ELECTRICAL LOSSES STUDIES IN NATIONAL GRID

BY:

MOHAMMED FAIZ IBRAHIM MOHAMMED

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Supervisor
Dr. Elfadil Zakaria Yahia

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Declaration of originality

I declare that this report entitled — ELECTRICAL LOSSES STUDIES IN NATIONAL GRID is my own work except as cited in the references. The report has not been accepted for any degree and is not being submitted concurrently in candidature for any degree or other award.

Signature: _________________________
Name: ____________________________
Date: _____________________________
ACKNOWLEDGMENT

All praise and thanks is due to Almighty God. I wish to thank Him for all that He has gifted us with, though He can never be praised or thanked enough.

I have to thank my research supervisor Dr. Elfadil Zakaria Yahia. Without his assistance and dedicated involvement in every step throughout the process, this project would have never been accomplished.

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Finally, I offer my regards and blessings to all of those who supported me in any respect during the completion of the project.
Dedication

-To my parents and to all family
-To my friends
-To all my favorite friends
-To my brothers
ABSTRACT

The global problem of the lower power availability to consumers is a consequence of power loss and no matter how carefully the power system network is designed, losses are unavoidable. Moreover, the present situation of losses in the power sectors is worrisome. The overall value of losses is fairly known as well as their likely sources. However, how large the magnitude of these losses is and where they come from remain unknown.

Energy losses occur in the process of supplying electricity to consumers due to technical and commercial losses. The technical losses are due to energy dissipated in the conductors and equipment used for transmission, transformation, sub-transmission and distribution of power. These technical losses are inherent in a system and can be reduced to an optimum level. The commercial losses are caused by pilferage, defective meters, and errors in meter reading and in estimating unmetered supply of energy.

A case study for technical losses was applied on the IEEE 14-buses using (ETAP) software which used Newton-Raphson method to solve load flow equations.

Also the mechanism that used to reduce the technical and non-technical losses was implemented and discussed briefly.
المستخلص

المشكلة العالمية لنقصان توفر الطاقة للمستهلكين سببها الفقودات في الشبكة ولا يمكن تفاديها حتى بعد تصميم الشبكة بحذر ودقة عالية. بالإضافة إلى ذلك الوضع الحالي للفقودات في مجال الطاقة المولد مقلق للغاية. القيمة الكلية للفقودات ومصادرها يمكن الحصول عليها ومعرفتها ولكن الحجم الكبير للفقودات ومن اين تأتي بظل مجهول.

تتحدث خسائر الطاقة في عملية تزويد الكهرباء للمستهلكين بسبب الخسائر التقنية والتجارية. وتعزى الخسائر التقنية إلى تبديد الطاقة في الموصلات والمعدات المستخدمة في نقل الطاقة وتحويلها ونقلها الفرعي وتوزيعها. وهذه الخسائر التقنية متأصلة في نظام ويمكن تخفيفها إلى المستوى الأمثل. وتعزى الخسائر التجارية إلى الاختلاس والعدادات المعيبة والأخطاء في قراءة العدادات وفي تقدير إمدادات الطاقة غير معددة.

تم استخدام برنامج حاسوبي (ETAP) لحساب الفقودات التقنية في (IEEE 14-BUS) الذي يستخدم طريقة نيوتن رابسون لحل معادلات السريان الاحمال ومن جهة اخرى تم حساب الفقودات غير التقنية باستخدام الإحصاءات التي تم جمعها من شركة التوزيع.

أيضا تم تنفيذ الآلية التي تستخدم للحد من الفقودات التقنية وغير التقنية ومناقشتها وتم إيجاد الحلول لهم من نتائج المحاكاة في حالة الفقد غير التقني.
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List of abbreviations

T& D Transmission and Distribution
NTL Non-Technical Losses
GDP Gross Domestic Product
SAIDI System Average Interruption Duration Index
DT Distribution Transformer
CT Current Transformer
LT Long Transmission
IURPA International Utilities Revenue Protection Association
WAPDA Water And Power Development Authority
WB World Bank
AMR Automatic Meter Reading
PLC Power Line Communication
GIS Geographic Information System
OLD One Line Diagram
UGS Under Ground cable recovery System
GGS Ground Grid System
IEC International Electronic Commission
ANSI American National Standards Institute
Chapter 1: Introduction

1.1 General Introduction

Power generation, transmission and distribution are the three activities in power industry. Energy is consumed and loss is incurred in every step of the above activities. Among the three activities, losses in power distribution is the maximum as it has grown up in an unplanned manner. Power utility company suffers for high loss. And some steps have been taken in some states to reduce losses. Further initiative and activities are required to improve in this area. Distribution loss consists of two parts: Technical loss and Commercial loss (Non-technical losses).

Technical losses is known as power dissipation in transmission lines due to the impedance of the line. Technical losses in distribution systems are directly related to consumers' load curves, which vary due to seasonality and / or rapid changes in load over the year, resulting in uncertainty in determining the amount of losses. These uncertainties can be determined from the elaboration of a decision support system that considers the random nature of load curves through a set of measurements along the feeders.

Non-technical losses are due to human manipulation or errors and are therefore external to the power system.

Also non-technical losses are very difficult to measure.

There is a several techniques to estimate and reduce this phenomenon but it cannot be eliminated never ever.

1.2 Problem Statement

The utility industry today has placed a high level of importance on improving efficiency. A proper review of losses experienced on a utility’s system can provide valuable insight into ways to manage these losses and improve efficiency while reducing wholesale power costs, improving voltage levels, and freeing up system capacity, potentially reducing costly investment in system improvements. In this project we will face fundamental problem

- How to reduce technical losses to the minimum
- How to reduce nontechnical losses and find the suitable techniques to fight it
1.3 Motivation

Understanding technical nontechnical losses and the techniques used to reduce it and it is influences in the network form a very good approach for this project. Also the knowledge and experience in the losses of the power systems would help in modeling and analyzing the problem.
1.4 Objectives

Project objectives can be summarized as follows:

a- Have a full understanding of types of the electrical losses and their calculations in the power system.
b- Use a computer program (ETAP) for the calculation of the technical losses in the system.
c- Using techniques to detect and calculate the non-technical losses in the system.

1.5 Thesis Layout:

This project contains seven chapters:

a- Chapter 2: this chapter gives a brief description of the types of technical losses and the component of the lines that increase the technical losses.
b- Chapter 3: Showing the techniques that used to calculate the technical and nontechnical losses and its also contains the reasons of these losses.
c- Chapter 4: this chapter contains the load flow analysis and the methods used in load flow and the component of the network.
d- Chapter 5: this chapter contains information about the software (ETAP) used to analyze the IEEE 14-bus system.
e- Chapter 6: this chapter provides conclusions of the above work and limitations of the system, it also provides the recommendations or for possible future work.
Chapter 2: Literature Review

2.1 Introduction

Losses are existing in the power system no matter how carefully the system is designed. Electric power losses are wasteful energy caused by external factors or internal factors, and energy dissipated in the system. They include losses due to resistance, atmospheric conditions, theft, miscalculations etc. Losses incurred between sources of supply to load center (or consumers).


![Simple Diagram of an Electric Transmission and Distribution System](image)

The losses can be further sub grouped depending upon the stage of power transformation and transmission system as Transmission Losses (400kV/220kV/132kV/66kV), as Sub transmission losses (33kV/11kV) and Distribution losses (11kV/0.4kv).

The commercial losses are caused by defective meters, and errors in meter reading and in [2] estimating unmetered supply of energy.

2.2 Transmission and Distribution Losses

2.2.1 Technical Losses

The technical losses are due to energy dissipated in the conductors, equipment used for transmission line, transformer, sub transmission line and distribution line and magnetic losses in transformers.

Technical losses are normally 22.5%, and directly depend on the network characteristics and the mode of operation.

The major amount of losses in a power system is in primary and secondary distribution lines. While transmission and sub-transmission lines account for only about 30% of the total losses.
Therefore primary and secondary distribution systems must be properly planned to ensure within limits.

The unexpected load increase was reflected in the increase of technical losses above the normal level.

Losses are inherent to the distribution of electricity and cannot be eliminated.

**There are two Type of Technical Losses:**

**a) Permanent / Fixed Technical losses:**

Fixed losses do not vary according to current. These losses take the form of heat and noise and occur as long as a transformer is energized

Between 1/4 and 1/3 of technical losses on distribution networks are fixed losses. Fixed losses on a network can be influenced in the ways set out below:

- Corona Losses.
- Leakage Current Losses.
- Dielectric Losses.
- Open-circuit Losses.
- Losses caused by continuous load of measuring elements
- Losses caused by continuous load of control elements.

**b) Variable Technical losses:**

Variable losses vary with the amount of electricity distributed and are, more precisely, proportional to the square of the current. Consequently, a 1% increase in current leads to an increase in losses of more than 1%.

Between 2/3 and 3/4 of technical (or physical) losses on distribution networks are variable Losses.

- By increasing the cross-sectional area of lines and cables for a given load, losses will fall. This leads to a direct trade-off between cost of losses and cost of capital expenditure. It has been suggested that optimal average utilization rate on a distribution network that considers the cost of losses in its design could be as low as 30 per cent.

- Joule losses in lines in each voltage level
- Impedance losses
- Losses caused by contact resistance

A common example of such losses is the power loss caused by resistance of transmission lines.

The average power loss in a transmission line can be expressed as

\[ P_{\text{loss}} = P_{\text{source}} - P_{\text{load}} \]
Where $P_{\text{source}}$ means the average power that the source is injecting into the transmission line and $P_{\text{load}}$ is the power consumed by the load at the other end of the transmission line.
This is a simple enough calculation, except that power and current are both time dependent functions and that energy—not power—is the quantity that gets translated into money. Energy is power accumulated over time, or

$$W_{loss} = \int_{a}^{b} P_{loss}(t) \, dt$$  \hspace{1cm} (2.2)

With and bas the starting and ending points of the time interval being evaluated, respectively. As a result, we need a fairly accurate description of $P_{loss}$ as a function of time to make a reliable prediction of energy loss ($W_{loss}$). And power, in a single-phase case, with sinusoidal current and voltage can be represented by

$$P_{1-\varphi} = I \, V \, \cos \theta$$  \hspace{1cm} (2.3)

With P, V and I being the average power, rms voltage and rms current of the element in question, respectively. The term $\cos \theta$ is the power factor of the element in question, while $\theta$ is the phase difference between the voltage and the current waveforms. So that the information needed to calculate the average power loss sampled at an instant of time in a transmission line or an arbitrary element in a power system has to be one of the following sets (all variables are single phase, rms values and average power:

i. Voltage across the element, resistance, or

$$P = \frac{V^2}{R}$$  \hspace{1cm} (2.4)

ii. Current and resistance, or

$$P = I^2 R$$  \hspace{1cm} (2.5)

iii. Voltage, current and phase difference between the two, or

$$P = IV \, \cos \theta$$  \hspace{1cm} (2.6)
These sets of data and choices of calculations are the options that an engineer will have for computing power losses in a load-flow analysis\(^2\). But in order to gain V or I, both rms values, the voltage must be known at two ends of the element that is evaluated, at all times or as averages. This means the terminals that feed consumer loads must be appropriately monitored at all times using some of the more sophisticated meters that could store and compute average and [2]. instantaneous values that the load-flow analyst is interested in. The information about the power sources and loads listed above are needed to determine expected losses in the power system using load-flow analysis software (ETAP)
Figure 2.2 shows a simple power system with two buses (nodes), one a generator, and the other a load. For the simulations undertaken for this research, the voltage, current, power, and power factor of the generator have known values at the same time intervals, and, consequently, the current going through the transmission line. Information of the load’s power and power factor are unknown, but at this point the information at the generator is sufficient to determine what’s happening to the transmission line using simple calculations:

\[
P_{\text{loss}} = P_{\text{source}} - P_{\text{load}}
\]

![Bus Power System - Line Diagram of a Simple Two-Bus Power System](image)

With \( S_{\text{load}}, V_{\text{load}}, P_{\text{loss}}, I, \) and rate the load apparent power, load voltage, power loss in the transmission line, current in the transmission line, and transmission line resistance, respectively (all values are complex values), while \( I^\ast \) is the complex conjugate of the current. The same relationships hold when analyzing these quantities as phasors or rms values.

Technical losses are possible to compute and control, provided the power system in question consists of known quantities of loads. In this thesis, it will be argued that the distortion of load quantities caused by NTL will distort the computations for technical losses caused by existing loads, thereby rendering any results ineffectual.\[2\]
2.2.2 Non-Technical Losses (NTL)

Non-Technical losses, on the other hand, are caused by actions external to the power system or are caused by loads and condition that the Technical losses computation failed to take into account. Non-Technical losses are more difficult to measure because these losses are often unaccounted for by the system operators and thus have no recorded information. Non-technical losses (NTL), on the other hand, occur as a result of theft, metering inaccuracies and unmetered energy. NTLs, by contrast, relate mainly to power theft in one form or another. Theft of power is energy delivered to customers that is not measured by the energy meter for the customer. This can happen as a result of meter tampering or by bypassing the meter. Losses due to metering inaccuracies are defined as the difference between the amount of energy actually delivered through the meters and the amount registered by the meters. The most probable causes of Non Technical Losses (NTL) are:[3]

(i) Tampering with meters to ensure the meter recorded a lower consumption reading

(ii) Errors in technical losses computation

(iii) Tapping (hooking) on LT lines

(iv) Arranging false readings by bribing meter readers

(v) Stealing by bypassing the meter or otherwise making illegal connections

(vi) By just ignoring unpaid bills

(vii) Faulty energy meters or un-metered supply

(viii) Errors and delay in meter reading and billing

(ix) Non-payment by customers.

As NTL cannot be computed and measured easily, but it can be estimated from preliminary results, i.e. the result of technical losses are first computed and subtracted from the total losses to obtain the balance as NTL
2.3 Transmission and Distribution Line Components:

-A transmission line is a distributed element in which voltage and current depend on both time and space.

-A property of a distributed system is that waves can travel both in a forward and reverse direction.

-The voltage at any given point is the superposition of the forward and reverse traveling waves.

-The following circuit models a short transmission line:

\[
\begin{array}{c}
\text{R}_{\text{Line}} \\
\text{X}_{\text{Line}} \\
\end{array}
\]

Unlike the electric machines studied so far, transmission lines are characterized by their distributed parameters: distributed resistance, inductance, and capacitance. The distributed series and shunt elements of the transmission line make it harder to model. Such parameters may be approximated by many small discrete resistors, capacitors, and inductors.

\[
\begin{array}{cccccccc}
\text{R} & \text{L} & \text{R} & \text{L} & \text{R} & \text{L} & \text{R} & \text{L} \\
\text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} & \text{C} \\
\end{array}
\]

Figure 2.4  Transmission Line Model including inductance, capacitance and resistance.
2.3.1 SHUNT CONDUCTANCE

The conductance term represents leakage current through the dielectric material. In a typical discrete capacitor, the resistance term represents resistance of the wires connecting the capacitor to the circuit, although other energy loss terms might be lumped in as well, if it improves the accuracy of the model.

If so what is the benefit of modelling it in this way as opposed to just a second resistor in series with the capacitor?

Very basically, a resistance in series with the capacitor would not allow any dc leakage current. A conductance in parallel with a capacitance does allow dc leakage.

Also a series resistance term would generally lead to different behavior as frequency increased. The shunt term would be

\[ Y_{sh} = j\omega C / (1 + j\omega CR) \]

which would be increasing in magnitude at low frequencies and then flat above the pole frequency at \( \omega = 1/RC \). Whereas with the more usual model we have

\[ Y_{sh} = G + j\omega C \]

which has a zero but no poles.

2.3.2 RESISTANCE

The primary source of losses incurred in a transmission system is in the resistance of the conductors. The resistivity of a conductor is a property of the material that the conductor is made from. It varies with both type and temperature of the material. At the same temperature, the resistivity of aluminum is higher than the resistivity of copper.

The DC resistance of a conductor is given by:

\[ R_{DC} = \rho l / A \] (2.8)

Where \( l \) is the length of conductor; \( A \) is cross-sectional area, \( \rho \) is the resistivity of the conductor.

AC resistance of a conductor is always higher than its DC resistance due to the skin
effect forcing more current flow near the outer surface of the conductor. The higher the frequency of current, the more noticeable skin effect would be. At frequencies of our interest (50-60 Hz), however, skin effect is not very strong.
The resistivity increases linearly with temperature over normal range of temperatures. If the resistivity at one temperature is known, the resistivity at another temperature can be found from:

\[
\rho_{T2} = \rho_{T1} \frac{M+T_2}{M+T_1}
\]

(2.9)

Where \( T_1 \) and \( \rho_{T1} \) are temperature 1 in oC and the resistivity at that temperature, \( T_2 \) and \( \rho_{T2} \) are temperature 2 in oC and the resistivity at that temperature, and \( M \) is the temperature constant.

### 2.3.3 Capacitance

The capacitance of a transmission line comes about due to the interaction between the electric fields from conductor to conductor and from conductor to ground. The capacitance of the transmission line can be found using the Gauss’s law:

\[
\iiint D \cdot dA = Q
\]

(2.10)

where \( A \) specifies a closed surface; \( dA \) is the unit vector normal to the surface; \( q \) is the charge inside the surface; \( D \) is the electric flux density at the surface:

\[
D = \varepsilon E
\]

(2.11)

where \( E \) is the electric field intensity at that point; \( \varepsilon \) is the permittivity of the material:
The permittivity of free space $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m

2.3.4 INDUCTANCE

The basic concept from our understanding of electromagnetic field theory is that a conductor carrying current has a magnetic field around it. When the alternating current present in a transmission system is accompanied by alternating magnetic fields, the lines of force of the magnetic fields are concentric circles having their centers at the center of the conductor and are arranged in planes perpendicular to the conductors. The interaction of these magnetic fields between conductors in relative proximity creates flux linkage.

The series inductance of a transmission line consists of two components, internal and external inductances, which are due the magnetic flux inside and outside the conductor respectively. The inductance of a transmission line is defined as the number of flux linkages (Wb-turns) produced per ampere of current flowing through the line:

$$L = \frac{\varphi}{I}$$

Consider a conductor of radius $r$ carrying a current $I$. At a distance $x$ from the center of this conductor, the magnetic field intensity $H_x$ may be found from Ampere’s law:
2.4 Reasons for High Transmission and Distribution (T&D) Losses in Several Countries

Non-technical losses in the power sector are almost non-existent or negligibly small in developed countries, as most of the population can afford to pay tariffs reflecting costs of supply (even if they are higher than those reflecting optimized performance of the service providers)[13]. In contrast, although mixed, the situation tends to be significantly different in developing countries. Many electricity utilities in developing countries succeeded in significantly reducing or eliminating non-technical losses in electricity supply on a sustainable manner, but others continue to show high losses.

In all successful cases, a large share of non-technical losses was concentrated in users able to pay for cost-reflective tariffs. Thus, non-technical losses can be reduced with little loss of welfare, while their continuation jeopardizes the financial sustainability of the power sector and harms well-behaving-electricity consumers, taxpayers, socially disadvantaged segments, and the country as a whole. Elimination of those losses (with the exception unmetered consumption explicitly and transparently defined in the regulatory framework) should be a matter of high national priority for every country.

2.4.1 [13] Latin America

High total losses were prevalent in most Latin American countries at the beginning of the 1990s, in a scenario characterized by poor performance of state-owned enterprises, poor service quality, and low access rates. Average tariff levels were usually below the cost of supply (exacerbated by inefficiencies in the performance of the utilities, particularly high non-technical losses) and both government subsidies and tariff cross-subsidization (in general from industrial and commercial to residential customers) were the usual practices. A vicious downward circle or “low-level trap” was the norm, as external subsidies were just keeping inefficient utilities afloat while the quality of service to existing customers progressively worsened. As a consequence, the willingness of the population to pay for higher tariffs steadily declined over time, reducing the income source for the power sector and deepening the crisis.

In India, most of distribution activities are carried out by utilities owned by state governments. The exceptions are Reliance and Tata, two private companies serving Mumbai which have always been private. While both Reliance and Tata show total losses of about 11–12 percent.

The performance of state-owned utilities is generally bad, with losses exceeding 30 percent in most cases. Seven states started reform and restructuring of their power sectors in the 1990s, involving unbundling and corporatization of state-owned utilities. Privatization of only six distribution companies has gone forward so far and three of those have failed. The state of
Orissa was the first to unbundle its electricity companies in 1996, followed by three failed attempts at privatizing distribution companies. Privatization of the New Delhi Vidyut Board in July 2002 was an ambitious undertaking, given its more than 4 million customers and losses greater than 50 percent of all power purchased at the time of takeover by new private owners, Reliance and Tata. The privatized companies have reduced total losses markedly. The case of the North Delhi Power Limited, described in section 4.3, is probably the most recent example of a great success in sustainable loss reduction using state-of-the-art management and information technology tools currently available worldwide.
2.4.2 Former Soviet Union

In the 1980s, the performance of electricity distribution utilities of the counties in the former Soviet Union was characterized by universal access, reasonably acceptable service quality, but poor financial performance. High total losses and poor collection rates, due to weak metering, billing, and payment collection accounted for the companies’ financial distress. Starting in the 1990s, most EU accession countries have successfully privatized their distribution companies. Ukraine and Georgia are moving in the same direction. However, the situation remains almost unchanged and the commercial performance of distribution companies is poor in Russia and most of the other countries in the former Soviet block.

2.4.3 Saharan Africa

A draft 2008 World Bank report describes the performance of the utilities in Sub-Saharan countries. The median utility in that region presents huge inefficiencies. Only 50 percent of electricity generated is paid for, due to a combination of low percentages of amounts of electricity injected in distribution networks being billed and low rates of collection of the billed amounts. The variation in performance is enormous, with the highest inefficiencies in Nigeria, where the utility is capturing only 25 percent of the revenues owed. Some recent studies have shown that hidden costs of distribution losses in Sub-Saharan Africa are usually more than 0.5 percent of GDP, and may be as large as 1.2 percent of GDP in some countries[13]. The exceptions are the state-owned and operated utilities of Botswana and South Africa. Botswana Power Corporation has long provided reliable, high-quality service. It has expanded the network in both urban and rural areas, covered its costs and posed no burden on the government budget. It has also reduced system losses to 10 percent and earned a decent return on assets. Electricity
losses in Botswana are lower than in South Africa, whose power sector is operated by Eskom, one of the largest utilities in the world, with about 15 percent total losses.

2.5 Measures for Reducing Technical Losses

2.5.1 Short Term Measures

i. Identification of the weakest areas in the distribution system and strengthening.

ii. Improving them so as to draw the maximum benefits of the limited resources.

iii. Reducing the length of LT lines by relocation of distribution sub stations/ Installations of additional distribution transformers (DTs).

iv. Installation of lower capacity distribution transformers at each consumer premises instead of cluster formation and substitution of DTs with those having lower no load losses such as amorphous core transformers.

v. Installation of shunt capacitors for improvement of power factor.
2.5.2 Long Term Measures

i. Mapping of complete primary and secondary distribution system clearly depicting the various parameters such as conductor size line lengths etc.

ii. Compilation of data regarding existing loads, operating conditions, forecast of expected loads etc.

iii. Carrying out detailed distribution system studies considering the expected load development during the next 8-10 years.

iv. Preparation of long-term plans for phased strengthening and improvement of the distribution systems along with associated transmission system.

v. Estimation of the financial requirements for implementation of the different phases of system improvement works.

vi. Formulation of comprehensive system improvement schemes with detailed investment program so as to meet system requirement for first 5 years.[4][1]

2.6 Measures for Reducing Non-Technical Losses

According to the International Utilities Revenue Protection Association (IURPA), research carried out on utilities worldwide indicates that service quality, customer relationships, and overall service satisfaction can minimize revenue losses. This has been demonstrated in Pakistan where rampant power theft has contributed financial crisis for WAPDA (Water & Power Development Authority). The World Bank and Asian Development Bank which had supplied the bulk of WAPDA’s development loans wanted the authority to recover its unpaid dues, cut power theft and reduce its T&D Losses. Accordingly WAPDA was forced to raise power rates. But instead of improving the financial situation, this action resulted in increased financial crisis of WAPDA due to increased incidence of theft and unpaid bills. In view of this, the authority applied extreme measures to curb power theft. [4]

2.6.1 Various Techniques Adopted for Measurement and Reduction of Non-Technical Losses

- Integral management of metering, reading, billing, collection, disconnection-reconnection due to unpaid bills, and inspection of meters
- Implementation of policies for customer service and programs for payment of old debts and commercial regularization
- Increasing the number of points of contact for customer service to move the company closer to its clients
- Marketing programs aimed at creating awareness that electricity is a commercial good with a price
2.7 Summary of Some Non-Technical Loss Reduction Methods

2.7.1 Measurement & Estimation

Non-technical losses represent an avoidable financial loss for the utility. Although it is clear that the amounts of electricity involved in non-technical losses are being consumed by users that do not pay for them, experience shows that a significant percentage of those amounts (in some cases more than 50 percent) becomes reduced demand when those users have to pay for that electricity because they adjust their consumption to their ability to pay for electricity services. That reduction in demand has exactly the same effect as a reduction in technical losses: less electricity needs to be generated. Thus, from the country’s perspective, reductions in nontechnical losses are also positive.

2.7.2 Monitoring

From a social point of view, non-technical losses have several perverse effects. Customers being billed for accurately measured consumption and regularly paying their bills are subsidizing those users who do not pay for electricity consumption. There is a wide range of situations creating non-technical losses. A classic case is a theft of electricity through an illegal connection to the grid or tampering of a consumption meter. But examples also include unmetered consumption by utility customers who are not accurately metered for a variety of reasons. In all the cases some level of poor management of the utility in execution of its operations is present.

2.7.3 Detection

Utility companies consistently suffer from the harassing of Non-Technical Loss (NTL) frauds globally. In the traditional power grid, electricity theft is the main form of NTL frauds. In
Smart Grid, smart meters thwart electricity theft in some ways but cause more problems, e.g., intrusions, hacking, and malicious manipulation. Various detectors have been proposed to detect NTL frauds, but they either rely on user behavior analysis which requires a large amount of historical data or needs a lot of extra devices which are expensive. A detector named NFD (NTL Fraud Detection), is proposed to detect NTL frauds with only a small amount of data and one additional device.

### 2.7.4 Recovery

Electricity theft is de facto subsidization of those who steal by customers regularly paying bills according to their consumption. The same usually applies in the case of unmetered customers, unless this situation is explicitly and transparently defined by the competent authorities and reflected in the legal and regulatory framework of the sector—in some countries some categories of consumers (e.g., agriculture users in India and Bangladesh) are unmetered and pay a fixed amount for electricity irrespective of the amounts consumed, which means in practice that they are subsidized by consumers in other categories, tax payers, or both. Depending on the financial situation of the power sector, the savings from reductions in non-technical losses could be channeled to:

1. reduce tax-payers subsidies or tariffs paid by customers.
2. achieve an average tariff level allowing recovery of costs reflecting efficient sustainable performance (critical to assure service quality).
3. subsidize consumption of selected categories of socially sensitive existing users.
4. extend access to electricity supply to currently unserved population (in general the poorest and socially unprotected).

### 2.8 Summary of literature

The efficient use of electrical energy will slow the destruction of the environments natural resources and will also reduce the cost of electricity for the consumers. As discussed in the literature study the technical losses in an electricity distribution network can be calculated. Thus reduction in electricity generation will be due to non-technical losses and a strategy to limit the non-technical losses will be derived in the next chapter.
Chapter 3 Losses in Power System

3.1 Introduction

Electric power losses are wasteful energy caused by external factors or internal factors, and energy dissipated in the system.

Distribution losses, defined as the difference between the electricity entering the distribution network and that leaving it, arise for technical and other reasons.

The technical reasons relate to the physics of electricity distribution though affected by the engineering and economic decisions in, for example, specifying the sizes of cables and transformers. The other reasons cause ‘non-technical’ losses and include theft, measurement inaccuracy and timing differences.

Losses are important as there is an environmental and economic cost associated with them. Whilst technical losses are directly related to carbon emissions and have an impact on generation capacity, all losses have to be paid for by users of the network.

3.2 Technical Losses in Power System

The correct evaluation of technical losses on power line is an important quality measure and a pathway to reduce energy losses in order to increase the efficiency.

Technical loss evaluation can be determined using various approaches in the consideration of pattern of generation and loads with different degrees of accuracy.

According to technical losses can be investigated by the effect of circulating current because of the interconnection of electricity supply networks, the voltage regulation, the phase balance, and the power factor.

Loss determination seems at first, quite simple; losses are the energy input to the grid minus the energy delivered to consumers. However, in practice, it is not that easy.

In most cases, mathematical formulations have to be simplified to get the solutions because of the extremely limited capability to solve real-world large-scale power system problems.

Loss evaluations are very much dependent on the available data. If high accuracy is desired, a lot of high quality data are necessary. Historically, available data in most cases are limited for a detailed model work. This problem can be overcome by the use of mathematical models and computer simulations.
3.3 Technical Loss Analysis Methods

The literature on technical loss evaluation or analysis is almost in a flux; but a common challenge that has been confronting researchers for long time now is how to tackle the problem of inaccuracy in the correct assessment of energy losses.

There are two basic methods that can be used to calculate technical energy losses: a method based on subtraction of metered energy purchased and metered energy sold to customers and the method based on modeling losses in individual components of the system (Yasen, 2010).

Researches on network losses in the literature have mostly been carried out on theoretical calculations that are based on simple model data; this is insufficient to give a correct calculation assessment of losses which are important for several reasons. It is not simply possible, as revealed from past works, to obtain a comprehensive model to satisfy theoretical equations.

Even though with the available data and tools needed for calculating losses in power system, current techniques have certain drawbacks regarding such calculations such as limited data and therefore may need a fairly accurate description of power losses as a function of time to make a reliable prediction of energy losses.

Generally, technical losses can be evaluated or computed using several formulae in considering the 18 pattern of generation and loads (Cory, 2008) by means of any of the following methods considered for related technical losses analysis:

3.4 Computation of $I^2R$ in Transmission Line

Consider the circuit model of a simple three-phase radial transmission line between two points of generating source and receiving/load to be trivial (ideal conductor) [12] as illustrated in the one-line diagram of Figure 3.3.1 The three-phase line loss is given as

$$P_{loss} = P_L = 3I^2R$$

Figure 3.1: One-line diagram with one source and one load
It can be deduced from Figure 3.3 that $I^2R$ line losses are inherent in all conductors because of the finite resistance of conductors. The current $I$ is obtained as:

$$|I| = \frac{P_G}{(\sqrt{3})V_G \cos \theta_G}$$  

(3.4)

where $P_G$ is the generated power (load power and losses), $V_G$ is the magnitude of the generated voltage (line-to-line) and $\cos \theta_G$ is the generator power factor leading.

Combining equations (3.3) & (3.4), gives

$$P_L = \frac{R}{|V_G|^2 \cos^2 \theta_G} (P_G^2)$$  

(3.5)

Assuming fixed generator voltage and power factor, the losses can be written as

$$P_L = B P_G^2 \quad \text{where} \quad B = \frac{R}{|V_G|^2 \cos^2 \theta_G}$$  

(3.6)

where $B$ = the loss coefficient

3.5 Evaluation of Line losses using B-Loss Coefficient

In a large interconnected network where power is transmitted over a long distances with a low local density area, losses are a major factor. These losses are thus approximated as a second order function of generation. If a second power generation is present to supply the load as shown in Figure (3.5), the transmission losses can be expressed as a function of the two plant loadings represented by

$$P_L = P_1^2B_{11} + 2P_1P_2B_{12} + P_2^2B_{22}$$  

(3.7)

Figure 3.2: Radial system with one additional generation
Transmission losses become a major factor to be considered when electric energy is transmitted over long distances or in the case of relatively low load density, over a vast area. The active power losses may amount to 20 to 30% of total generation at a frequency of 50Hz in some situations.

In industrial systems, the losses are made up of complex combination of fixed (core and corona) and variable (I² dependent) losses. That is

\[ P_L = B_0 + B_1 P_G^2 \]  \hspace{1cm} (3.8)

where
\( B_0 \) represents fixed loss
\( B_1 \) represents variable loss
\( P_G \) is the generated power

It should be noted that the calculation of B-loss coefficients is more complex in large industrial systems.

### 3.6 Differential Loss Method of Loss Evaluation

Power loss can also be expressed as the difference between the transmitted power and received power:

\[ P_{\text{loss}} = P_{\text{Sent}} - P_{\text{Received}} = P_S - P_R \]  \hspace{1cm} (3.9)

The relationship between the power sent, power received and associated losses in the transmission network is illustrated in Figure 3.5

![Figure 3.3: The relationship between power sent and power received.](image)

\[ \eta = \frac{P_{\text{Received (p.u)}}}{P_{\text{Sent}}} = \frac{P_R}{P_S} \]  \hspace{1cm} (3.10)

\[ \eta = \frac{P_{\text{Sent}} - P_{\text{Loss in the line}}}{P_{\text{Sent}}} = \frac{P_S - P_L}{P_S} \]  \hspace{1cm} (3.11)

\[ \eta = 1 - \frac{P_L}{P_S} = 1 - \frac{P_{\text{Loss in the line}}}{P_{\text{Sent}}} \]  \hspace{1cm} (3.12)

Therefore, efficiency \( \eta \) of a transmission line can also be defined as

\[ \eta = \frac{P_R}{P_S} = \frac{P_R}{P_R + P_L} \]  \hspace{1cm} (3.13)

where PS is the power sent, is the load power received and PL is the net sum of the power lost in the transmission system.
3.7 Transmission Loss evaluation using Dopazo Formula

In (Dopazo), the authors derived an exact formula for calculating transmission losses by making use of the bus powers and the system parameters. Let $S_i$ be the total injected bus power at bus $i$; this is equal to the generated power minus the load at bus $i$. The summation of all such powers over all the buses gives the total losses of the system as

$$P_L + jQ_L = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} V_i I_i^* = V_{bus}^T I_{bus}$$

(3.14)

Here, $P_L$ and $Q_L$ are the real and reactive power losses of the system respectively. $V_{bus}$ and $I_{bus}$ are respectively the column vectors of voltages and currents of all the buses.

Thus

$$V_{bus} = Z_{bus} I_{bus}$$

(3.15)

where $Z_{bus}$ is the bus impedance matrix of the transmission network and is given by

$$Z_{bus} = R + jX = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix} + j \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nn} \end{bmatrix}$$

(3.16)

The equation for the loss can be written as

$$P_L + jQ_L = (I_p + jI_q)^T (R + jX) (I_p - jI_q)$$

(3.17)

3.8 Solutions Adopted For Technical Losses

3.8.1 Strategic Planning

Strategic planning is an organization form of project management that is designed to handle all types of projects ranging from small feasible studies to massive projects. The most important person involved in the strategic planning process is the project manager.

The project manager’s involvement in the project and the communication to executives and lower level personnel often make the difference between a well implemented strategy and one of catastrophe. This section will discuss important considerations to implement a strategy.
3.8.2 Planning The Strategy

Planning a strategy is a function that should be performed by project managers. Project managers normally use a matrix structure in an effort to obtain the most effective and efficient utilization of resources while they attempt to achieve the objectives of the project within the constraints of time, performance and cost. For a project to be within constraints the goals and objectives of the strategic plan must be clearly identified, together with any limiting factors haltering the time, cost and performance of the project. Project managers prefer to work in concrete rather than abstract notation and therefore they must implement the strategic plan they developed themselves. Project managers that plan a strategy should take the following into consideration:

- Environmental analysis
- Setting objectives
- List alternative strategies
- List possible threats and opportunities
- Prepare forecasts
- Select a strategy portfolio
- Prepare action programs
- Monitor and control the project
3.9 Non-Technical Losses

Non-technical losses (NTL) are difficult – if not impossible – to detect using information that is typically collected by utility companies. In some areas, the loads are not even metered or are metered communally, rendering any loss calculations – technical or not – for that area useless. The approach used by both utility companies contacted involves primarily involves field staff monitoring meters and access points in the system on a regular basis.

Sometimes this involves regular meter readers receiving special training for spotting irregularities, and sometimes – when high voltage and large consumption is involved – it involves meter technicians making dedicated meter and transformer inspection trips.

The reason that meter inspection is the main method of NTL detection is because the utilities consider electricity theft to be the major source of NTL and the majority of electricity theft cases involves meter tampering or meter destruction. The term “meter” used in this and other chapters refers to the watt-hour recording meters used in virtually every household to record and calculate electric bills by utility companies.

3.10 Watt-Hour Meter

The principles of operation for watt-hour meters essentially have not changed since the 1880s and the 1890s, when the watt-hour meter was invented. The basic principle for a single-phase energy measurement meter, first commercially used in 1894, is as follows. First, there are two coils that produce electromagnetic fluxes: a coil, connected across the two leads, that produces a flux proportional to the voltage and a coil connected in series with one of the leads that produces a flux proportional to the current. The dot product of those two fluxes creates a force proportional to the load power. An illustration of the basic components of the watt-hour meter is shown in Figure 3.6 below. The development of these meters, technological improvements, and alternative designs, which reflected the growing power industry in the late 19th century

In early designs, such as the ones shown in Figure 3.7 below, the meters were not enclosed and all the parts and the meter installation were easily accessible to anyone. However, as early as 1899, the minutes of meter committees of the Association of Edison Illuminating Companies [meter paper] showed that electricity theft was a concern early on. In response to the committees’ recommendations, the following improvements – along with other efficiency and accuracy improvements – were added:

- a dust- and insect-proof cover

- a cover and frame so shaped and retained together as to render dishonest and curious tampering with the internal mechanism as nearly impossible as may be.

- means for fully protecting from malicious tampering the heads of all screws in the base which bind the damping magnets, etc., in place without rendering them inaccessible to those authorized to reach them.
This suggests that the problem of electricity theft has obviously been around almost as long as power systems have been around. Modern meters, such as those in Figures 3.8 below, are relatively well enclosed and have seals that would reveal tampering. However, theft can and does occur. Most utilities train their staff to spot tampering, but sometimes the access to the inner mechanisms can be achieved with a very small hole, possibly drilled using small tools and done at less obvious parts of the enclosure.
3.11 Methods of Electricity Theft

There are two main categories for methods of electricity theft: directly connecting an unregistered load to a power line, and tampering with a registered load’s meter in order to reduce the size of the bill the utility charges that load. Once the meter seals are broken, there are many things that can be done to the meter to slow or stop it. Below is a list of various methods of electricity theft recorded by the Provincial Energy Authority of Thailand (PEA).

3.12 High Voltage Meters (12kV or 24kV, 3-phase, 3 or 4-wire primary)

High voltage three-phase watt-hour meters are installed throughout the PEA system to monitor loads that consume high volumes of energy requiring high voltage. Three-phase watt-hour meters use the technique known as the “two watt-hour meters” connection to measure consumption. Because the load is connected with high voltage and
consumes high current levels, the current and voltage sensing are achieved by using current transformers (CT) and voltage taps, respectively. The schematic that illustrates the connections is shown in Figure 3.9 below

![Schematic of current transformers and voltage taps](image)

Figure 3.7 Three-phase Watt-hour Meter Connection

### 3.13 Methods of Meter Violations

Tampering with terminal seals is by far the most common method of meter violations, because the terminal seals are easy to reach, located immediately below the meter itself. Once the terminals were broken, it is be simple to connect one of the control wires or CT wires to ground, making it appear to the meter that at lease one phase does not show voltage or current. The cases of seal tampering, both terminal and meter seals, refer to cases where seals were broken but no visible tampering was done to the meters or the terminals themselves.

#### 3.13.1 Breaking Control Wires

Control wires refer to the secondary wires of the current transformer (CT). Meters for large loads measure high currents and must use CTs to step the current level down to make it compatible with the components in the meter.

Once the insulation of the control wire is broken, external taps could be connected to reduce the current going into the meter, causing the meter to read less current than reality.

#### 3.13.2 Tampering With Meter Seals

Tampering with meter seals is another common form of violation, tampering with meter seals means the person now has access to the meter itself. There are many ways to tamper with meters that will be discussed later.
**Shorting Control Wires 3.13.3**

Like breaking control wires, this would divert the current reading in the meter. In this case the current going to the meter would be zero.

The effect on the meter is immediate and obvious: with zero-current, the power and energy readings become zero, or the accumulated consumption becomes stationary.

**Breaking the Voltages Taps 3.13.4**

Voltage taps in the meter housing allows the meter to read the voltage of the load. Once these are broken (or shorted to ground, or have another line connected to it), the reading the meter gets is distorted from reality, reading a lower voltage in cases of electricity theft.

In the unlikely event that the person wants the meter to read higher values, the voltage taps could be connected to a higher voltage level, and result in higher consumption readings.

Many meters would not work properly or would be damaged by this type of action, because the internal equipment must operate within rated conditions in order to function properly.

**3.13.5 Direct Connections To The Grid**

An obvious way to eliminate consumption records is to bypass the meter altogether. The major obstacle to this is that most high voltage loads are built and connected at the request of the customers, such as a new shopping mall asking for 12-kV lines to run to the back of the property to keep the front clear.

Since the customers are the ones who ask for the connections, direct connections like this would be fairly easy to discover. Also, not many electricians would like to subject themselves to a “hot” high voltage line without the power company there to assist with safety.

**3.13.6 Tampering With The Meter**

Once the meter seals are broken and there’s easy access to the meter inside the housing, and there are several things that can be done to slow or stop the meter readings. A common way is to mechanically obstruct the spinning disc and the axis that does the recording.

Another popular action is to turn back the dials that bill collectors eventually read. Obviously this wouldn’t work for digital-display meters, but all of the PEA-installed meters in Thailand are spinning disc type manufactured in the 1980s or before.
3.13.7 Switching CT Wire

This is a subtle and effective way to reduce electric bills. Many models of three-phase meters use only two current transformers (CTs) to read current data from phases A and B, and assume the load is balanced between all three phases. In reality, large facilities like factories or offices have unbalanced loads.

Depending on the engineer who designed the load connections, this imbalance could vary between 10 and 20 percent of the most heavily loaded phase. C phase is almost always the phase with the least load and lowest power factor, which is why CTs are connected to the A and B phases. By switching the CTs or the wires from their secondary windings, the meter’s current reading is altered.

Switching A and B phases would result in a reversal of phase difference seen by the meter, affecting the power factor reading, and power/energy reading. If the CT from one of the phases is removed and placed on phase C, the power reading is lowered.

3.16 Low Voltage Meter (220 single phase)

A low voltage watt-hour meter is based on the principles of operation discussed in the beginning of the chapter. The parts of the meter where tampering often occur are shown in Figure 3.10 below.

Figure 3.8: Parts of a Single-phase Watt-hour Meter Where Tampering Often Occur.
3.15 Procedure to reduce power theft

The following approaches are used to reduce power theft:- [1]

i. Amnesty.
ii. Off-cycle readings & analysis.
iii. Random inspection.
iv. Use of check meters.
v. Elevated meters (sometimes with high voltage barriers)
vi. Metal casings for meters.
vii. 24-hour security guards.

The following are the technical ways and means to reduce electricity theft:

i. Installing electronic meters which can note time as well current unit reading at an interval of say every 10 minutes, store the readings of several weeks/months in the memory, and transmit the readings to a distance of say 20-30 meters when they receive a signal for reading. This will also reduce the time/cost of reading electric meters.

ii. The meters should be at the connection point to end users as well as at the intermediate branch points.

iii. At several points there should be two meters in series, so that if a person is rigging meters, he will have to rig both the meters, not just one.

iv. By obtaining readings of these meters, it is easy to determine the points at which the electricity is being stolen.
Chapter 4: Load Flow Analysis

4.1 Introduction

A load-flow solution is the most frequently performed type of study of electric power systems that is applied in day-to-day operation as well as in short-term and long-term planning.

In the power-flow method, the power flowing in each line of the interconnected transmission network can be determined by giving the power consumption at all buses in the electric power system and the power generations at all the generating facilities.

In other words, the net amount of real and reactive power flowing into and out of each bus should be practically equal to zero (or within a small tolerance) and the total power supply and demand in the system should be balanced. Power station employs three common load flow calculation methods: Newton-Raphson (N-R), Gauss-Seidel (GS) and Fast-decoupled.

They possess different convergent characteristics, and sometimes one is more favorable in terms of achieving the best performance. Any of them selected will depend on the system configuration, generation, loading condition and initial bus voltages. Newton-Raphson method is still the main means of calculating the load flow of the electrical power system with its calculated results having very big referential significances.

The N-R method, because of its unique convergence quadratic characteristics and formulation of the power flow equations in polar form, is mathematically superior to the GS method.

It has a very fast convergence speed compared to other load-flow calculation methods. It also has the advantage that the convergence criteria are specified to ensure convergence for bus real power and reactive power mismatches. This criterion gives direct control of the accuracy specified for the load-flow solution and therefore, it is found to be more efficient and practical and recommended for use with any system as a first choice method (ETAP, 2010). Hence N-R iterative method was used in this study.

4.2 Classification of Buses in Power System Network

In power system, each node or bus is associated with four quantities; these are voltage, phase angle of voltage, active or real power and reactive power. To solve the problem of load-flow, two out of these quantities must be specified and the remaining two are required to be determined through the solution process. Depending on the quantities that have been specified, the buses are classified as follows[11]
4.2.1 Load bus

The load or PQ buses are the buses where the total injected complex power is specified and no generator is connected to it. That is, the active (P) and the reactive (Q) power of the load demands are known and the voltage magnitude and phase angle of the bus are unknown.

4.2.2 Voltage Controlled Bus

Or generator buses; at these buses, the real power (P) and voltage magnitude (V) are specified. The voltage magnitude is made constant by adjusting the reactive power.

The maximum and the minimum limits on the value of the reactive power are also specified, while the phase angle of the voltage and the reactive power are to be determined.

4.2.3 Slack Bus

Also known as floating or swing or take-up slack bus. This bus is a special generator bus that serves as the reference bus for the power system. Its voltage is assumed to be fixed in both magnitude and phase.

The real and reactive powers of the slack bus are uncontrolled, hence not specified. It supplies whatever real and reactive power necessary to make the power flow operating in steady state.

Since transmission losses cannot be predetermined, it is therefore required to have at least one slack bus selected whose real power generation can be rescheduled to supply the difference between total systems load plus losses and the sum of active powers specified at generation buses.

Slack bus should therefore be properly selected in multi-generating stations such as Nigeria power system in order to minimize the system power mismatch in the load flow studies.

4.3 Formulation of Load Flow Equations

In load-flow, the underlying principles involved with calculating the values of the power that flows through elements of power systems are briefly discussed for more in-depth analysis.

The analysis of an electrical power system starts with the formulation of a referenced nodal system and it describes the relationship that exists between the electrical variables (voltages and currents) as it is stated by the second Kirchhoff’s law or nodal law.

A typical bus of a power system network is as shown in Figure 4.1. Transmission lines are represented by their equivalent π-model where impedances have been converted to per unit admittances on common MVA base.\[11\]
Application of KCL to this bus results in

\[ I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad j \neq i \]  

(4.1)

Where
- \( I_i \) = the injected loader current
- \( V_i \) = the nodal voltage
- \( y_{ij} \) = the element of bus admittance

The total apparent power at bus i is given as

\[ S_i = V_i I_i^* \text{ or } P_i + jQ_i = V_i I_i^* \]

or
\[ I_i = \frac{P_i-jQ_i}{V_i^*} \]  

(4.2)

where \( P_i \) and \( Q_i \) are the real and reactive powers respectively.

Substituting for \( I_i \) in equation 4.1 yields

\[ \frac{P_i-jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad j \neq i \]  

(4.3)

From the above relation, the mathematical formulation of the power flow problem results in a system of algebraic nonlinear equations which are normally solved by iterative techniques.
After the iteration solution of bus voltage, the next step is the computation of line flows and line losses given as in Figure 4.2 shows a line connecting two buses i and k. Here, we assume the normal of Π- Representation transmission line. Let current flow from bus i toward bus k, we then have

\[ I_{ik} = (V_i - V_k)y_{ik} + V_i y_{iko} \]  

(4.4)

where \(V_i\) and \(V_k\) are the bus voltages at the buses i and k respectively.

The power flow in the line i-k at bus i is given as

\[ S_{ik} = P_{ik} + jQ_{ik} \]

\[ = V_i I_{ik}^* \]

\[ = V_i (V_i^* - V_k^*) y_{ik} + V_i V_k^* y_{iko} \]  

(4.5)

Similarly, the power flow in the k-i at bus k is given as

\[ S_{ki} = V_k (V_k^* - V_i^*) y_{ki} + V_k V_i^* y_{kio} \]  

(4.6)

Figure 4.2: Π- Representation of a Line between two buses

Thus, the power flows over all the lines can be computed.

### 4.3.1 The Newton-Raphson Power Flow Iterative Solution

The method is the most widely used method for solving simultaneous, non-linear algebraic equations obtained in equation 4.3. Recall equation 4.1:

\[ I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \quad j \neq i \]  

(4.1)
This equation can be rewritten in terms of the bus admittance matrix as

\[ I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad j \neq i \quad (4.7) \]

In the above equation, \( j \) includes bus \( i \). Since in the power flow problem real power and voltage magnitude are specified for the voltage-controlled buses, the power flow equation of N-R is formulated in polar form. Therefore, expressing equation 4.7 in polar form gives

\[ I_i = \sum_{j=1}^{n} |Y_{ij}| |V_j| \angle (\theta_{ij} - \delta_j) \quad (4.8) \]

The complex power at bus \( i \) is

\[ P_i - jQ_i = V_i^* I_i \quad (4.9) \]

Using equation 4.8 in equation 4.9 gives

\[ P_i - jQ_i = |V_i| \angle - \delta_i \sum_{j=1}^{n} |V_j| |Y_{ij}| \angle (\theta_{ij} + \delta_j) \quad (4.10) \]

Separating the real and imaginary parts of the load flow equation results in

\[ P_i = \sum_{j=1}^{n} |V_i| |V_j| |Y_{ij}| \cos (\theta_{ij} - \delta_i + \delta_j) \quad (4.11) \]

\[ Q_i = - \sum_{j=1}^{n} |V_i| |V_j| |Y_{ij}| \sin (\theta_{ij} - \delta_i + \delta_j) \quad (4.12) \]

The load flow equations (4.11) and (4.12) (Very important two equations) constitute a set of nonlinear algebraic equations in terms of independent variables, voltage magnitude in per unit and phase angle in radians.

If \( S_i = P_i + jQ_i \) is a complex power specified at the beginning of load flow, then the discrepancy between the parameter specified or scheduled and that calculated is given by

\[ \Delta S_i^{(k)} = S_i^{\text{Sch}} - S_i^{\text{Cal}} \quad (4.13) \]

Similarly

\[ \Delta P_i^{(k)} = P_i^{\text{Sch}} - P_i^{\text{Cal}} \quad (4.14) \]

\[ \Delta Q_i^{(k)} = Q_i^{\text{Sch}} - Q_i^{\text{Cal}} \quad (4.15) \]
The terms of the power residuals equation are the differences between the scheduled and calculated values for real and reactive powers.

Expanding equations 4.11 and 4.12 in Taylor’s series about the initial estimate and neglecting all higher order terms results in the following matrix form of N-R method:

\[
\begin{bmatrix}
\Delta P \\
\Delta Q
\end{bmatrix} =
\begin{bmatrix}
J_1 & J_2 \\
J_3 & J_4
\end{bmatrix}
\begin{bmatrix}
\Delta \delta
\end{bmatrix}
\]  
(4.16)

Where \( \Delta P \) and \( \Delta Q \) are the real and reactive power mismatch vectors between specified value and calculated value respectively. \( \Delta|V| \) and \( \Delta \delta \) represent magnitude vectors bus voltage and angle respectively in an incremental form J1 through J4 are called Jacobian sub-matrices and the elements in the matrix are the partial derivatives of equations 4.11 and 4.12. For example, the diagonal and the off-diagonal elements of J1 are:

\[
\frac{\partial P_i}{\partial \delta_i} = \sum_{j \neq i} |V_i||V_j||V_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \\
(4.17)
\]

\[
\frac{\partial P_j}{\partial \delta_j} = -|V_i||V_j||V_{ij}|\sin(\theta_{ij} - \delta_i + \delta_j) \\
(4.18)
\]

Similarly the diagonal and off-diagonal elements of J2, J3 and J4 can be determined.

Thus, the Newton-Raphson method formulates and solves iteratively using the load flow of equation 4.16. This method begins with initial guesses of all unknown variables (voltage magnitudes and angles at load buses and voltage and angle at generator buses). The process of obtaining power-flow solution is continued until the power residuals are less than the specified accuracy \( \varepsilon \), i.e

\[
|\Delta P^{(k)}| \leq \varepsilon; |\Delta Q^{(k)}| \leq \varepsilon \\
(4.19)
\]

The convergence criteria for the N-R method according to (Etap, 2010), are typically set to 0.001MW and 0.0001Mvar. [11]
4.3.2 Gauss-Seidel Method

In numerical linear algebra, the Gauss–Seidel method, also known as the Liebmann method or the method of successive displacement, is an iterative method used to solve a linear system of equations.[9]

Though it can be applied to any matrix with non-zero elements on the diagonals, convergence is only guaranteed if the matrix is either diagonally dominant, or symmetric and positive definite.

There are two important characteristics of the Gauss-Seidel method should be noted. Firstly, the computations appear to be serial. Since each component of the new iterate depends upon all previously computed components, the updates cannot be done simultaneously as in the Jacobi method. Secondly, the new iterate depends upon the order in which the equations are \( x^{(k)} \) method. Secondly, the new iterate examined. If this ordering is changed, the components of the new iterates (and not just their order) will also change.[9]
4.3.2.1 Convergence

The convergence properties of the Gauss–Seidel method are dependent on the matrix \( A \). Namely, the procedure is known to converge if either:

i. \( A \) is symmetric positive-definite, or

ii. \( A \) is strictly or irreducibly diagonally dominant.

\[
\begin{align*}
    a_{11}x_1 + a_{12}x_2 + a_{13}x_3 + \ldots + a_{1n}x_n &= b_1 \\
    a_{21}x_1 + a_{22}x_2 + a_{23}x_3 + \ldots + a_{2n}x_n &= b_2 \\
    a_{n1}x_1 + a_{n2}x_2 + a_{n3}x_3 + \ldots + a_{nn}x_n &= b_n
\end{align*}
\]  

(4.20)

General Form for any row ‘i:

\[
x_i = \frac{c_i - \sum_{j=1, j \neq i}^{n} a_{ij}x_j}{a_{ii}}, \quad i = 1, 2, \ldots, n.
\]  

(4.21)

Calculating the Absolute Relative Approximate Error:

\[
|\varepsilon_a|_i = \left| \frac{x_i^{\text{new}} - x_i^{\text{old}}}{x_i^{\text{new}}} \right| \times 100
\]  

(4.22)

The iterations are stopped when the absolute relative approximate error is less than a pre-specified tolerance for all unknowns.
And since

\[ P_{\text{inj}} - jQ_{\text{inj}} = V_i^* \sum_{k=1}^{n} Y_{ik} V_k = V_i^* \{ Y_{ii} V_i + Y_{in} V_n + \cdots + Y_{in} V_i + \cdots + Y_{in} V_n \} \quad (4.23) \]

Then

\[ V_i = \frac{1}{Y_{ii}} \left[ \frac{P_{\text{inj}} - jQ_{\text{inj}}}{V_i^*} - Y_{ii} V_i - Y_{in} V_n - \cdots - Y_{in} V_i \right] \]

\[ (4.24) \]
Chapter 5 Technical Losses Calculations Using ETAP

5.1 Introduction to ETAP Software [10]

ETAP is a fully graphical Enterprise package. ETAP Base Package is a set of core tools, embedded analysis modules, and engineering libraries that allow you to create, configure, customize, and manage your system model. Core tools allow you to quickly and easily build 3-phase and 1-phase AC and DC network one-line diagrams with unlimited buses and elements including detailed instrumentation and grounding components.

Base Package includes an intelligent one-line diagram, element editors, verified and validated engineering device libraries, configuration manager, report manager, project and study wizards, multi-dimensional database, theme manager, data exchange, and user access management. Embedded analysis modules, such as Cable Ampacity, Cable Sizing, and Transmission Line Constants, provide integrated as well as stand-alone capabilities to design, analyze, and size equipment.

Network Analysis includes a powerful set of analytical tools that allow for simulation, prediction, design and planning of system behavior utilizing an intelligent one-line diagram and the flexibility of a multi-dimensional database. Network Analysis includes Arc Flash, Short Circuit, Load Flow, Motor Acceleration, and Load Analyzer modules.

ETAP allows you to easily create and edit graphical one-line diagrams (OLD), underground cable raceway systems (UGS), three-dimensional cable systems, advanced time-current coordination and selectivity plots, geographic information system schematics (GIS), as well as three-dimensional ground grid systems (GGS).
The program operation emulates real electrical system operation as closely as possible also ETAP combines the electrical, logical, mechanical, and physical attributes of system elements in the same database.

5.1.1 ETAP Grid-Distribution

ETAP GRID-Distribution is an integrated power system simulation, planning, protection, and real-time distribution management system software for visualizing, managing, optimizing and automating distribution networks from state-wide to city-wide power distribution networks.

5.1.2 ETAP Grid-Transmission

ETAP GRID-Transmission provides an intelligent Network Topology Builder integrated with ETAP’s Base and Network Analysis modules such as Transmission Line Model, SVC Model, HVDC Link, Load Flow, Fault Analysis, Capacitor Placement, Dynamic Stability, Reliability Assessment, Distance Protection, Substation Automation, Energy Management, and eSCADA system.

5.1.3 ETAP Real Time

ETAP Real-Time technology allows you to predict, control, visualize, optimize, summarize and automate your power system. Distributed and web-based technologies provide the tools to make informative decisions based on planned or unplanned events from any location.

5.1.4 Distribution Managament System

ETAP ADMS is an integrated electrical system design and real-time power distribution management system. ETAP ADMS incorporates SCADA, Distribution Management Applications & Outage Management System (OMS) functionality in a single solution.

5.1.5 Microgrid Controller

ETAP is used by microgrid developers and engineers for detailed analyses and sizing of distributed energy resources and associated equipment. Microgrid Master Controller brings the design to life by connecting the system model with real-time data.
5.1.6 Features of ETAP

- Unlimited AC & DC elements
- 1-phase (2 & 3 Wire), 2-phase (2 & 3 Wire), 3-phase (3 & 4 Wire)
- Unlimited buses: license dependent at run-time
- Nested views (composite networks & MCC)
- Power grid
- Synchronous & induction generators
- Photovoltaic array (PV Interconnection Study)
- Exciters, governors, & stabilizers
- Voltage & frequency dependent lumped load
- Cable, line, reactor, & impedance branches
- 2W & 3W transformers with voltage regulators
- 2W & 3W transformers with buried delta winding
- Open-Delta transformer
- Remote connectors
- Harmonic filter
- Static Var Compensator (SVC)
- Instrument transformers (CT & VT)
- Protective devices & meters
- Single & double throw switches
- Grounding switch
- Bus duct
- Batteries, DC motors, DC loads & branches
- Battery Chargers, Rectifiers & Inverters
- Uninterruptible Power Supply (UPS)
- DC-DC converters
5.2 Electrical Test Model

A single line diagram of the IEEE 14-bus standard system is shown in Figure 5.1.

![IEEE 14-bus Single Line Diagram](image)

Figure 5.1: IEEE 14-bus Single Line Diagram.

It consists of five synchronous machines with IEEE type-1 exciters, three of which are synchronous compensators used only for reactive power support. There are 12 loads in the system totaling 259 MW and 81.3 Mvar. Total generation includes real power generation of 272.6 MW and 108.83 Mvar of reactive power. Load bus voltages are maintained between 0.9 and 1.1 p.u. [12]
Chapter 5  Technical Losses Calculations Using ETAP

Table 5.1 shows the IEEE 14-bus components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buses</td>
<td>14</td>
</tr>
<tr>
<td>Branches</td>
<td>20</td>
</tr>
<tr>
<td>Generators</td>
<td>5</td>
</tr>
<tr>
<td>Power Grids</td>
<td>0</td>
</tr>
<tr>
<td>Loads</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 5.1: IEEE 14-bus components

Table 5.2 Bus Data for IEEE 14-Bus System

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Bus Voltage Magnitude Per Unit</th>
<th>Phase Angle Degrees</th>
<th>Generation Real MW</th>
<th>Reactive MVAR</th>
<th>Load Real MW</th>
<th>Reactive MVAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.060</td>
<td>0.0</td>
<td>232.4</td>
<td>-16.9</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>2</td>
<td>1.045</td>
<td>-4.98</td>
<td>40.0</td>
<td>42.4</td>
<td>21.7</td>
<td>12.7</td>
</tr>
<tr>
<td>3</td>
<td>1.010</td>
<td>-12.72</td>
<td>0.0</td>
<td>23.4</td>
<td>94.2</td>
<td>19.0</td>
</tr>
<tr>
<td>4</td>
<td>1.019</td>
<td>-10.33</td>
<td>0.0</td>
<td>0.0</td>
<td>47.8</td>
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<td>5</td>
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<td>1.6</td>
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<td>16.6</td>
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<td>0.0</td>
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</table>
IEEE 14 bus system is selected as case study to calculate the Technical losses using the ETAP software.

Figure 5.2: IEEE 14-bus test system.
5.2.1 Different cases of Load Flow Analysis in transmission circuit above

5.2.1.1 Case 1: Normal Loading Condition of The System (Actual loading of the system)

Figure 5.3: Normal Loading Condition
Table 5.3: Load Flow Rustles

<table>
<thead>
<tr>
<th>CKT / Branch</th>
<th>From-To Bus Flow</th>
<th>To-From Bus Flow</th>
<th>Losses</th>
<th>% Bus Voltage</th>
<th>% Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MW</td>
<td>Mvar</td>
<td>MW</td>
<td>Mvar</td>
<td>kW</td>
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</table>

Table 5.3 shows the result of the losses for the normal loading of the system the total losses is 13401.5KW And 30125.3 Kvar
5.2.1.2 Case 2: Light loading condition (-25% of the actual loading)

Figure 5.4: Light Loading Condition (-25%)
Table 5.4 shows the result of the losses for the normal loading of the system, the total losses is 5331.8KW and 3648.5 Kvar.
5.2.1.3 Light Loading Condition (−50% of the actual load)

Figure 5.5: Light Loading Condition (−50%)
Table 5.5  Load Flow Result

<table>
<thead>
<tr>
<th>CKT / Branch</th>
<th>From-To Bus Flow</th>
<th>To-From Bus Flow</th>
<th>Losses</th>
<th>% Bus Voltage</th>
<th>% Drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>Mvar</td>
<td>MW</td>
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Table 5.5 shows the result of the losses for the heavy loading of the system and the total losses is 2137.9KW and -12656.9Kvar
5.2.1.4 Heavy Loading Condition (+25% of the actual load)

Figure 5.6: Heavy Loading Condition (+25%)
Table 5.6 Load Flow Result

<table>
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<tr>
<th>CNT/Branch ID</th>
<th>From-To Bus Flow MW</th>
<th>To-From Bus Flow MW</th>
<th>Losses MW</th>
<th>% Bus Voltage</th>
<th>% Drop in Vbus</th>
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</table>

Table 5.6 shows the result of the losses for the heavy loading of the system and the total losses is 19916.2KW and 81945.4Kvar

5.2.1.5 Heavy Loading Condition (+50% of the actual load)

The system cannot operate on this heavy loading condition because exceed the maximum allowed loading point.
5.2.2 Discussion

From the results of load flow analysis cases it found that the losses in the lines were affected by the different situation of system loadings so that any changing in the loads will cause different quantities of losses in the system.

It found that when ever you increase the loading the losses increases and when you decrease the load the losses decreases.

Its noticed that in the case of light loading(-25%) , normal loading and heavy loading(+25%) the load supplied is an inductive load (positive reactive power sign). In the light loading case (-50%)

The supplied load is a capacitive load (negative reactive power sign) the reason behind this is because now you have too much energy supplied and less energy consumed which is very damaging to the synchronous electric machines.

In some other cases of IEEE buses systems (e.g. IEEE 9-BUS System) the results of the same loading conditions were as follows:
-When we increased the load the losses decreased!
-When we decreased the load the losses increased!

The minimum amount of losses were in the optimum situation of the system (actual loads)

But in our case (IEEE 14-BUS System) the results were very convenient because it's known that the incremental in loads causes increase in losses
Chapter 6:

Conclusion and Future Work

Conclusion 6.1

The project investigates the losses in power system technical and nontechnical losses. The mechanisms that used to determine the technical losses was discussed in details with it is equations.

a- Technical losses

The technical loss is the main component of the distribution loss.

Technical losses was simulated for the IEEE 14 bus system, this system was analyzed and the results of it was represented on tables (5.2, 5.3, 5.4, 5.5) various cases was done for the technical losses by varied loads (normal, light and heavy).

Also some other IEEE bus systems were investigated to be compared with the 14-bus system and figure out if it has the same results.

b- Nontechnical losses

Nontechnical losses (theft) ways were discussed and the ways to reduce it.
6.2 Future Work

6.2.1 Technical losses improvement

The following topics can be recommended for future researches

a- Network reconfiguration: It gives an option to handle the increased demand – and increases system reliability. Construction of more numbers of high voltage distribution lines as and where they are techno-commercially feasible.

b- Load research is needed

c- Regulating voltage in distribution circuit by automatic voltage booster

d- Power factor improvement, close to 1, by automatic power factor controller, using at different places.

Non-technical losses improvement 6.2.2

To improve the nontechnical losses there is many ways:

a- Replacement of defective meters by electronic meters / smart meters.

b- Development of process and ways for theft detection and suitable correction of the same.

c- Law enforcing and stringent action to the theft of power.

d- Customer oriented management approach, like implementation of call centre for 24 hours, improving customer care.
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1Dnyaneshwar Y. Watpade, 2P. M. Sonwane
1Maharashtra State Electricity Distribution Company Limited, Nasik
2K. K. Wagh Institute of Engineering Education & Research, Nasik [12]

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