading levels. This means excessive load shedding for the majority of conditions that are not as severe . In response to a dip or rate-of-change in frequency ,frequency relays operate a set of fixed circuit breakers ,independent of their actual operating load. Some breakers might have a load that may be quite different than the value considered in the studies. Additionally ,the sequence of operation of the breakers may not be correct and/or optimal .

2.1.2.3 Analysis Knowledge is Always Lost

To determine the frequency relay settings requires simulation of hundreds of transient stability studies .The objective of this analysis is to find the minimum fault clearing time and determine the minimum required load shedding by trial and error methods. The engineer performing the study learns the behavior of the system and can intuitively predict the response of the system under various operating conditions.

However, the only study result utilized by the load shedding system is a set of frequency relay settings. All other pertinent analysis results, along with the engineer's knowledge of the system, are lost.

2.1.3 Programmable Logic Controller-Based Load Shedding

With a Programmable Logic Controller (PLC) scheme, load shedding is initiated based on the total load versus the number of generators online and/or detection of under-frequency conditions. Each substation PLC is programmed to initiate a trip signal to the appropriate feeder breakers to shed a preset sequence of loads. This static sequence is continued until the frequency returns to a normal, stable level.

A PLC-based load shedding scheme offers many advantages such as the use of a distributed network via the power management system, as well as an automated means of load relief. However, in such applications monitoring of the power system is limited to a portion of the network with the acquisition of scattered data. This drawback is further compounded by the implementation of pre-defined load priority tables at the PLC level that are executed sequentially to curtail blocks of load regardless of the dynamic changes in the system loading, generation, or operating configuration. The system-wide operating condition is often missing from the decision-making process resulting in insufficient or excessive load shedding. In addition, response time (time between the detection of the need for load shedding and action by the circuit breakers) during transient disturbances is often too long requiring even more load to be dropped.

2.2 Intelligent Load Shedding Approach

An effective load shedding approach requires a comprehensive understanding of power system dynamics and process constraints, combined with knowledge of system disturbances. This required information is summarized below:

2.2.1 Pre-Disturbance Operating Conditions:

• Total system load demand
• Total system power exchange to the grid
• Generation of each on-site unit
• Spinning reserve for each on-site unit
• Control settings for each running unit
• Settings and loading conditions for all major rotating machines
• System configurations (tie-line numbers, tie-line status and power transferring, bus-tie status and flows, transformers and feeder status and loading, loading of each load, especially loading for the sheddable loads, etc.)

2.2.2 Post-Disturbance Operating Conditions:

• New system load demand
• Remaining generation from on-site generation
• Spinning reserve for each remaining unit
• Time duration to bring up the spinning reserve
• New system configurations
• Status, settings and loading conditions of the remaining major rotating machines
• Status of each sheddable load

2.2.3 Nature And Duration Of The Disturbance:

• Electrical and/or Mechanical faults
• Complete or partial loss of power grid connection
• Complete or partial loss of on-site generation
• Load addition (impact)
• Location of disturbance
• Duration of disturbance and its termination (self-clearance, fault isolation, protection device tripping, etc.)
• Subsequent system disturbances

2.2.4 System Transient Response To A Disturbance:

• System frequency response (decay, rate-of change, final frequency)
• System voltage response
• Rotor angle stability of each remaining unit
• Operation of protective devices

A load shedding system, which can incorporate the above parameters into its calculation and decision making process, must possess certain intelligence. More and more of industrial facilities are being equipped with the modern data acquisition and monitoring system capable of detecting and reordering on-line operating data and disturbances conditions. In addition, power system modeling and simulation software tools have been significantly improved to perform various system analyses from a simple load flow study to more advanced studies such as transient stability analysis. In recent years, modern system analysis software programs have been designed as a component of a larger power management system in order to perform system analysis using real-time data. In addition, techniques such as Neural Network (NN), Generic Algorithms (GA), Simulated Annealing (SA), Fuzzy Logic (FL), Expert Systems (ES), etc, have emerged in the field of power systems offering more effective problem solving, knowledge representation and reasoning, search, planning and action, for some highly non-linear problems, which often cannot be solved using conventional techniques.

With the combination of such technological advances in power systems, an automated, intelligent, load shedding system can be designed to meet the following objectives:

• Map a complex, highly nonlinear, nonparametric, load shedding problem, to a finite space with a limited number of data collection points

• Automatic recall of system configuration, operating condition, and system response to disturbances

• Pattern recognition capability to predict system response to disturbances

• Systems knowledgebase trainable by user defined cases

• Self-learning capability to new system changes

• Make prompt decisions regarding which loads to shed based on the online status of sheddable loads.

• Shed the minimum amount of load to maintain system stability

Illustrated in Figure 2.3 is an Intelligent Load Shedding (ILS) scheme, which includes several basic functional blocks, defined below.

Knowledge base utilizes carefully selected input and output data under different cases, based on off-line system studies and simulations. System dynamic responses including frequency variation are amongst the outputs of the knowledgebase.

Advanced Monitoring constantly surveys the system operating condition changes, and calculates tie-line flows, on-site generations, transformers and feeder loading as well as evaluates status of the sheddable loads.

Network Models contain system topology, connection information, and electrical properties of system components.

Trigger Lists compiled based on pre-specified system disturbance types.

Load Shed Optimizer computes optimal load shedding tables corresponding to system changes.

Distributed Controls utilize PLCs to rapidly execute the load shedding actions based on detection of disturbance triggers from the system.

With the architecture described above, an ILS scheme provides the following benefits:

• Time-variant load shedding tables, which reflect true status, and loading conditions for the sheddable loads.

• Optimal combination of sheddable loads to maximize load preservation.

• Fast response to disturbance triggers (less than 100 ms in most cases).

• Environment to accelerate operator training with the ability to simulate and validate load shed decisions.

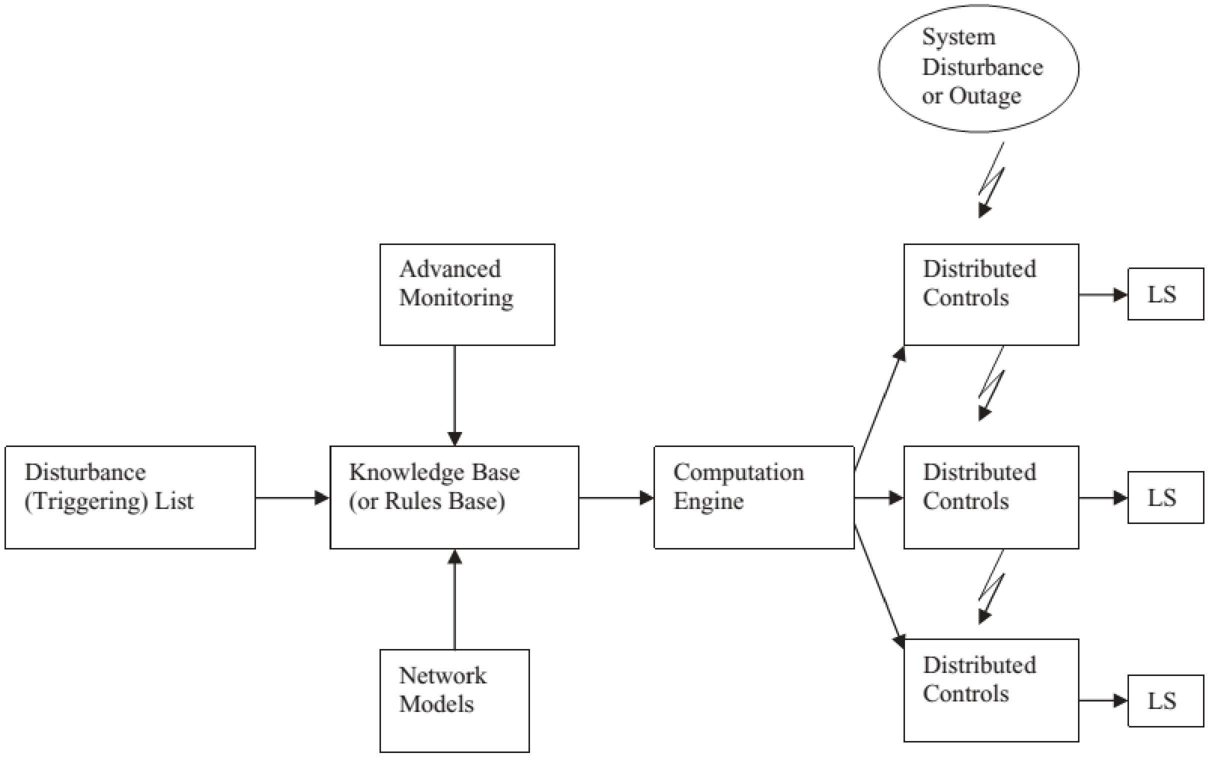

Figure 2.3 Function block diagram of the ILS scheme

Further details on this proposed scheme are explained in a companion paper titled "An Intelligent Load Shedding (ILS) System Technology Application in A Large Industrial Facility" to be presented at IEEE 2005 IAS Annual Meeting.

2.3 Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is a method for ranking decision alternatives and selecting the best one when the decision maker has multiple criteria. It answers the question, "Which one?" .With AHP, the decision maker selects the alternative that best meets his or her decision criteria and develops a numerical score to rank each alternative decision based on how well each alternative meets them [9].

In AHP, preferences between alternatives are determined by making pair wise comparisons. In a pair wise comparison, the decision maker examines two alternatives by considering one criterion and indicates a preference. These comparisons are made using a preference scale, which assigns numerical values to different levels of preference. The standard preferred scale used for the AHP is 1-

9 scale which lies between “equal importance” to “extreme importance” where sometimes different evaluation scales can be used such as 1 to 5 [9].

In the pair wise comparison matrix, the value 9 indicates that one factor is extremely more important than the other, and the value 1/9 indicates that one factor is extremely less important than the other, and the value 1 indicates equal importance. Therefore, if the importance of one factor with respect to the second factor is given, then the importance of the second factor with respect to the first is the reciprocal. The ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements [9].

Reference [10] proposed AHP as a decision aid to solve unstructured problems in economics, social and management sciences. AHP has been applied in a variety of contexts: from the simple everyday problem of selecting a school to the complex problems of designing alternative future outcomes of a developing country, evaluating political candidacy, allocating energy resources, and so on. The AHP enables the decision-makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under multiple criteria environment in the conflation [9].

The application of the AHP to the complex problem usually involves four major steps [9].

(a) Break down the complex problem into a number of small constituent elements and then structure the elements in a hierarchical form.

(b) Make a series of pair wise comparisons between the elements according to a ratio scale.

(c) Use the eigenvalue method to estimate the relative weights of the elements.

(d) Aggregate the relative weights and synthesis them for the final measurement of given decision alternatives [9].

The AHP is a powerful and flexible multi-criteria decision-making tool for dealing with complex problems where both qualitative and quantitative aspects need to be considered. The AHP helps analysts to organize the critical aspects of a problem into a hierarchy rather like a family tree [9].

The essence of the process is decomposition of a complex problem into a hierarchy with a goal at the top of the hierarchy, criteria and sub-criteria at levels and sublevels of the hierarchy, and decision alternatives at the bottom of the hierarchy [9]. Figure 2.4 illustrates the scheme of the Analytic Hierarchy Process (AHP).

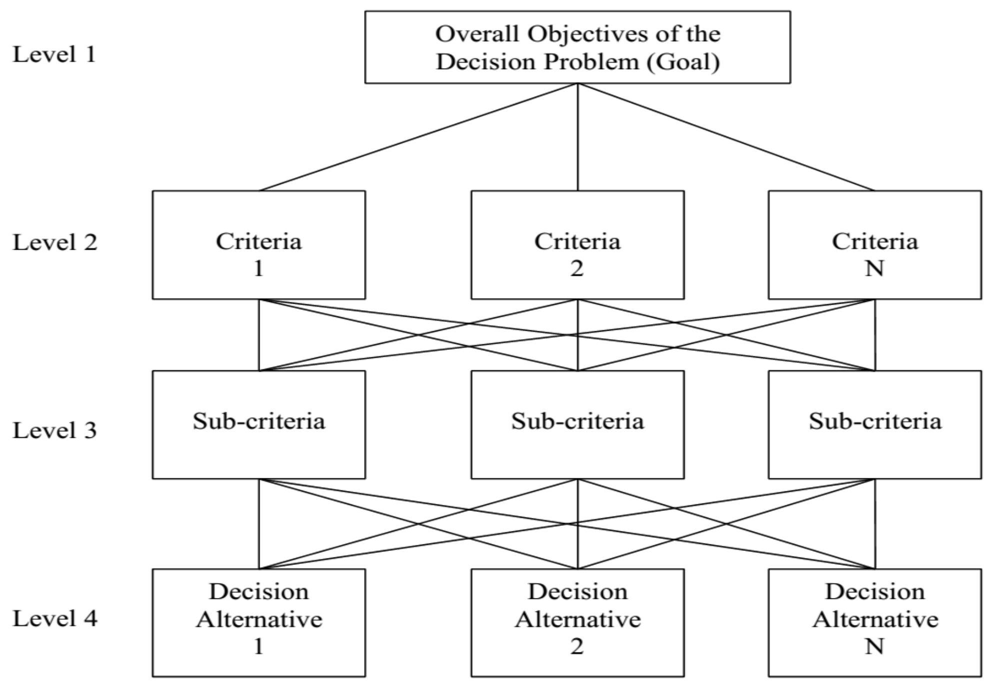

Figure 2.4 The Analytic Hierarchy Process (AHP) schemes [11]

Elements at the given hierarchy levels are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives are obtained. The entries of the final weight coefficient vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of the hierarchy [9].

A decision maker may use this vector according to his particular needs and interests. To elicit pair wise comparisons performed at a given level, a matrix A is created in turn by putting the result of pair wise comparisons of element i with element j into the position a_{ji} as given in Equation (2.1) [9].

$$A = \begin{array}{c} \\ C_1 \\ C_2 \\ C_3 \\ C_4 \\ C_5 \\ C_6 \\ . \\ C_n \end{array} \begin{array}{c} \begin{array}{cccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & . & C_n \end{array} \\ \begin{bmatrix} 1 & a_{12} & a_{13} & a_{14} & a_{15} & a_{16} & . & a_{1n} \\ a_{21} & 1 & a_{23} & a_{24} & a_{25} & a_{26} & . & a_{2n} \\ a_{31} & a_{32} & 1 & a_{34} & a_{35} & a_{36} & . & a_{3n} \\ a_{41} & a_{42} & a_{43} & 1 & a_{45} & a_{46} & . & a_{4n} \\ a_{51} & a_{52} & a_{53} & a_{54} & 1 & a_{56} & . & a_{5n} \\ a_{61} & a_{62} & a_{63} & a_{64} & a_{65} & 1 & . & a_{6n} \\ . & . & . & . & . & . & 1 & . \\ a_{n1} & a_{n2} & a_{n3} & a_{n4} & a_{n5} & a_{n6} & . & 1 \end{bmatrix} \end{array} . \qquad (2.3)$$

Where

n = criteria number to be evaluated

C_i = i^{th} criteria, (i=1, 2, 3,…., n)

A_{ij} = importance of i^{th} criteria according to j^{th} criteria (j=1, 2, 3,…., n) [9]

After obtaining the weight vector, it is then multiplied by the weight coefficient of the element at a higher level (that was used as the criterion for pair wise comparisons). The procedure is repeated upward for each level, until the top of the hierarchy is reached.

The overall weight coefficient, with respect to the goal for each decision alternative is then obtained. The alternative with the highest weight coefficient value should be taken as the best alternative. The Analytical Hierarchy Process is a well-known decision-making analytical tool used for modeling unstructured problems in various areas, e.g., social, economic, and management sciences [9].

Table 2.1 shows the fundamental scale of values to represent the intensities of judgments. There are several intensities of importance. Each of the intensities of the importance is attached with the definition and explanation. Table 2.1 can be used as the reference when proceed to do the AHP analysis [12].

Table 2.1: The fundamental scale of absolute numbers [12]

Intensity of importance	Definition	Explanation
1 2 3 4 5 6 7 8 9	Equal importance Weak Moderate importance Moderate plus Strong importance Strong plus Very strong Very, very strong Extreme importance	Two activities contribute equally to the objective Experience and judgment slightly favor one activity over another Experience and judgment strongly favor one activity over another An activity is favored very strongly over another; its dominance demonstrated in practice The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

A number of research projects on the application and using of analytical hierarchy process (AHP) approach have been found in the last decade ago. Lin et al. [13] applied the analytical hierarchy process in power lines maintenance. The main issue of this paper is to arrange for the power lines maintenance scientific and logical in the power department. Power lines maintenance is a complex process with many influencing factors, which cover the knowledge of kinds of subjects, such as management, security, scheming and so on.

2.4 Calculation tool

In this thesis, all the calculations are performed by using Matlab program. And the results of the analysis are presented by ETAP software.

Matlab is a multi-paradigm numerical computing environment. A proprietary programming language developed by Math Works, Matlab allows matrix manipulation, plotting of function and data, implementation of algorithms, creation of user interfaces, and interfacing with programs written in other language, including C, C++, C#, Java, Fortran and Python.

ETAP stands for electrical transient and analysis program (software program for electrical engineers).

CHAPTER 3

METHODOLOGY

3.1 Intelligent Load Shedding

3.1.1 The Need for ILS

Due to the inherent drawbacks of existing load shedding methods, an intelligent load shedding system is necessary to improve the response time, accurately predict the system frequency decay, and make a fast, optimum, and reliable load shedding decision. This system must have the following capabilities:

• Able to map a very complex and nonlinear power system with a limited number of data collection points to a finite space.

• Automatically remember the system configuration, operation conditions as load is added or removed, and the system response to disturbances with all of the system configurations.

• Recognize different system patterns in order to predict system response for different disturbances.

• Utilize a built-in knowledge base trainable by user-defined cases.

• Adaptive self-learning and automatic training of system knowledge base due to system changes.

• Make fast, correct, and reliable decisions on load shedding priority based on the actual loading status of each breaker.

• Shed the minimum amount of load to maintain system stability and nominal frequency.

• Shed the optimal combinations of load breakers with complete knowledge of system dependencies.

In addition to having the above list of capabilities, ILS system must have a dynamic knowledge base. For the knowledge base to be affective, it must be able to capture the key system parameters that have a direct impact on the system frequency response following disturbances. These parameters include:

• Power exchanged between the system and the grid both pre and post disturbance.

• Generation available before and after disturbances.

• On-site generator dynamics.

• Updated status and actual loading of each sheddable load.
• The dynamic characteristics of the system loads. This includes rotating machines, constant impedance loads, constant current loads, constant power loads, frequency dependent loads, or other types of loads.

Additional Requirements for ILS System

Some additional requirements must be met during the designing and tuning of an ILS scheme:

• Carefully selected and configured knowledge base cases.
• Ability to prepare and generate sufficient training cases for the system knowledge base to insure accuracy and completeness.
• Ability to insure that the system knowledge base is complete, correct, and tested.
• Ability to add user-defined logics.
• Ability to add system dependencies.
• To have an online monitoring system that is able to coherently acquire real-time system data.
• The ability to run in a preventive and predictive mode so that it can generate a dynamic load shedding table that corresponds to the system configuration changes and pre-specified disturbances (triggering).
• A centralized distributed local control system for the power system that ILS system supervises.

3.1.2 Function Block Diagram of the ILS:

The system knowledge base is pre-trained by using carefully selected input and output databases from offline system studies and simulations. System dynamic responses, including frequency variation, are among the outputs of the knowledge base.

The trained knowledge base runs in the background of an advanced monitoring system, which constantly monitors all of the system operating conditions. The network models and the knowledge base provide power system topology, connection information, and electric properties of the system component for ILS. The disturbance list is prepared for all prespecified system disturbances (triggers). Based on the input data and system updates, the knowledge base periodically sends requests to the ILS computation engine to update the load shedding tables, thus ensuring that the optimum load will be shed when a disturbance occur. The load shedding tables in turn are downloaded to the distributed controls that are located close to each sheddable load. When a disturbance occurs, fast load - shedding action can be taken.

3.1.3 Implementation Configuration of ILS

ILS knowledge base and computation engine reside in an ILS server computer. The server interfaces with an advanced real-time power system monitoring and simulation system that continuously acquires real-time system data. Based on ILS calculations, the server dynamically updates the load shedding tables and downloads that information to the distributed PLCs. Upon detection of any disturbance by the PLCs, load shedding is initiated. The load circuit breakers will be tripped based on the pre-generated optimal load shedding tables. This is shown in Figure 3.1

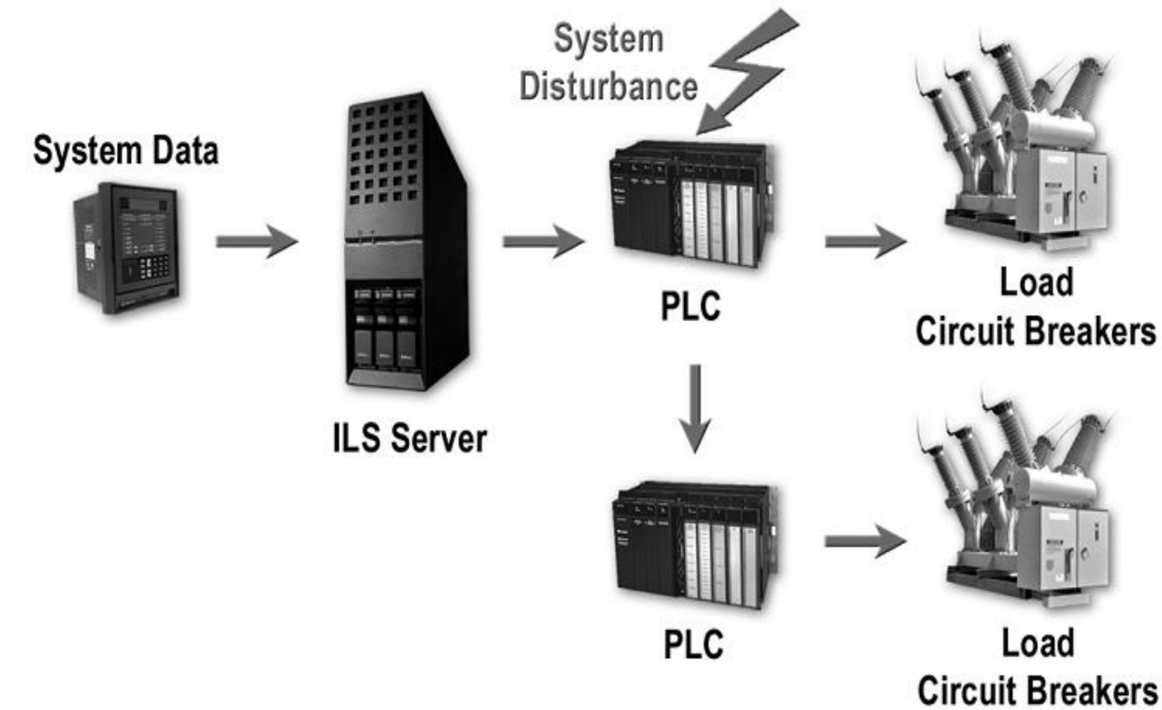

Figure 3.1 ILS Implementation Diagram

3.2 Formulation Of Optimal Load Shedding

In a competitive resource allocation environment, buy/sell decision support systems are needed to find economical ways to serve critical loads with limited sources under different uncertainties. Therefore, a value - driven load – shedding approach is proposed for this purpose. The mathematical model of load shedding is expressed as follows.

3.2.1 Objective Function — Maximization of Benefit Function

$$Max\ H_i = \sum_{j=1}^{ND(k)} w_{ij}\ v_{ij}\ x_{ij} \tag{3.1}$$

$$or\ Min\ (-\ Hi)$$

Where

x_{ij} : Decision variable (it equals 0 or 1) on load bus j at the ith time stage

ND(k): Total number of load sites in load center k

w_{ij}: Load priority to indicate the importance of the j load site of the i time stage

v_{ij}: Independent load values (or costs) in a specific load bus j at the i time stage ($/kW or $/MW)

H: Benefit function

In objective function (3.1), decision variable x_{ij} equals 1 if load demand P_{ij} is satisfied; otherwise, it equals 0 if the load demand is not satisfied, i.e., load shed appeared on the jth load site at the ith time stage. There are several different kinds of loads in a power system, such as critical load, important load and unimportant load, etc., and w_{ij} can reflect the relative importance of the different kind of loads. The more important the load site is (e.g., first important load), the larger the w_{ij} of the load site will be. In addition, each specific load has its independent load value (cost) v_{ij}, which are the value / cost per kW load at this location. Therefore, the unit of v_{ij} is $/kW.

3.2.2 Constraints of Load Curtailment:

The constraints of load curtailment reflect the system congestion case. These constraints include limited capacity in each load centre and the whole system, as well as available transfer capacity of the key line (e.g., tie - line connecting different load centre or source), which can be expressed as follows:

$$\sum_{j \in k} P_{ij}\, x_{ij} \ \leq P_{ik} \tag{3.2}$$

$$\sum_{j=1}^{ND} P_{ij}\, x_{ij} \ \leq P_D \tag{3.3}$$

$$\sum_{j \in k} P_{ij}\, x_{ij} \ = P_{sk} \ \leq P_{SKATC} \tag{3.4}$$

Where

P_{ij}: Load demand of the j load site of the i time stage

P_{iK}: Total amount of load centre k available at the i time stage

P_D: Total amount of system load available at the i time stage

P_{SK}: Transmission power on the line connecting load centre k

P_{SKATC}: Available transfer capacity of the line connecting load centre k

It is noted that the power flow equation or Kirchhoff's current law must be satisfied during the load shedding, i.e.

$$\sum_{G\to\omega} P_{iG} + \sum_{T\to\omega} P_{iT} + \sum_{j\to\omega} x_{ij} P_{ij} = 0 \qquad \omega \in n \tag{3.5}$$

$$-P_{iT\,max} \le P_{iT} \le P_{iT\,max}$$

where n is the total node number in the system; G → ω represents that generator G is adjacent to node ω; T → ω represents that transmission line T is adjacent to node ω; and j → ω represents that load j is adjacent to node ω. The direction of power flow is specified when the power enters into the node, while the negative when it leaves from the node. Equation (3.5) gives the system network security constraints.

3.3 Optimal Load Shedding With Network Constraints

3.3.1 Calculation of Weighting Factors by AHP:

It is very difficult to compute exactly the weighting factor of each load in Sudan national grid. The reason is that the relative importance of these loads is not the same, which is related to the power market operation and security conditions. According to the principle of AHP described in Chapter 2, the weighting factors of the loads can be determined through the ranking computation of a judgment matrix, which reflects the judgment and comparison of a series of pair of factors. The hierarchical model for computing the load weighting factors is shown in Figure 3.2, in which PI is the performance index of load center k.

The judgment matrix A-LD of the load shedding problem can be written as follows:

$$A - LD = \begin{bmatrix} w_{D1}/w_{D1} & w_{D1}/w_{D2} & \cdots & w_{D1}/w_{Dn} \\ w_{D2}/w_{D1} & w_{D2}/w_{D2} & \cdots & w_{D2}/w_{Dn} \\ \vdots & \vdots & \cdots & \vdots \\ w_{Dn}/w_{D1} & w_{Dn}/w_{D2} & & w_{Dn}/w_{Dn} \end{bmatrix} \quad (3.6)$$

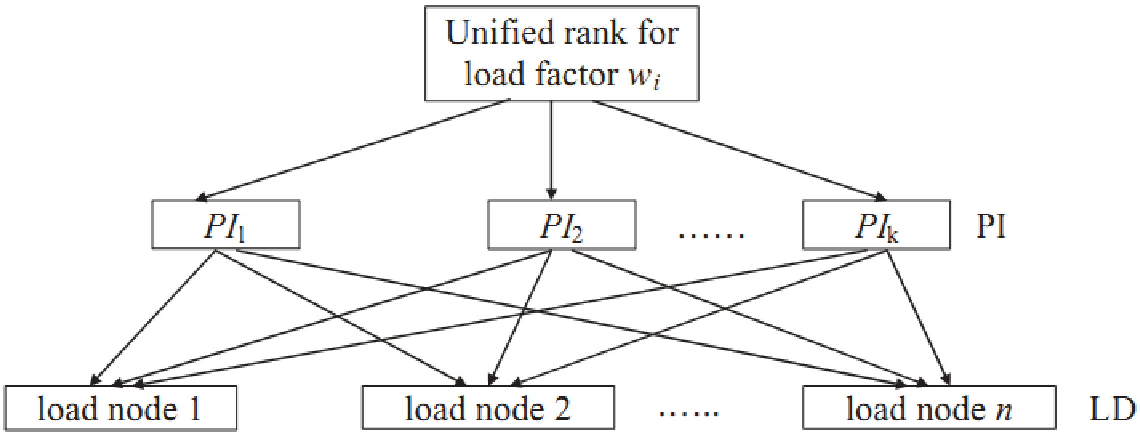

Figure 3.2 Hierarchy model of load weighting factor rank

Where, w_{Di}, which is just what we need, is unknown. w_{Di} / w_{Dj}, which is the element of the judgment matrix A- LD, represents the relative importance of the ith load compared with the jth load. The value of w_{Di} / w_{Dj} can be obtained according to the experience of electrical engineers or system operators using some ratio scale methods. For example, a "1 – 9" scale method from Chapter 2 can be used.

Similarly, the judgment matrix A-PI can be written as follows:

$$A - PI = \begin{bmatrix} w_{k1}/w_{k1} & w_{k1}/w_{k2} & \cdots & w_{k1}/w_{kn} \\ w_{k2}/w_{k1} & w_{k2}/w_{k2} & \cdots & w_{k2}/w_{kn} \\ \vdots & \vdots & \cdots & \vdots \\ w_{kn}/w_{k1} & w_{kn}/w_{k2} & & w_{kn}/w_{kn} \end{bmatrix} \quad (3.7)$$

Where w_{Ki} is unknown. w_{Ki}/w_{Kj}, which is the element of judgment matrix A-PI, represents the relative importance of the ith load center compared with the jth load center. The value of w_{Ki}/w_{Kj} can also be obtained according to the experience of electrical engineers or system operators using some ratio scale methods.

Therefore, the unified weighting factor of the load w_I can be obtained from the following equation:

$$w_i = w_{kj} \times w_{Di} \quad D_i \in K_j \quad (3.8)$$

Where $D_i \in K_j$ means load D_i is located in load center K_j.

3.3.2 Network Flow Model

After the weighting factors are computed by AHP, the above optimization model of load shedding corresponds to a network flow problem and can be solved by network flow programming (NFP). According to Chapter 2, the general NFP model can be written as

$$Min\ F = \sum C_{ij} f_{ij} \tag{3.9}$$

Such that

$\sum(f_{ij} - f_{ji}) = r$

$0 \leq f_{ij} \leq U_{ij}$

However, there exist three disadvantages in the general NFP algorithm [14], i.e.

(a) The initial arc flows must be feasible.

(b) The lower bound of flows should be zero.

(c) All flow variables must be nonnegative.

Because of these disadvantages, it is difficult to solve the optimal load shedding problem effectively by using the general NFP algorithm. A special NFP algorithm, "the out - of - kilter algorithm" (OKA), which is analyzed in Chapter 2, is adopted. The mathematical representation of the OKA network can be written as follows:

$$Min\ F = \sum C_{ij} f_{ij} \tag{3.10}$$

Such that
$\sum(f_{ij} - f_{ji}) = 0$
$L_{ij} \leq f_{ij} \leq U_{ij}$

Obviously, the optimal load - shedding model that is mentioned in Section (3.2) can be transformed into the OKA model shown in equations (3.10) and solved by the OKA. The details on the OKA model and algorithm can be found [15].

3.4 Illustrative Example Of ILS Scheme In IEEE 30 Bus

The simulation system for load shedding is the IEEE 30 - bus system. The capacity of the generator is given in Table 3.1. The daily load data including the independent load value/cost at each load site are listed in Table 3.2, in which the loads are divided into three load centers. Suppose generator G1 is out of service. The total source power is only 225.0 MW. This, in turn, leads to a power shortage for IEEE 30 - bus system, i.e., the power supply is limited at some time stages. The total system generation resources and load demands are shown in Figure 3.3.

Table 3.1 Capacity of generators for IEEE 30 -bus system

Gen	**PG1**	**PG2**	**PG5**	**PG8**	**PG11**	**PG13**
P_{max} (Mw)	200	80	50	35	30	30
P_{min} (Mw)	50	12	10	10	10	10

Table 3.2 Load data for IEEE 30 -bus system

Load Center	**Load Node**	**vij ($/kW)**	**Load t1 0.00: 4.00 (MW)**	**Load t2 4.01: 8.00 (MW)**	**Load t3 8.01: 12.00 (MW)**	**Load t4 12.01: 16.00 (MW)**	**Load t5 16.01: 20.00 (MW)**	**Load t6 20.01: 24.00 (MW)**
CK1	**PD2**	300.0	15.15	19.53	21.7	19.62	19.53	17.36
CK1	**PD3**	300.0	1.89	2.43	2.7	2.57	2.43	2.16
CK1	**PD4**	300.0	5.46	6.86	7.8	7.41	6.86	6.24
CK1	**PD6**	280.0	65.94	84.78	94.2	85.49	84.78	75.36
CK1	**PD7**	280.0	15.96	20.52	22.8	21.66	20.52	18.24
CK1	**PD8**	300.0	21.00	27.00	30.0	27.50	27.00	24.00
CK1	**PD10**	300.0	4.06	5.22	5.8	5.51	5.22	4.64
CK1	**PD12**	280.0	7.84	10.08	11.2	10.64	10.08	8.96
CK1	**PD14**	280.0	4.34	5.58	6.2	5.89	5.58	4.96
CK2	**PD15**	245.0	5.74	7.38	8.2	7.79	7.38	6.56
CK2	**PD16**	220.0	2.45	3.15	3.5	3.33	3.15	2.80
CK2	**PD17**	280.0	6.30	8.10	9.0	8.55	8.10	7.20
CK2	**PD18**	220.0	2.24	2.82	3.2	3.04	2.82	2.56
CK2	**PD19**	245.0	6.65	8.65	9.5	9.03	8.65	7.60
CK3	**PD20**	280.0	1.54	1.98	2.2	2.09	1.98	1.76
CK3	**PD21**	280.0	12.25	15.75	17.5	16.63	15.75	14.00
CK3	**PD23**	220.0	2.24	2.82	3.2	3.04	2.82	2.56
CK3	**PD24**	220.0	6.09	7.83	8.7	8.27	7.83	6.96
CK3	**PD26**	300.0	2.45	3.15	3.5	3.33	3.15	2.80
CK3	**PD29**	220.0	1.68	2.16	2.4	2.28	2.16	1.92
CK3	**PD30**	245.0	7.42	9.54	10.6	10.07	9.54	8.48

The judgment matrices A-LD and A-PI are provided in Tables 3.3 and 3.4, respectively. The weighting factors that reflect the relative importance of each load or each load center are computed by AHP. The results of the weighting factors are listed in Table 3.5. The optimal load shedding schemes are computed and obtained by the proposed approach. The calculation results are shown in Tables 3.6 and 3.7.

In Table 3.6, the decision variable x= 1 means that this load is committed, and x= 0 means that this load is curtailed. It can be known from Tables 3.6 and 3.7 that load curtailment appeared at time stage t2~t6. Loads 15, 16, 18, 19, 29, and 30 are curtailed at time stage t2~t5. Load 24 is curtailed at time

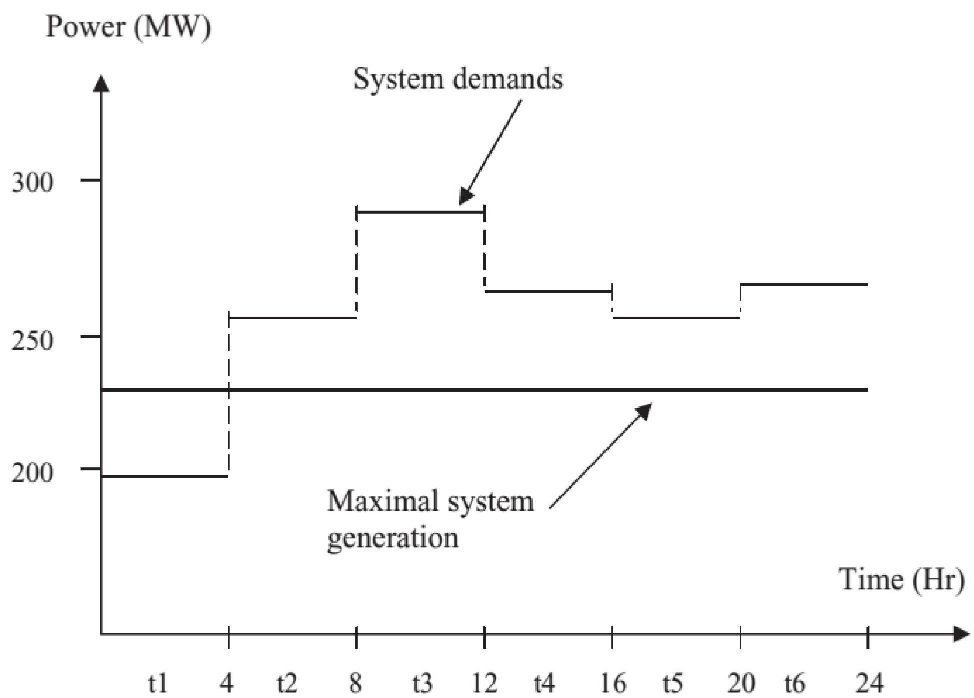

Figure 3.3 Total system generation and load demands

Table 3.3 Judgment matrix A – PI

PI	CK1	CK2	CK3
CK1	1	2	5
CK2	1/2	1	1/2
CK3	1/5	2	1

Table 3.4 Judgment matrix A - LD (1)

LD	2	3	4	6	7	8	10	12	14	15
2	1	2	2	1/3	1/5	2	1/2	2	2	3
3	1/2	1	1/2	1/4	2	1/2	1	2	2	3
4	1/2	2	1	1/2	2	1/3	2	2	3	2
6	3	4	2	1	4	2	3	3	3	3
7	5	1/2	1/2	1/4	1	1/2	2	2	2	3
8	1/2	2	3	1/2	2	1	3	2	2	4
10	2	1	1/2	1/3	1/2	1/3	1	2	3	3
12	1/2	1/2	1/2	1/3	1/2	1/2	1/2	1	1	2
14	1/2	1/2	1/3	1/3	1/2	1/2	1/3	1	1	2
15	1/3	1/3	1/2	1/3	1/3	1/4	1/3	1/2	1/2	1
16	1/3	1/2	1/3	1/4	1/3	1/4	1/3	1/2	1/3	1/2
17	1/2	2	1/2	1/2	1/3	1/2	2	1/2	1/2	3
18	1/3	1	1/2	1/3	1/3	1/3	1/2	1/2	1/3	1/2
19	1/3	1/2	1/2	1/3	1/3	1/3	1/3	1/2	1/3	1/2
20	1/3	1/2	1/3	1/3	1/3	1/3	1/2	1/3	1/2	5
21	1/3	1/3	1/2	1/3	1/4	1/4	1/3	1/3	1/2	5
23	2	3	1/2	1/2	1/2	1/2	1/2	1/2	1/3	3
24	1/3	1/3	1/2	1/3	1/3	1/2	1/3	1/3	1/3	1/3
26	1/3	1/3	1/2	1/3	1/2	1/3	1/3	1/2	1/2	3
29	1/3	1/3	1/3	1/3	1/3	1/2	1/3	1/3	1/3	1/2
30	1/3	1/3	1/2	1/3	1/3	1/3	1/2	1/3	1/3	2

Table 3.4 Judgment matrix A-LD (2)

LD	16	17	18	19	20	21	23	24	26	29	30
2	3	2	3	3	3	3	1/2	3	3	3	3
3	2	1/2	1	2	2	3	1/3	3	3	3	3
4	3	2	2	2	3	2	2	2	2	3	2
6	4	2	3	3	3	3	2	3	3	3	3
7	3	3	3	3	3	4	2	3	2	3	3
8	4	2	3	3	3	4	2	2	3	2	3
10	3	1/2	2	3	2	3	2	3	3	3	2
12	2	2	2	2	3	3	2	3	2	3	3
14	3	2	3	3	2	2	3	3	2	3	3
15	2	1/3	2	2	1/5	1/5	1/3	3	1/3	2	1/2
16	1	1/3	2	3	1/2	1/2	1/3	3	1/2	2	1/2

17	3	1	2	2	3	3	2	2	2	3	3
18	1/2	1/2	1	1/2	2	2	1/2	3	1/3	2	1/2
19	1/3	1/2	2	1	2	3	1/3	2	1/2	3	1/2
20	2	1/3	1/2	1/2	1	3	1/2	2	1/3	2	4
21	2	1/3	1/2	1/3	1/3	1	1/3	2	1/2	3	4
23	2	1/2	2	3	2	3	1	3	2	3	3
24	1/3	1/2	1/3	1/2	1/2	1/2	1/3	1	1/2	1/2	1/3
26	2	1/2	3	2	3	2	1/2	2	1	4	3
29	1/2	1/3	1/2	1/3	1/2	1/3	1/3	2	1/4	1	1/2
30	2	1/3	2	2	1/4	1/4	1/3	3	1/3	2	1

Table 3.5 Weighting factors computed by AHP

Load Center	**Weighting Factor wKj**	**Load Node**	**vij ($/kW)**	**Weighting Factor wDi**	**Unified Weighting Factor wi**
CK1	0.6118	**PD2**	300.0	0.0698	0.0427
CK1	0.6118	**PD3**	300.0	0.0536	0.0328
CK1	0.6118	**PD4**	300.0	0.0694	0.0424
CK1	0.6118	**PD6**	280.0	0.1132	0.0693
CK1	0.6118	**PD7**	280.0	0.0762	0.0466
CK1	0.6118	**PD8**	300.0	0.0884	0.0541
CK1	0.6118	**PD10**	300.0	0.0623	0.0381
CK1	0.6118	**PD12**	280.0	0.0525	0.0321
CK1	0.6118	**PD14**	280.0	0.0525	0.0321
CK2	0.1789	**PD15**	245.0	0.0230	0.0041
CK2	0.1789	**PD16**	220.0	0.0236	0.0042
CK2	0.1789	**PD17**	280.0	0.0554	0.0099
CK2	0.1789	**PD18**	220.0	0.0260	0.0047
CK2	0.1789	**PD19**	245.0	0.0264	0.0047
CK3	0.2092	**PD20**	280.0	0.0299	0.0062
CK3	0.2092	**PD21**	280.0	0.0257	0.0054
CK3	0.2092	**PD23**	220.0	0.0539	0.0113
CK3	0.2092	**PD24**	220.0	0.0169	0.0035
CK3	0.2092	**PD26**	300.0	0.0391	0.0082
CK3	0.2092	**PD29**	220.0	0.0175	0.0037
CK3	0.2092	**PD30**	245.0	0.0249	0.0052

Table 3.6 Optimal load shedding schemes and comparison for IEEE 30 -bus system

Methods	**AHP**	**LP**	**AHP**	**LP**	**AHP**	**LP**	**AHP**	**LP**	**AHP**	**LP**	**AHP**	**LP**
Time stage	**t1**	**t1**	**t2**	**t2**	**t3**	**t3**	**t4**	**t4**	**t5**	**t5**	**t6**	**t6**
X2	1	1	1	1	1	1	1	1	1	1	1	1
X3	1	1	1	1	1	1	1	1	1	1	1	1
X4	1	1	1	1	1	1	1	1	1	1	1	1
X6	1	1	1	1	1	1	1	1	1	1	1	1
X7	1	1	1	1	1	1	1	1	1	1	1	1
X8	1	1	1	1	1	1	1	1	1	1	1	1
X10	1	1	1	1	1	1	1	1	1	1	1	1
X12	1	1	1	1	1	1	1	1	1	1	1	1
X14	1	1	1	1	1	0	1	1	1	1	1	1
X15	1	1	0	0	0	0	0	0	0	0	1	1
X16	1	1	0	0	0	0	0	0	0	0	1	1
X17	1	1	1	1	1	0	1	1	1	1	1	1
X18	1	1	0	0	0	0	0	0	0	0	1	0
X19	1	1	0	0	0	0	0	0	0	0	1	1
X20	1	1	1	1	1	0	1	1	1	1	1	1
X21	1	1	1	1	0	1	1	1	1	1	1	1
X23	1	1	1	0	1	0	1	0	1	0	1	1
X24	1	1	0	0	0	0	0	0	0	0	0	1
X26	1	1	1	1	1	1	1	1	1	1	1	1
X29	1	1	0	0	0	0	0	0	0	0	1	0
X30	1	1	1	1	0	0	0	0	1	1	1	1

Stage t2 ~t6. Load 21 is curtailed at time stages t3 and t4, and Load 20 is curtailed at time stage t3. The total load curtailments at each time stage are summarized in Table 3.7. It is noted that network security constraints are satisfied at any time period through the use of the proposed approach.

To further verify the AHP - based NFP approach, linear programming (LP) is used to solve the same load shedding problem without load priority factor w_{ij} that is determined by AHP. The corresponding results are compared with those obtained by the AHP - based NFP method and also listed in Tables 3.6 and 3.7 (Figures. 3.4 and 3.5). In the LP method, the loads with small MW demands and small costs are first considered for curtailment. The LP method also cannot handle or consider the relative importance of the load locations. The result comparison shows that the AHP - based NFP approach is truly optimal. It not only has maximal load benefits but also considers the relative importance of the load sites. For example, load site

23, which is always curtailed in the LP method when system generation is limited, is not curtailed in the AHP - based NFP method although it has a minimal load cost (220$/kW) and small MW load demands.

Table 3.7 Summary and comparison of optimal load shedding for IEEE 30-bus system for LP (1)

Time stage	T1	T2	T3	T4	T5	T6
Max system gen (MW)	225	225	225	225	225	225
System demands (MW)	198.69	255.33	283.9	263.74	255.33	227.12
Committed loads (MW)	198.69	220.52	217.2	216.89	220.52	222.64
Total load shedding (MW)	0	34.81	66.7	46.85	34.81	4.48
Objective Hi	-	-	-	-	-	-
Benefit $\Sigma\, v_{ij} P_{ij}\, (X10^3)\$$	55058	62696	62246	62048	62696	61952

Table 3.7 Summary and comparison of optimal load shedding for IEEE 30-bus system for AHP (2)

Time stage	T1	T2	T3	T4	T5	T6
Max system gen (MW)	225	225	225	225	225	225
System demands (MW)	198.69	255.33	283.9	263.74	255.33	227.12
Committed loads (MW)	198.69	223.34	220.3	219.93	223.34	220.16
Total load shedding (MW)	0	31.99	63.6	43.81	31.99	6.96
Objective Hi	131.4	125.7	122.9	124.41	125.7	130.63
Benefit $\Sigma\, v_{ij} P_{ij}\, (X10^3)\$$	55058	62761	62922	62717	62761	61406

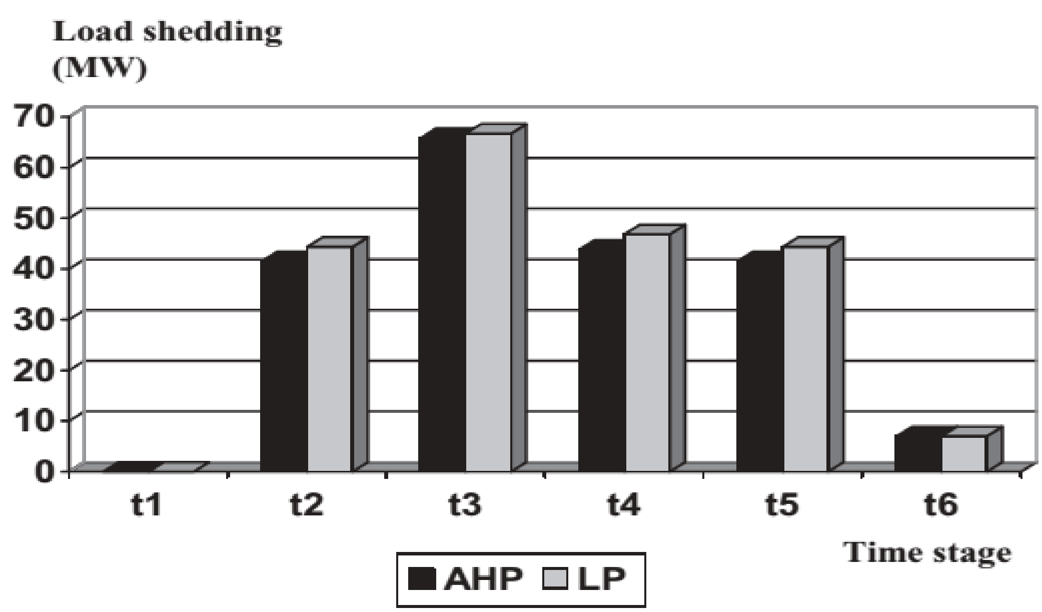

Figure 3.4 Comparison of optimal load shedding results

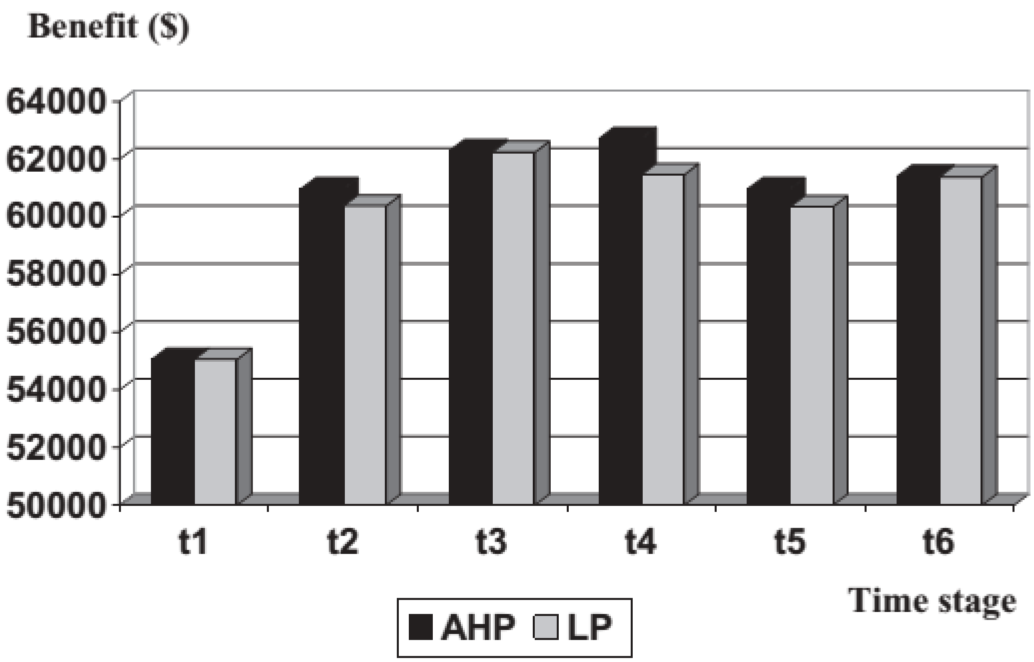

Figure 3.5 Comparison of the benefits from load shedding

CHAPTER 4

SIMULATION AND RESULTS

4.1 Proposed Intelligent Load Shedding Scheme

The following chapter discusses the proposed intelligent load shedding scheme which is applied in Sudan national grid by using ETAP program and the algorithm. This has been the main objective of the thesis. The intelligent load shedding scheme mainly has included the measurement of important parameters such as total generation and loads in the grid for estimating the magnitude of disturbance. The initial estimation of the disturbance is based on the rate of change of frequency. The weighting factors of loads and the amount of load to be shed from each bus is calculated by AHP using Matlab program. In this thesis six scenarios of disturbances (loss of generation) considered for load shedding are simulated with ILS scheme. The disturbance of frequency in power grid is performed to demonstrate the advantages of intelligent load shedding methods over conventional load shedding methods which is already used in Sudan national grid.

4.2 Sudan National Grid

The real network of Sudanese electrical power grid was chosen as a test power network. This regional network can be assumed as the typical for the whole country's network in terms of its design and existing problems. The simplified single line diagram of the grid is given at figure 4.1 The network has 82 busses, 81 lines, 15 transformers, 8 power plants and 54 loads. This network includes three voltage levels: a 500, 220 and 110 kV which forms the main part of the transmission system in the Sudanese electrical network, the power generated in Sudan comes from seven power plants, Merowe which represent the slack bus bar, Garri, Rosaries, Khartoum North, Rabak, Sennar, Japal Awlia and Girba, and one tie line feeder from Ethiopia in SHD bus bar. Transmission line charge supplies the network by a proper amount of reactive power due to the long length of lines which totaling 5469.735 km long. This data is taken at peak load in May 2017, the total loading level of the system is 2585.8 MW and 1428.3 Mvar, and the total power generated is 2656.5 Mw, 660 Mvar. Network data is shown at appendix B.

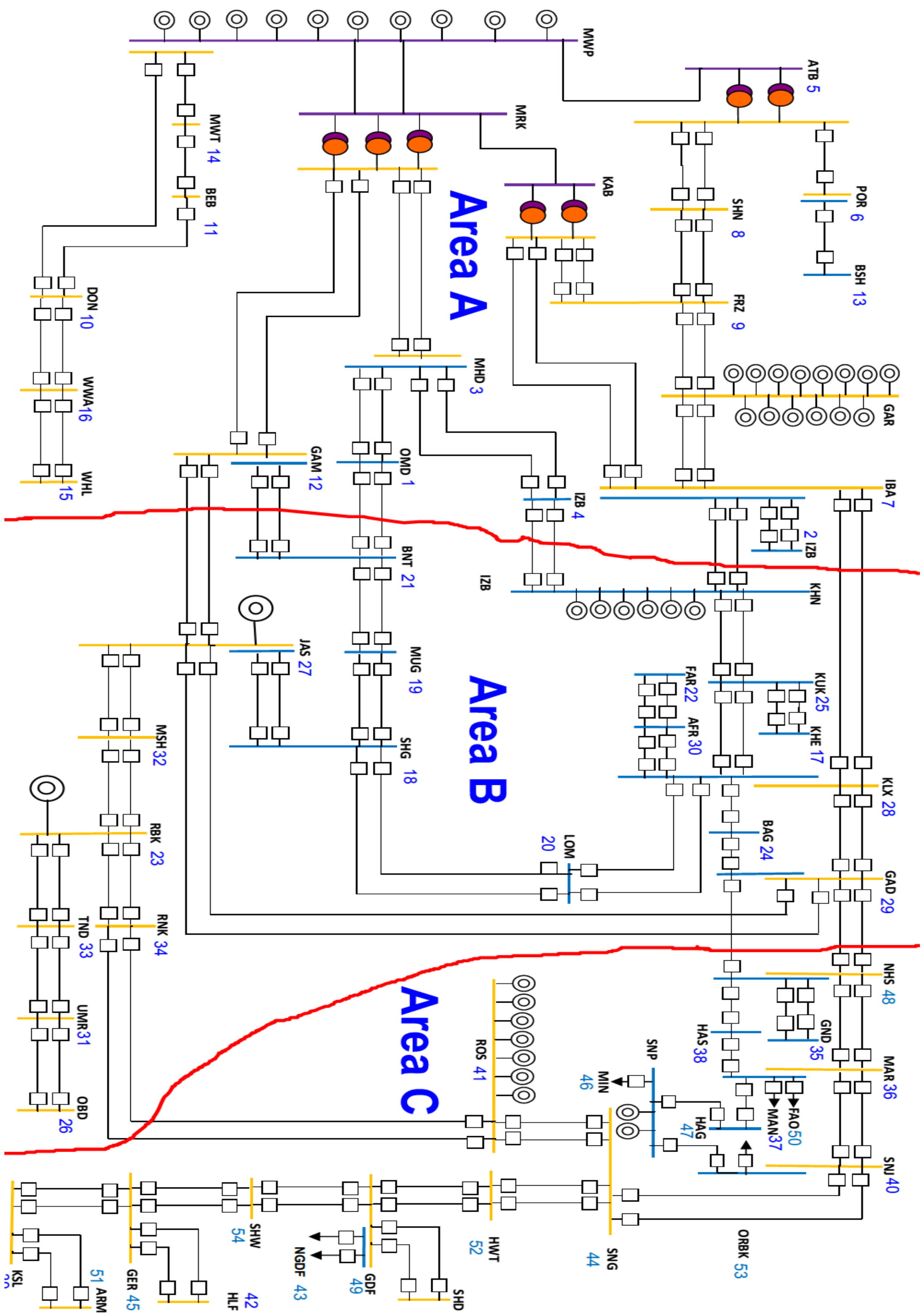

Figure 4.1 Single line diagram of Sudan national grid.

4.3 Implementation And Simulation On Sudan National Grid

The simulation system for load shedding is Sudan national grid. The capacity of the generator and loads data are given in appendix B. in which the loads are divided into three load center Areas is given at Figure 4.1. And the weighting factors that reflect the relative importance of each load or each load center are computed by AHP using Matlab program which is given in appendix A. The judgment matrices A-LD and A-PI are calculated by expert engineers in national local dispatch center (LDC) and provided in Tables 4.1 and 4.2, respectively. The results of the weighting factors are listed in Table 4.3.

In this thesis five scenarios of disturbance generators plant outage and overload are supposed according to ratio of total power that generators plant lost contribute in the grid. And the flow chart which it is used in ILS scheme is given in figure 4.2. Wherever a power imbalance occurs, frequency varies. So it is used to analysis the result of ILS scheme in thesis.

The expression for frequency change is:

$$\frac{df}{dt} = -\frac{\Delta p}{2H} \tag{4.1}$$

Where Δp is step change between load and generation, H is inertia constant,

In an interconnected power system consist of several generators Hsystem is obtained from the equation below:

$$Hsystem = \frac{H_1\, MVA_1 + H_2 MVA_2 + \dots + H_n\, MVA_n}{MVA_1 + MVA_2 + \dots + MVA_n} \tag{4.2}$$

And for introduced power system we assume that the frequency permissible range is 49.5 to 50Hz.

Table 4.1 Judgment matrix A - PI

PI	**CK1**	**CK2**	**CK3**
CK1	1	2	3
CK2	1/2	1	2
CK3	1/3	1/2	1

Table 4.2 Judgment matrix A - LD (1)

LD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
2	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
3	2	2	1	2	3	2	3	4	2	4	4	2	2	3
4	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
5	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
6	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
7	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
8	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
9	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
10	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
11	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
12	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
13	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
14	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
15	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
16	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
17	2	2	1	2	3	2	3	4	2	4	4	2	2	3
18	2	2	1	2	3	2	3	4	2	4	4	2	2	3
19	2	2	1	2	3	2	3	4	2	4	4	2	2	3
20	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
21	2	2	1	2	3	2	3	4	2	4	4	2	2	3
22	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
23	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
24	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
25	2	2	1	2	3	2	3	4	2	4	4	2	2	3
26	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
27	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
28	2	2	1	2	3	2	3	4	2	4	4	2	2	3
29	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
30	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
31	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
32	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
33	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
34	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
35	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
36	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2

Table 4.2 Judgment matrix A - LD (2)

LD	15	16	17	18	19	20	21	22	23	24	25	26	27
1	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
2	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
3	3	4	1	1	1	2	1	2	2	3	1	2	2
4	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
5	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
6	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
7	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
8	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
9	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
10	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
11	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
12	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
13	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
14	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
15	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
16	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
17	3	4	1	1	1	2	1	2	2	3	1	2	2
18	3	4	1	1	1	2	1	2	2	3	1	2	2
19	3	4	1	1	1	2	1	2	2	3	1	2	2
20	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
21	3	4	1	1	1	2	1	2	2	3	1	2	2
22	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
23	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
24	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
25	3	4	1	1	1	2	1	2	2	3	1	2	2
26	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
27	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
28	3	4	1	1	1	2	1	2	2	3	1	2	2
29	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
30	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
31	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
32	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
33	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
34	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
35	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
36	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1

Table 4.2 Judgment matrix A - LD (3)

LD	28	29	30	31	32	33	34	35	36	37	38	39	40	41
1	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
2	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
3	1	2	2	4	4	4	4	3	2	4	3	3	3	2
4	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
5	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
6	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
7	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
8	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
9	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
10	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
11	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
12	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
13	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
14	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
15	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
16	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
17	1	2	2	4	4	4	4	3	2	4	3	3	3	2
18	1	2	2	4	4	4	4	3	2	4	3	3	3	2
19	1	2	2	4	4	4	4	3	2	4	3	3	3	2
20	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
21	1	2	2	4	4	4	4	3	2	4	3	3	3	2
22	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
23	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
24	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
25	1	2	2	4	4	4	4	3	2	4	3	3	3	2
26	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
27	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
28	1	2	2	4	4	4	4	3	2	4	3	3	3	2
29	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
30	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
31	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
32	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
33	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
34	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
35	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
36	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1

Table 4.2 Judgment matrix A - LD (4)

LD	42	43	44	45	46	47	48	49	50	51	52	53	54
1	3	2	2	2	3	3	2	2	2	3	2	2	3
2	3	2	2	2	3	3	2	2	2	3	2	2	3
3	4	3	3	3	4	4	3	3	3	4	3	3	4
4	3	2	2	2	3	3	2	2	2	3	2	2	3
5	2	1	1	1	2	2	1	1	1	2	1	1	2
6	3	2	2	2	3	3	2	2	2	3	2	2	3
7	2	1	1	1	2	2	1	1	1	2	1	1	2
8	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
9	3	2	2	2	3	3	2	2	2	3	2	2	3
10	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
11	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
12	3	2	2	2	3	3	2	2	2	3	2	2	3
13	3	2	2	2	3	3	2	2	2	3	2	2	3
14	2	1	1	1	2	2	1	1	1	2	1	1	2
15	2	1	1	1	2	2	1	1	1	2	1	1	2
16	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
17	4	3	3	3	4	4	3	3	3	4	3	3	4
18	4	3	3	3	4	4	3	3	3	4	3	3	4
19	4	3	3	3	4	4	3	3	3	4	3	3	4
20	3	2	2	2	3	3	2	2	2	3	2	2	3
21	4	3	3	3	4	4	3	3	3	4	3	3	4
22	3	2	2	2	3	3	2	2	2	3	2	2	3
23	3	2	2	2	3	3	2	2	2	3	2	2	3
24	2	1	1	1	2	2	1	1	1	2	1	1	2
25	4	3	3	3	4	4	3	3	3	4	3	3	4
26	3	2	2	2	3	3	2	2	2	3	2	2	3
27	3	2	2	2	3	3	2	2	2	3	2	2	3
28	4	3	3	3	4	4	3	3	3	4	3	3	4
29	3	2	2	2	3	3	2	2	2	3	2	2	3
30	3	2	2	2	3	3	2	2	2	3	2	2	3
31	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
32	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
33	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
34	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
35	2	1	1	1	2	2	1	1	1	2	1	1	2
36	3	2	2	2	3	3	2	2	2	3	2	2	3

Table 4.2 Judgment matrix A - LD (5)

LD	1	2	3	4	5	6	7	8	9	10	11	12	13	14
37	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
38	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
39	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
40	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
41	1	1	1/2	1	2	1	2	3	1	3	3	1	1	2
42	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
43	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
44	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
45	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
46	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
47	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
48	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
49	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
50	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
51	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2
52	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
53	1/2	1/2	1/3	1/2	1	1/2	1	2	1/2	2	2	1/2	1/2	1
54	1/3	1/3	1/4	1/3	1/2	1/3	1/2	1	1/3	1	1	1/3	1/3	1/2

Table 4.2 Judgment matrix A - LD (6)

LD	15	16	17	18	19	20	21	22	23	24	25	26	27
37	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
38	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
39	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
40	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
41	2	3	1/2	1/2	1/2	1	1/2	1	1	2	1/2	1	1
42	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
43	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
44	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
45	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
46	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
47	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
48	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
49	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
50	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
51	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3
52	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
53	1	2	1/3	1/3	1/3	1/2	1/3	1/2	1/2	1	1/3	1/2	1/2
54	1/2	1	1/4	1/4	1/4	1/3	1/4	1/3	1/3	1/2	1/4	1/3	1/3

Table 4.2 Judgment matrix A - LD (7)

LD	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**
37	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
38	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
39	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
40	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
41	1/2	1	1	3	3	3	3	2	1	3	2	2	2	1
42	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
43	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
44	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
45	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
46	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
47	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
48	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
49	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
50	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
51	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3
52	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
53	1/3	1/2	12	2	2	2	2	1	1/2	2	1	1	1	1/2
54	1/4	1/3	1/3	1	1	1	1	1/2	1/3	1	1/2	1/2	1/2	1/3

Table 4.2 Judgment matrix A - LD (8)

LD	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**52**	**53**	**54**
37	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
38	2	1	1	1	2	2	1	1	1	2	1	1	2
39	2	1	1	1	2	2	1	1	1	2	1	1	2
40	2	1	1	1	2	2	1	1	1	2	1	1	2
41	3	2	2	2	3	3	2	2	2	3	2	2	3
42	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
43	2	1	1	1	2	2	1	1	1	2	1	1	2
44	2	1	1	1	2	2	1	1	1	2	1	1	2
45	2	1	1	1	2	2	1	1	1	2	1	1	2
46	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
47	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
48	2	1	1	1	2	2	1	1	1	2	1	1	2
49	2	1	1	1	2	2	1	1	1	2	1	1	2
50	2	1	1	1	2	2	1	1	1	2	1	1	2
51	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1
52	2	1	1	1	2	2	1	1	1	2	1	1	2
53	2	1	1	1	2	2	1	1	1	2	1	1	2
54	1	1/2	1/2	1/2	1	1	1/2	1/2	1/2	1	1/2	1/2	1

Table 4.3 Weighting factors computed by AHP

Station	Load (MW)	Load center	Weighting Factor
OMD	139	1	0.0128
IZB	129.1	1	0.0128
MHD	119.6	1	0.0211
IZG	105.6	1	0.0128
ATB	147.1	1	0.0076
POR	70	1	0.0128
IBA	89.2	1	0.0076
SHN	50.7	1	0.0041
FRZ	38	1	0.0128
DON	48	1	0.0041
DEB	42	1	0.0041
GAM	28	1	0.0128
BSH	20	1	0.0128
MWT	34	1	0.0076
WHL	4	1	0.0076
WWA	1.6	1	0.0041
KHE	143.7	2	0.0116
SHG	128	2	0.0116
MUG	110.2	2	0.0116
LOM	96.4	2	0.0071
BNT	119.6	2	0.0116
FAR	75.6	2	0.0071
RBK	78.3	2	0.0071
BAG	43.4	2	0.0042
KUK	51	2	0.0116
OBD	41.5	2	0.0071
JAP	36	2	0.0071
KLX	68.3	2	0.0116
GAD	5	2	0.0071
AFR	48.2	2	0.0071
UMR	9	2	0.0023
MSH	20.7	2	0.0023
TND	2.3	2	0.0023
RNK	1.7	2	0.0023
GND	55.5	3	0.0023
MAR	84.6	3	0.0039

Station	Load (MW)	Load center	Weighting Factor
MAN	45.2	3	0.0012
HAS	15	3	0.0023
KSL	27.1	3	0.0023
SNJ	18.4	3	0.0023
ROS	24.4	3	0.0039
HLF	20.4	3	0.0012
NGDF	13.5	3	0.0023
SNG	11.4	3	0.0023
GER	24.2	3	0.0023
MIN	15.2	3	0.0012
HAG	7.1	3	0.0012
NHS	33	3	0.0023
GDF	20	3	0.0023
FAO	8.6	3	0.0023
ARM	2.6	3	0.0012
HWT	3.1	3	0.0023
RBK2	6.7	3	0.0023
SHK	5	3	0.0012

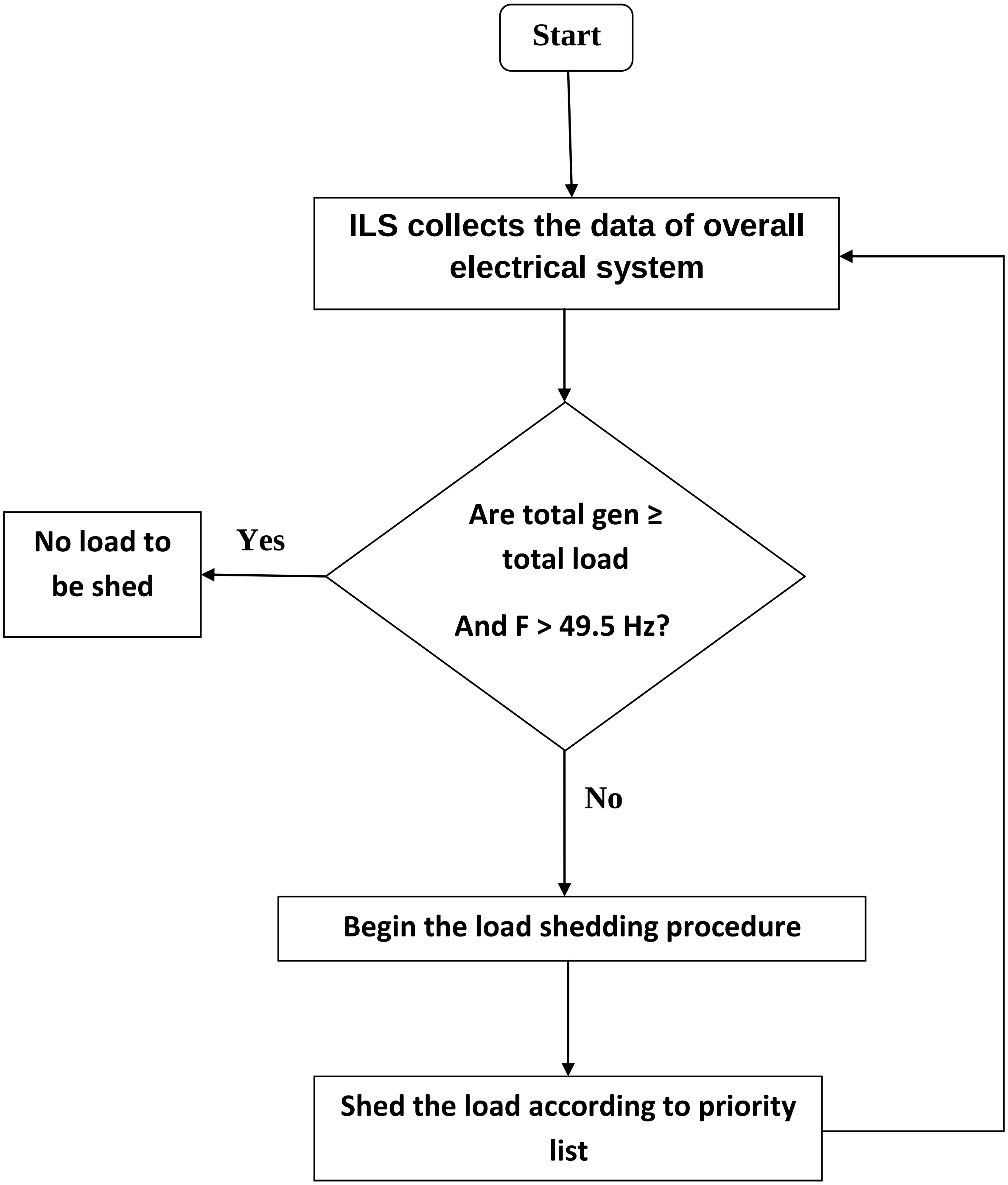

Figure 4.2 ILS algorithm flow chart

4.4 Result And Discussion

4.4.1 Scenario (A) All Rabak Generators Lost

Rabak plant is a steam turbine generator, which supply the grid by 480 MW (about 18.7% of total generation of network) and it is a second biggest plant generation in the grid after Merowe plant. So the sudden loss of this plant causes system frequency to decrease less than 46 Hz that can lead to total blackout of the network if there is no optimal load shedding is applied. However, when intelligent load shedding scheme is used, the response of frequency is quickly comeback to its normal value by shedding only 480.5MW of load as shown in figure 4.3.

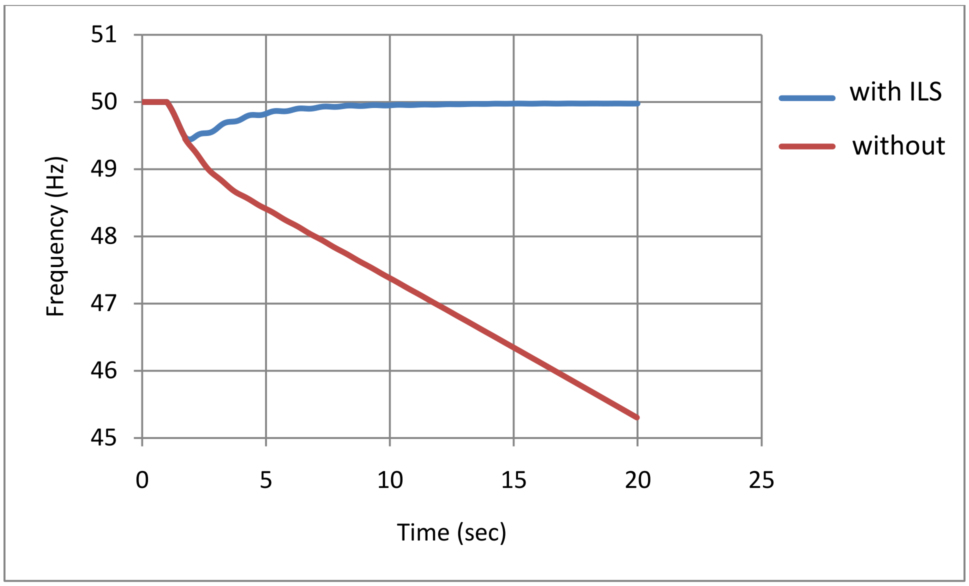

Figure 4.3 scenario (A) Frequency Response with ILS Scheme and without

4.4.2 Scenario (B) All Garri Generators Lost

Garri plant is a combine turbine generator, which supply the grid by 360 MW (about 14% of total generation of network) and it is a third biggest plant generation in the grid with Khartoum North plant. So the sudden loss of this plant causes system frequency to decrease less than 48 Hz and by using ILS scheme, the total load has been shedded just 379MW and It was enough to return frequency to rated value as given in figure 4.4.

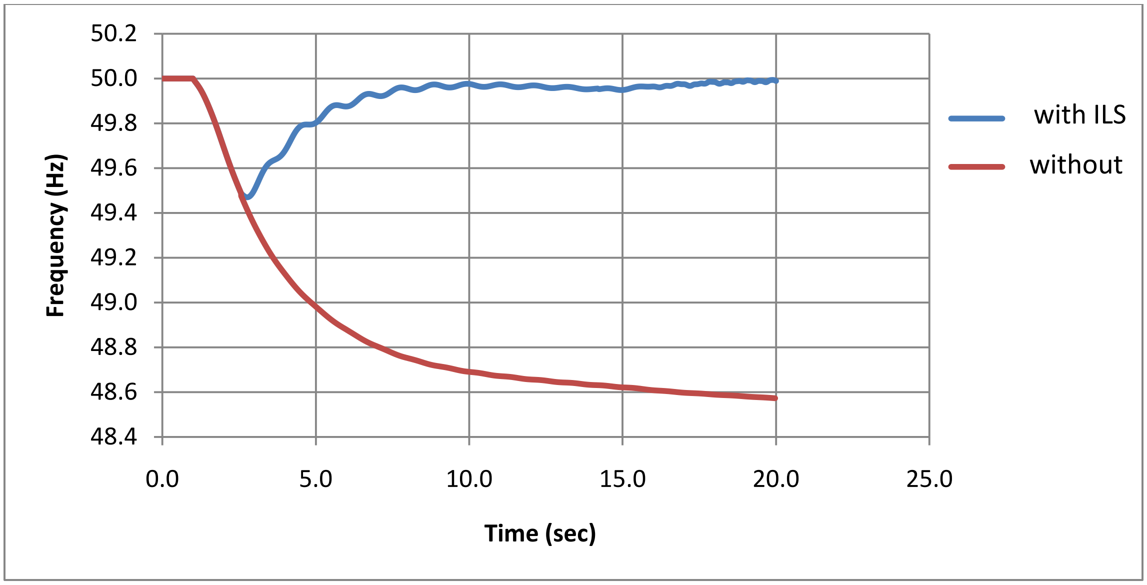

Figure 4.4 scenarios (B) Frequency Response with ILS Scheme and without

4.4.3 Scenario (C) All Rosaries Generators Lost

Rosaries is hydro turbine generators which contribute by 10.6% of total power in grid (272 MW) and sudden outage of this plant can cause in frequency decay less than 49Hz and by using ILS scheme, the frequency improves above the specified lower limit. It settles at a value close to 50Hz and just 289MW of the total load have been shedded as showing in figure 4.5.

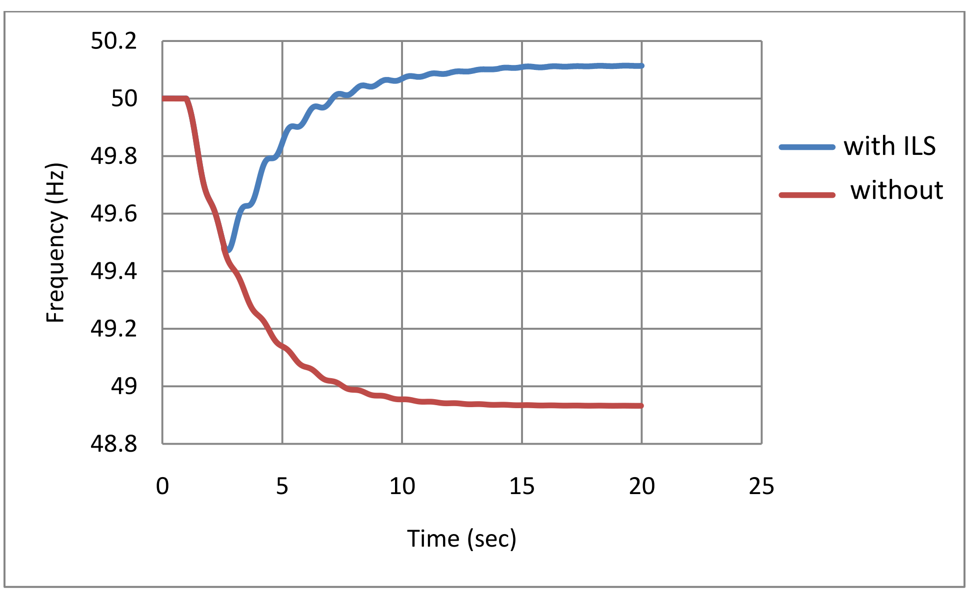

Figure 4.5 scenarios(C) Frequency Response with ILS Scheme and without

4.4.4 Scenario (D) System Overloaded

In this scenario the grid is overloaded by suddenly adding load equals to 272.8MW to the network which equivalent 12% of total load in the grid. Which cause in frequency reduce to 48.8Hz and by using ILS scheme the frequency is quickly comeback to its normal value by shedding only 321.5MW of load as shown in figure 4.6.

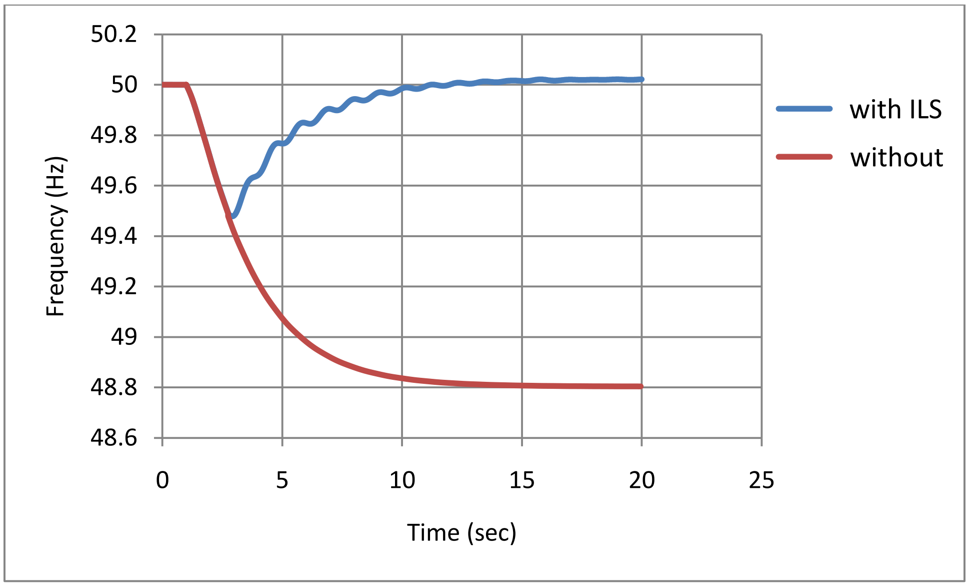

Figure 4.6 scenarios (D) Frequency Response with ILS Scheme and without

4.4.5 Scenario (E) Khartoum North Plant and Rosaries Plant Lost

The loss of two plants Khartoum North and Rosaries can potentially escalade very quickly to a total system shutdown if the proper amount of load is not shed before the remaining system becomes unstable, the frequency will reduce to more than 43HZ because they share by one quarter of the grid power 652 MW. And by using ILS scheme the total load equals 655MW is shedded to return frequency to rated value as given in figure 4.7.

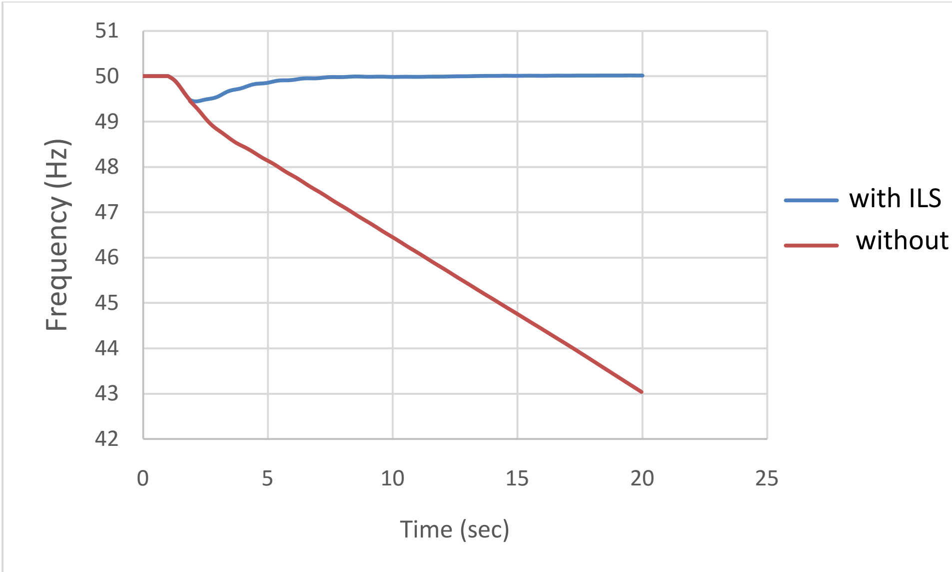

Figure 4.7 scenarios (E) Frequency Response with ILS Scheme and without

Overall, the intelligent load shedding scheme has prevented the system from bordering over into unstable region. In cases where the system was stable but frequency was below the desired values, intelligent load shedding has helped improve frequency parameters to suit the limits which have been preset for it. Thus the intelligent load shedding scheme has shown sufficient, desirable and acceptable improvements in the frequency value.

4.5 Comparison Of Load Shedding Methods

To demonstrate the effectiveness of the proposed methodology, system under study has been made to undergo the same five scenarios are performed by under frequency load (UFLS) and intelligent load shedding (ILS) method. Under frequency load shedding design, number of steps, step frequency, and percentage load shedding amount for 81 relay which is applicable now in Sudan national grid is shown in Table 4.4

In this comparison, the fifth scenarios have divided in two groups, group A includes scenarios B, C and D, and group B includes scenarios A and E, because each scenarios of group have approximately same result.

Table 4.4 Under frequency relay setting for load shedding

Step	Frequency Hz	Load %	Load MW
Step1	49.2	6%	154
Step2	49.1	7%	180
Step3	49	8%	206
Step4	48.9	7%	180
Step5	48.7	7%	180
Step6	48.5	9%	232
Step7	48.3	7%	180
Step8	48.1	10%	257
Step9	48	1%	26

4.5.1 Group (A)

Figures 4.8, 4.9 and 4.10 depict frequency response of scenarios B, C and D respectively; with under frequency relay load shedding and intelligent load shedding methods. In the cases of under frequency load shedding, as the system frequency reaches below 49.2 Hz at 2 sec, under frequency relay is activated and first step load shedding is implemented between (4.6-5.4) secs for three scenarios. Notice the disturbances start after 1 sec of normal operation.

The system frequency in scenario B still not recovered and it crosses 49.1 Hz (second step load shedding threshold) and second step load shedding is implemented at 5.2 sec while scenarios C and D have satisfied by one step load shedding. After 1-step or 2-step load shedding system frequency is improved up to 49.7, 49.5 and 49.4Hz respectively after approximately 14 secs in the three scenarios which they are acceptable frequency range but they are not the rated frequency 50Hz. thus It was found that the total amount of load shed using under frequency relay method 334, 154 and 154MW respectively. For the same scenarios in case of intelligent load shedding scheme, the frequency just reaches 49.5 Hz in the three scenarios and by one step, it comebacks to approximately rated frequency by shedding only amount of loads that nearly equals to power lost in every scenario 379, 299 and 321MW respectively, resulting in a total load shedding time almost 5 sec.

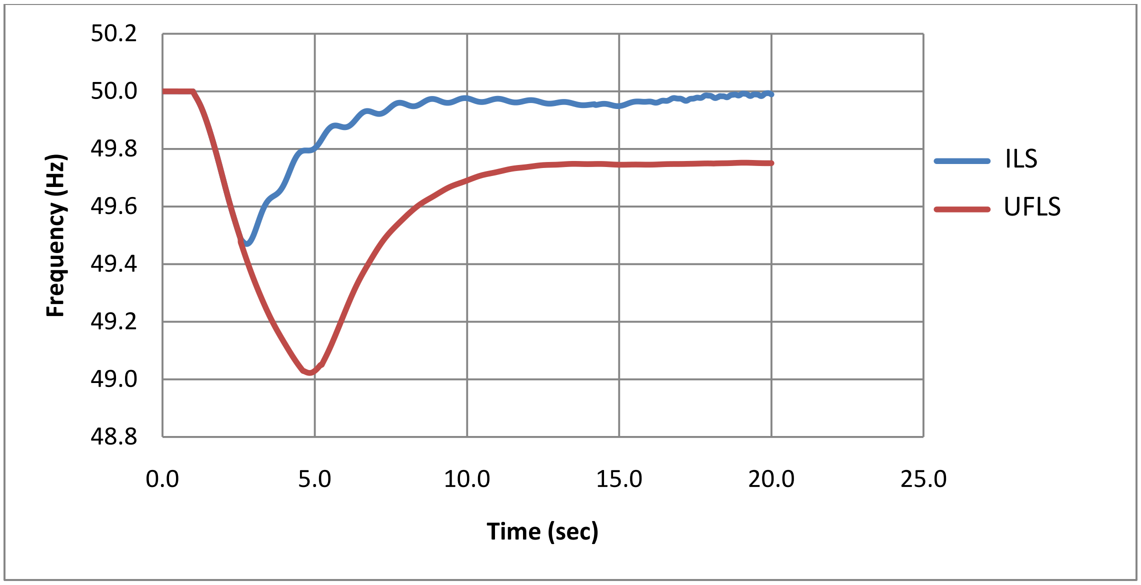

Figure 4.8 scenarios (B) Frequency Response with ILS Scheme and UFLS

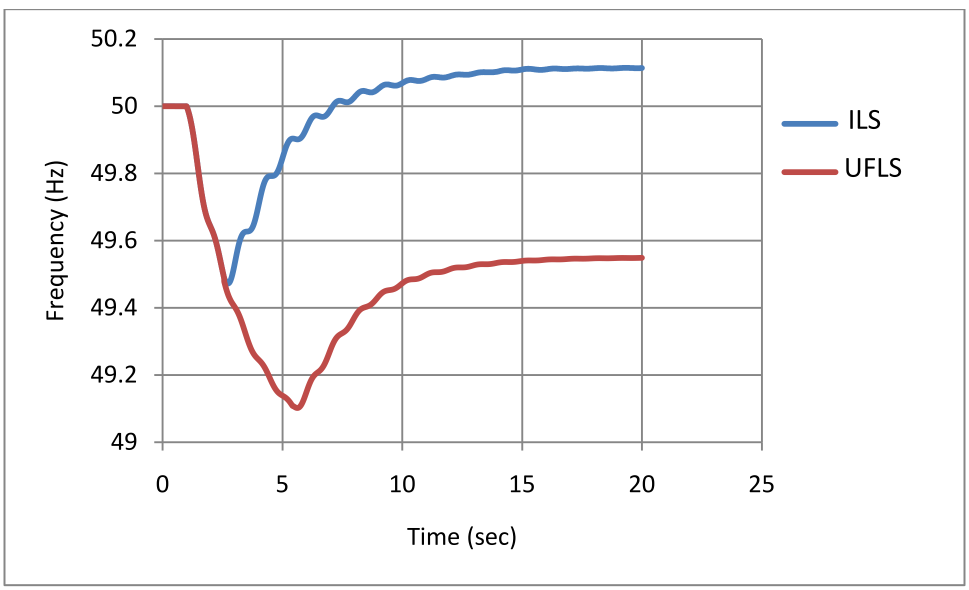

Figure 4.9 scenarios(C) Frequency Response with ILS Scheme and UFLS

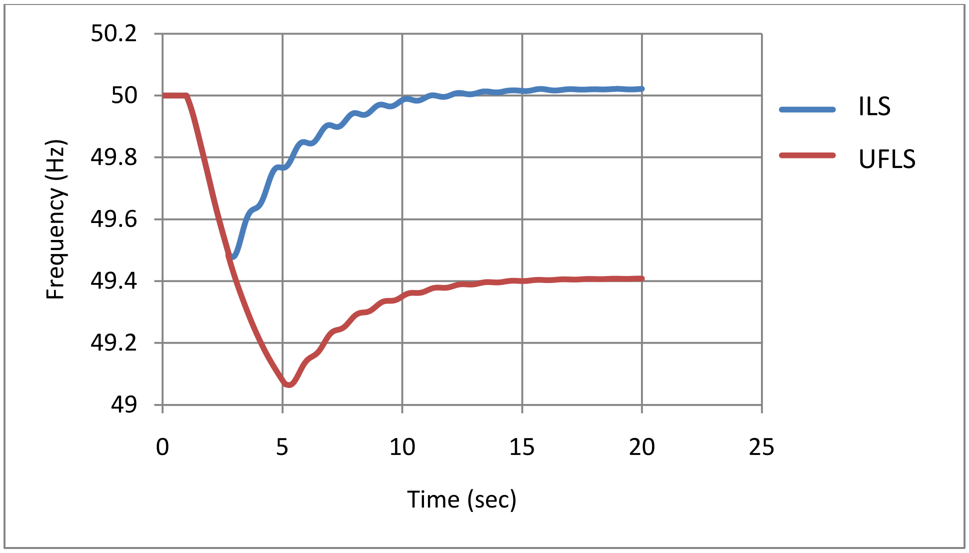

Figure 4.10 scenarios (D) Frequency Response with ILS Scheme and UFLS

4.5.2 Group (B)

Figures 4.11 and 4.12 depict frequency response of scenarios A and E respectively; with under frequency relay load shedding and intelligent load shedding methods. In the cases of under frequency load shedding, as the system frequency reaches below 49.2 Hz at 2 sec, under frequency relay is activated and first step load shedding is implemented at 3.3 sec for both scenarios. Notice the disturbances start after 1 sec of normal operation. The system frequency still not recovered and it crosses 49.1 Hz (second step load shedding threshold) and second step load shedding is implemented at 3.5 sec. also The system frequency still not recovered and it crosses 49 Hz (third step load shedding threshold) and third step load shedding is implemented at 3.7 sec. Thus still the system frequency not recovered and it crosses 48.9 Hz (fourth step load shedding threshold) and fourth step load shedding is implemented at 4 sec in the both scenarios. After fourth steps load shedding system frequency is improved up to 50.8 and 50.6Hz respectively after approximately 15 sec in the both scenarios which they are over frequency range. Which means the amount of load have been shedded 721MW for both scenarios more than required? For the same scenarios in case of intelligent load shedding scheme, the frequency just reaches 49.5 Hz in the three scenarios and by one step, it comebacks to approximately rated frequency by shedding only amount of loads that almost equals to power lost in every scenario 480.5 and 654.4MW respectively, resulting in a total load shedding time of 5 sec.

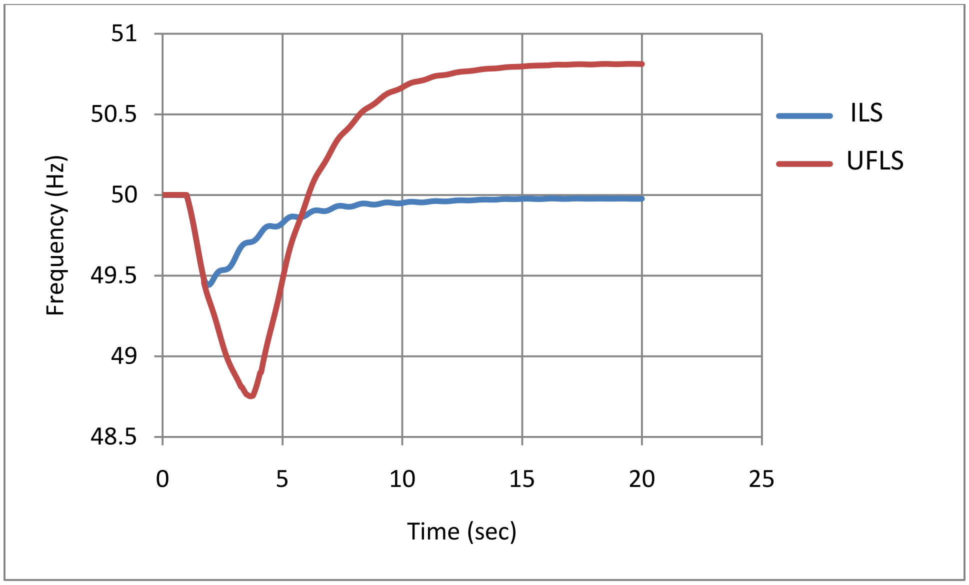

Figure 4.11 scenario (A) Frequency Response with ILS Scheme and UFLS

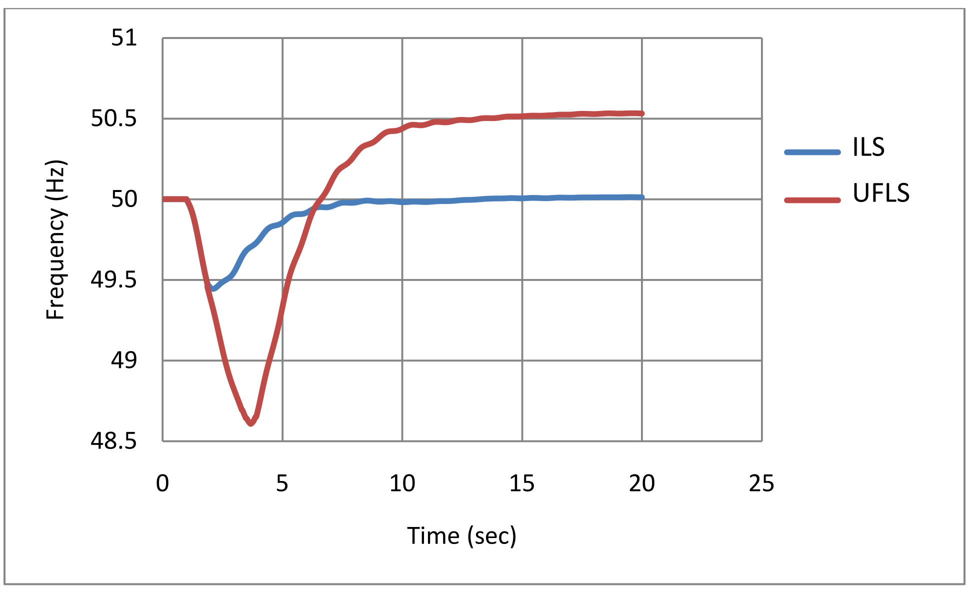

Figure 4.12 scenarios (E) Frequency Response with ILS Scheme and UFLS

Summary a comparison of ILS system response time with that of frequency relay load shedding is illustrated in table 4.5 and 4.6 as shown, frequency relay load shedding will be delayed until the system frequency drops below the relay set point (Stage 1). Additional load shedding will be needed if the system frequency does not recover to normal (Stage 2). Thus the total response time for the frequency relay based load shedding is much longer than ILS system. And the total load has been shedded always less or more than required to adjust the frequency to rated value 50Hz.

Table 4.5 comparison between ILS and UFLS schemes Group A

Group A	Final frequency Hz		MW shed		Time (sec)	
	UFLS	ILS	UFLS	ILS	UFLS	ILS
Scenario B	49.7	50	334	379	14	5
Scenario C	49.5	50.1	154	299	14	5
Scenario D	49.4	50	154	321	14	5

Table 4.6 comparison between ILS and UFLS schemes Group B

Group B	Final frequency Hz		MW shed		Time (sec)	
	UFLS	ILS	UFLS	ILS	UFLS	ILS
Scenario A	50.8	50	721	480.5	15	5
Scenario E	50.6	50	721	654.4	15	5

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In this thesis an approach for improvement of frequency stability using intelligent load shedding scheme is developed for Sudan national grid. By executing the transient stability analysis for various operation scenarios, the training data set of AHP model, which includes, total system power generation, spinning reserve, total load, and frequency decay rate as input, and the minimum amount of load shedding required as output, has been prepared. To verify the effectiveness of the proposed intelligent load shedding as compare to the present under frequency relay based load-shedding, schemes are applied in the simulation on ETAP software to investigate the dynamic response of system frequency.

Load shedding in power system grid serves as the ultimate guard that protects the system from an overload induced collapse. This critical load preservation is normally done with the use of circuit breaker interlocks, under frequency relaying, and PLC-based schemes. Common drawbacks of these schemes include lack of detailed pre- and post-disturbance data, real-time system configuration, type and duration of the disturbances, as well as other important information. This thesis has introduced an intelligent optimal and fast load shedding technology referred to as ILS. ILS combines system online data, equipment ratings, user-defined control parameters; a knowledge base obtained from offline system simulations, system dependencies, and continually updated dynamic load shed tables. This system can perform load shedding in less than 100 milliseconds from the initial occurrence of a disturbance. ILS technology has been successfully installed and operational at network facilities.

5.2 Recommendations

At the end of this study, the following recommendation can be used as basis for future work in Sudan national grid to improve the performance of load shedding scheme and to get rid of blackout which has been overtire the system every year.

- The setting of under frequency relay for load shedding should be updated to be suitable for increasing of power demand and system generation.
- The configuration of load shedding scheme must be rehabilitated by intelligent load shedding scheme.
- Another advance operation system program such as ETAP software has to be configured in Sudan network to overcome the slow time response of previous programs.

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APPENDICES

Appendix A: MATLAB program to carry out loads calculation weighting factors and the amount of load be shed by ILS scheme by AHP.

```
Clear
Clc
% the calculation of loads weighting factors
PI= [1 2 3; 0.5 1 2; 0.333 0.5 1];
LD=[1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3
1/2 1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3
3 2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3
2 2 3;
 1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
 2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1
1 1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3
2 4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
 1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
 1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
 1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
 1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
```

1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2
4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2
4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2
4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2

4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2
4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
2 2 1 2 3 2 3 4 2 4 4 2 2 3 3 4 1 1
1 2 1 2 2 3 1 2 2 1 2 2 4 4 4 4 3 2
4 3 3 3 2 4 3 3 3 4 4 3 3 3 4 3 3
4;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;

1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1 1 1/2 1 2 1 2 3 1 3 3 1 1 2 2 3 1/2
1/2 1/2 1 1/2 1 1 2 1/2 1 1 1/2 1 1 3 3 3 3
2 1 3 2 2 2 1 3 2 2 2 3 3 2 2 2 3 2
2 3;
1/3 1/3 1/4 1/3 1/2 1/3 1/2 1 1/3 1 1 1/3 1/3 1/2 1/2 1
1/4 1/4 1/4 1/3 1/4 1/3 1/3 1/2 1/4 1/3 1/3 1/4 1/3 1/3 1 1
1 1 1/2 1/3 1 1/2 1/2 1/2 1/3 1 1/2 1/2 1/2 1 1 1/2
1/2 1/2 1 1/2 1/2 1;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2
2 2 1 1/2 2 1 1 1 1/2 2 1 1 1 2 2 1 1
1 2 1 1 2;
1/2 1/2 1/3 1/2 1 1/2 1 2 1/2 2 2 1/2 1/2 1 1 2
1/3 1/3 1/3 1/2 1/3 1/2 1/2 1 1/3 1/2 1/2 1/3 1/2 12 2 2

```
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/3  1/3  1/4  1/3  1/2  1/3  1/2  1   1/3  1   1   1/3  1/3  1/2  1/2  1
1/4  1/4  1/4  1/3  1/4  1/3  1/3  1/2  1/4  1/3  1/3  1/4  1/3  1/3  1   1
1   1   1/2  1/3  1   1/2  1/2  1/2  1/3  1   1/2  1/2  1/2  1   1   1/2
1/2  1/2  1   1/2  1/2  1;
 1/3  1/3  1/4  1/3  1/2  1/3  1/2  1   1/3  1   1   1/3  1/3  1/2  1/2  1
1/4  1/4  1/4  1/3  1/4  1/3  1/3  1/2  1/4  1/3  1/3  1/4  1/3  1/3  1   1
1   1   1/2  1/3  1   1/2  1/2  1/2  1/3  1   1/2  1/2  1/2  1   1   1/2
1/2  1/2  1   1/2  1/2  1;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/3  1/3  1/4  1/3  1/2  1/3  1/2  1   1/3  1   1   1/3  1/3  1/2  1/2  1
1/4  1/4  1/4  1/3  1/4  1/3  1/3  1/2  1/4  1/3  1/3  1/4  1/3  1/3  1   1
1   1   1/2  1/3  1   1/2  1/2  1/2  1/3  1   1/2  1/2  1/2  1   1   1/2
1/2  1/2  1   1/2  1/2  1;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/2  1/2  1/3  1/2  1   1/2  1   2   1/2  2   2   1/2  1/2  1   1   2
1/3  1/3  1/3  1/2  1/3  1/2  1/2  1   1/3  1/2  1/2  1/3  1/2  12   2   2
2   2   1   1/2  2   1   1   1   1/2  2   1   1   1   2   2   1   1
1   2   1   1   2;
 1/3  1/3  1/4  1/3  1/2  1/3  1/2  1   1/3  1   1   1/3  1/3  1/2  1/2  1
1/4  1/4  1/4  1/3  1/4  1/3  1/3  1/2  1/4  1/3  1/3  1/4  1/3  1/3  1   1
1   1   1/2  1/3  1   1/2  1/2  1/2  1/3  1   1/2  1/2  1/2  1   1   1/2
1/2  1/2  1   1/2  1/2  1];
A=prod(PI');
B=A.^ (1/3);
C=sum(B);
CK=B/C;
```

```
m=prod(LD');
W=m.^ (1/54);
K=sum(W);
PD=W/K;
% input data of load MW
D= [139 1;
    129.1 2;
    119.6 3;
    105.6 4;
    147.1 5;
    70 6;
    89.2 7;
    50.7 8;
    38 9;
    48 10;
    42 11;
    28 12;
    20 13;
    34 14;
    4 15;
    1.6 16;
    143.7 17;
    128 18;
    110.2 19;
    96.4 20;
    119.6 21;
    75.6 22;
    78.3 23;
    43.4 24;
    51 25;
    41.5 26;
    36 27;
    68.3 28;
    5 29;
    48.2 30;
    9 31;
    20.7 32;
    2.3 33;
    1.7 34;
    55.5 35;
    84.6 36;
    45.2 37;
    15 38;
    27.1 39;
    18.4 40;
    24.4 41;
```

```
    20.4 42;
    13.5 43;
    11.4 44;
    24.2 45;
    15.2 46;
    7.1 47;
    33 48;
    20 49;
    8.6 50;
    2.6 51;
    3.1 52;
    6.7 53;
    5 54];
SD=sum(D);
CK(1). *ones(1,16);
m=[CK (1). *ones (16,1); CK(2). *ones (18,1); CK(3).*ones(20,1)];
WF=m.*PD';
% code of intelligent load shedding by AHP
[f, g]=size(D);
for j=1:g-1
    v=WF';
z=D (: j);
While sum (z)> MW lost
    a= min (v (:));
    b=find (v==a);
    w=z (b (1));
    h=b (1);
    For i =2: length (b)
        If z (b (i)) <w
            w=z (b (i));
            h=b (i);
        End
    End
    Z (h) = [];
    v (h) = [];
End
Sum (z)
Z
v;
p=z.*v';
Hi=sum (p)
End
```

Appendix B: Sudanese electrical network data.

Bus data:

Bus number	Type*	Pg MW	Qg MVAr	Pd MW	Qd MVAr	Bs MVAr	Base KV
1	1	0	0	139	87.1	0	110
2	1	0	0	129.1	68.4	0	110
3	1	0	0	119.6	99.3	0	220
4	1	0	0	105.6	70.4	0	110
5	1	0	0	147.1	75.8	-125	500
6	1	0	0	70	10	-15	220
7	1	0	0	89.2	59.2	0	220
8	1	0	0	50.7	23.9	0	220
9	1	0	0	38	24.4	0	220
10	1	0	0	48	23	0	220
11	1	0	0	42	23	-11	220
12	1	0	0	28	15.6	0	220
13	1	0	0	20	2.5	0	110
14	1	0	0	34	16	0	220
15	1	0	0	4	26.3	-20	220
16	1	0	0	1.6	2.5	-20	220
17	1	0	0	143.7	69.4	0	110
18	1	0	0	128	76	0	110
19	1	0	0	110.2	42.4	0	110
20	1	0	0	96.4	46.6	0	110
21	1	0	0	119.6	78	0	110
22	1	0	0	75.6	37.4	0	110
23	2	480	0	78.3	44.5	0	220
24	1	0	0	43.4	24.5	0	110
25	1	0	0	51	22.4	0	110
26	1	0	0	41.5	17.6	0	220
27	2	20	0	36	20.6	0	220
28	1	0	0	68.3	33.9	-30	220
29	1	0	0	5	2.2	0	220
30	1	0	0	48.2	21.2	0	110
31	1	0	0	9	2.6	0	220
32	1	0	0	20.7	9.7	0	220
33	1	0	0	2.3	1.3	0	220
34	1	0	0	1.7	5.1	0	220
35	1	0	0	55.5	38.7	0	110
36	1	0	0	84.6	53.8	-30	220
37	1	0	0	45.2	21.8	0	110
38	1	0	0	15	7.9	0	110
39	1	0	0	27.1	16.2	-30	220

40	1	0	0	18.4	10.5	-30	220
41	2	272	0	24.4	11.8	-30	220
42	1	0	0	20.4	11.4	-30	220
43	1	0	0	13.5	5	0	110
44	1	0	0	11.4	6.8	-30	220
45	1	0	0	24.2	12.6	0	220
46	1	0	0	15.2	4.5	0	110
47	1	0	0	7.1	4	0	110
48	1	0	0	33	18.9	-30	220
49	1	0	0	20	10	-30	220
50	1	0	0	8.6	3	0	110
51	1	0	0	2.6	0.4	0	220
52	1	0	0	3.1	2	0	220
53	1	0	0	6.7	0	0	110
54	1	0	0	5	3.6	-30	220
55	3	1250	0	0	0	-250	500
56	1	0	0	0	0	-250	500
57	1	0	0	0	0	0	500
58	2	360	0	0	0	0	220
59	2	380	0	0	0	0	110
60	2	10	0	0	0	0	110
61	2	150	0	0	0	-30	220

*1 = PQ, 2 = PV, 3 = Slack

Line data:

From bus	To bus	R p.u.	X p.u.	B p.u.	Lines number	ratio
22	30	0.067	0.267	0.41E-05	2	1
51	39	0.067	0.302	0.41E-05	2	1
5	55	0.028	0.276	0.41E-05	1	1
5	8	0.067	0.302	0.41E-05	2	1
5	6	0.076	0.403	0.28E-05	1	1
21	12	0.067	0.267	0.41E-05	2	1
21	19	0.067	0.267	0.41E-05	2	1
21	1	0.067	0.267	0.41E-05	2	1
11	10	0.076	0.403	0.41E-05	1	1
11	14	0.076	0.403	0.41E-05	1	1
10	16	0.067	0.302	0.41E-05	2	1
50	49	0.348	0.421	0.27E-05	1	1
9	58	0.067	0.302	0.41E-05	2	1
9	57	0.067	0.302	0.41E-05	2	1
9	8	0.067	0.302	0.41E-05	2	1
29	24	0.348	0.421	0.27E-05	1	1
29	27	0.067	0.302	0.41E-05	2	1
29	28	0.076	0.403	0.28E-05	2	1
29	48	0.348	0.421	0.27E-05	1	1
29	48	0.076	0.403	0.28E-05	2	1
12	27	0.067	0.302	0.41E-05	2	1
12	56	0.067	0.302	0.41E-05	2	1
49	43	0.348	0.421	0.27E-05	1	1
49	52	0.067	0.302	0.41E-05	2	1
49	54	0.067	0.302	0.41E-05	2	1
45	42	0.067	0.302	0.41E-05	2	1
45	39	0.067	0.302	0.41E-05	2	1
45	54	0.067	0.302	0.41E-05	2	1
38	48	0.348	0.421	0.27E-05	1	1
7	58	0.067	0.302	0.41E-05	2	1
7	2	0.067	0.269	0.41E-05	2	1
7	28	0.067	0.302	0.41E-05	2	1
27	32	0.067	0.302	0.41E-05	2	1
59	7	0.067	0.267	0.41E-05	2	1
59	4	0.067	0.267	0.41E-05	2	1
59	25	0.0384	0.302	0.30E-05	2	1
28	30	0.067	0.267	0.41E-05	2	1
28	24	0.348	0.421	0.27E-05	1	1
28	25	0.087	0.379	0.30E-05	2	1
28	20	0.067	0.267	0.41E-05	2	1
36	50	0.348	0.421	0.27E-05	1	1
36	47	0.348	0.421	0.27E-05	1	1
36	38	0.348	0.421	0.27E-05	1	1
36	37	0.105	0.289	0.30E-05	1	1
36	48	0.076	0.403	0.28E-05	2	1
36	40	0.076	0.403	0.28E-05	2	1
3	4	0.067	0.267	0.41E-05	2	1

3	56	0.067	0.302	0.41E-05	2	1
3	1	0.067	0.267	0.41E-05	2	1
56	57	0.028	0.276	0.41E-05	1	1
55	10	0.076	0.403	0.28E-05	1	1
55	56	0.028	0.276	0.41E-05	2	1
55	14	0.076	0.403	0.14E-05	1	1
48	35	0.067	0.267	0.41E-05	2	1
23	32	0.067	0.302	0.41E-05	2	1
23	34	0.067	0.302	0.41E-05	2	1
23	33	0.067	0.302	0.41E-05	2	1
40	53	0.348	0.421	0.27E-05	1	1
41	34	0.067	0.302	0.41E-05	2	1
18	27	0.067	0.267	0.41E-05	2	1
18	20	0.067	0.267	0.41E-05	2	1
18	19	0.067	0.267	0.41E-05	2	1
44	52	0.067	0.302	0.41E-05	2	1
44	40	0.076	0.403	0.28E-05	2	1
44	35	0.076	0.403	0.28E-05	2	1
60	47	0.348	0.421	0.27E-05	1	1
60	46	0.348	0.421	0.27E-05	1	1
60	40	0.348	0.421	0.27E-05	1	1
31	26	0.067	0.302	0.41E-05	2	1
31	33	0.067	0.302	0.41E-05	2	1
16	15	0.067	0.302	0.41E-05	2	1

MVAbase = 1000.

Transformer data :

N.O	Station name	Transformer name	High rated apparent power (MVA)	Medium rated apparent power (MVA)	Low rated apparent power (MVA
1	KLX	TR01	100	100	40
2		TR02	100	100	40
3	LOM	TR01	100	100	40
4		TR02	100	100	40
5	SHG	TR01	100	100	40
6		TR02	100	100	30
7		TR03	35	25	-
8		TR04	35	25	-
9	JAS	TR01	150	150	50
10		TR02	150	150	50
11		TR05	150	150	50
12	MUG	TR01	100	100	30
13		TR03	100	100	40
14	KHE	TR01	100	100	40
15		TR02	100	100	40
16	SAH	TR01	100	100	40
17		TR02	100	100	40
18	FAR	TR01	60	40	20
19		TR02	60	40	20
20	GAD	TR01	60	60	30
21		TR02	60	60	-
22	BAG	TR01	35	35	17.5
23		TR02	35	25	10
24	IBAB	TR04	100	100	40
25		TR05	100	100	40
26	FRZ	TR01	100	100	-
27		TR02	100	100	-
28	IZG	TR01	B100	100	40

29		TR02	35	25	10
30		TR03	35	25	10
31		TR04	100	100	40
32		TR01	30	30	-
33	KUKU	TR02	30	30	-
34		TR03	30	30	-
35	IZB	TR01	100	100	-
36		TR02	100	100	-
39	MHD	TR02	100	100	40
40		TR03	100	100	40
41		TR01	100	100	30
42	OMD	TR02	35	25	10
43		TR03	100	100	30
44	BNT	TR01	100	100	40
45		TR02	100	100	40
46	GAM	TR01	150	150	50
47		TR02	150	150	50
48		TR01	300	300	75
49	MRK	TR02	300	300	75
50		TR03	300	300	75
51	KBA	TR01	300	300	75
52		TR02	300	300	75
53		TR01	150	150	-
54	IBAB	TR02	150	150	-
55		TR03	150	150	-
58		TR01	150	150	50
59	MHD	TR04	150	150	50
60		TR05	150	150	50
62		TR04	100	100	-
63	KLX	TR06	100	100	-
64		TR08	100	100	-
65	GAM	TR01	150	150	50
66		TR02	150	150	50

67		TR01	150	150	50
68	JAS	TR02	150	150	50
69		TR05	150	150	50
1	NHS	TR03	100	100	-
2		TR04	100	100	-
3	GND	TR01	60	60	20
4		TR02	60	60	20
5	HAS	TR01	35	35	17.5
6		TR03	35	25	10
7		TR03	60	60	20
8	MAR	TR04	60	60	20
9		TR05	35	35	-
10	MAN	TR01	35	35	17.5
11		TR02	35	25	10
12	FAO	TR01	7.5	7.5	-
13		TR02	7.5	7.5	-
14	HAG	TR01	17.5	10	10
16	ORBK	TR01	55	55	17
17	MIN	TR02	17.5	10	10
18		TR03	17.5	10	10
19	SNG	TR01	100	100	50
20		TR02	100	100	50
21	ROS	TR05	60	60	-
22		TR06	60	60	-
23	RNK	TR01	60	60	-
24		TR02	60	60	-
25	RBK	TR03	60	60	-
26		TR04	60	60	-
27	MSH	TR03	60	60	-
28		TR04	35	25	10
29	TND	TR01	60	60	-
30		TR02	60	60	-
31	UMR	TR01	60	60	-
32		TR02	60	60	-
33	OBD	TR01	60	60	-
34		TR02	60	60	-
35	MAR	TR01	80	80	-
36		TR02	80	80	-
37	NHS	TR01	150	150	-
38		TR02	150	150	-

39	SNJ	TR01	55	55	-
40		TR02	55	55	55
1	HWT	TR01	100	50	-
2		TR02	100	50	-
3	GDF	TR01	100	100	50
1	SHN	TR01	50	50	-
2		TR02	50	50	-
3	ATB	TR01	100	100	-
4		TR02	100	100	-
5		TR03	300	300	75
6		TR04	300	300	75
7	MWP	TR06	150	150	-
8		TR07	150	150	-
9	MWT	TR01	40	40	-
10		TR02	40	40	-
11	DEB	TR01	40	40	-
12		TR02	40	40	-
13	DON	TR01	100	100	-
14		TR02	100	100	-
15	WWA	TR01	60	60	-
16		TR02	60	60	-
17	WHL	TR01	60	60	-
18		TR02	60	60	-
41	RBK	TR01	100	100	-
42		TR02	100	100	-
43	MSH	TR01	40	40	-
44		TR02	100	100	-

4		TR02	100	100	50
5	SWK	TR01	50	50	-
6		TR02	50	50	-
7	GRB	TR01	100	100	50
8		TR02	100	100	50
9	HLF	TR01	100	100	-
10		TR02	100	100	-
11	KSL	TR01	100	100	-
12		TR02	100	100	-
13	ARM	TR01	50	50	-
14		TR02	50	50	-
15	POR	TR01	100	100	-
16		TR02	100	100	-