NEUTRAL CURRENT MITIGATION IN LOW VOLTAGE INSTALLATIONS

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Degree of Master of Science

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Abstract

Power quality problems with the ever increasing use of electrical and electronic loads has risen to a greater extent. It is quite common to blame the supply authority for lower power quality issues. CEB and LECO the main utilities in Sri Lanka are blamed of this problem. But what the consumers do not understand is that power generation is not low in power quality. It is the consumer himself, who makes the network a poor quality one. The bitter part is that consumers are in the losing side due to this poor network quality, which they take time to realize.

This research was intended to consider the energy loss caused due to unbalance and heavy neutral currents. Heavy neutral currents can be for two reasons. First may be due to unbalance in the network and second could be due to presence of harmonics. This current is a loss to the system in terms of cable losses, over capacity network requirement and added operation and maintenance cost. In turn presence of harmonics and unbalance currents distorts the voltage supplied to other equipment which in turn produces unbalance currents.

Several solution has been found by engineers to this problem. Finding the correct solution is important in this concept. The solution can be easily divided into two categories as energy efficient solutions and energy inefficient solution. For an example if a facility is having high neutral current with high temperature in the neutral current, one solution will be to overate the neutral cable to accommodate the extra current. But on the other hand this will be an inefficient solution, which is trying to accommodate the waste energy comfortably. But if a solution is looked into reducing the neutral current by phase balancing or reducing harmonics, this will be an energy efficient solution. I have extensively discussed energy efficient solutions as a rectification to this problem and other solutions should be discouraged.

The case studies done at varying consumer location proved a much promising solution to, this problem with a sustainable saving from the bills. I have also

implemented a logical unit which will reduce the time consumed for manual phase swapping by fast load flow analysis of the network.

Declaration

The work submitted in this dissertation is the result of my own investigation, except where otherwise stated.

It has not already been accepted for any degree, and is also not being concurrently submitted for any other degree.

M I S Ameer
1st MARCH 2010

We endorse the declaration by the candidate.

Reinzie Fernando

UOM Verified Signature

Upul Jayatunga

Contents

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My sincere thanks go to the officers in Post Graduate Office, Faculty of Engineering, University of Moratuwa, Sri Lanka for helping in various ways to clarify the things related to my academic works in time with excellent cooperation and guidance. Sincere gratitude is also extended to the people who serve in the Department of Electrical Engineering office.

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Lastly, I should thank many individuals, friends and colleagues of my batch who have not been mentioned here personally in making this educational process a success. I could not have made it without your supports.

List of figures

List of tables

Chapter 1

1.0 Introduction

1.1 Background

The key aspects of electrical system have been introduced from over 100 years. Starting from there people have used different ideas and mechanisms to generate, transmit, distribute and utilize electricity. A power utilization system in Sri Lanka would be most commonly at low voltage, which is 3 phase 400V 50Hz. Ideally and as we have learnt 3phase 400V supply to a load is balanced. This means all the phases are equal in magnitude at 230V and the phases are equally spaced at 120° phase angles. Also if it is an ideal load the currents are equal in magnitude and equally spaced. Ideally the neutral current will be zero.

But in real industrial life we hardly find such situations. Most of the time supply voltages from source are not balanced. The voltage of each phase is not at 230V and they are not equally spaced. Also on the other hand when it comes to a set of single phase loads mostly the currents are not equal. Even in the case of 3phase loads there is a possibility that currents can be unbalanced. The currents of a load centre are not equal in magnitude and not equally spaced. In most situations the sinusoid current waveform is totally distorted with foreign components added due to the non linearity of the loads.

Harmonics has been a nuisance to operational engineers causing problems in the installation with heavy currents in the neutral and supply voltage entirely distorted. Harmonics is quite common these days due to the heavy use of electronic equipment including switch mode power supplies, variable speed and frequency drives, uninterrupted power supplies just to name a few.

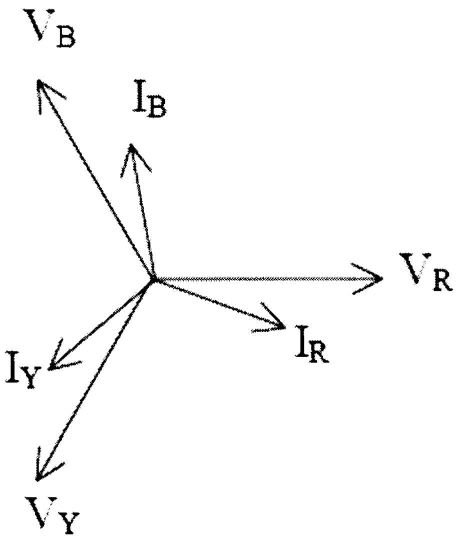


Figure 1 : A balanced system

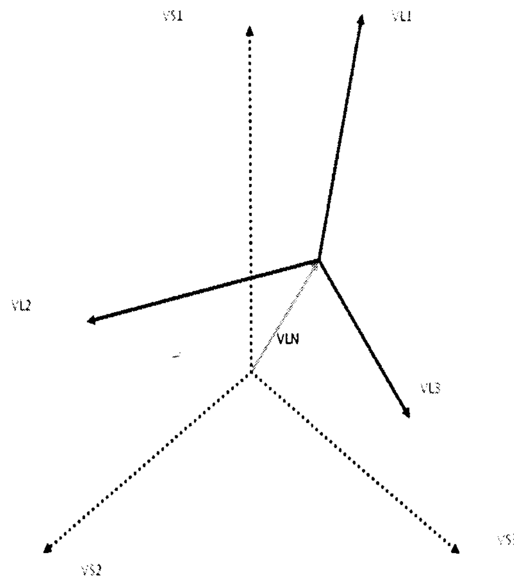


Figure 2 : An unbalanced system

The two figures above depict a balanced and an unbalanced system in a phasor diagram. Interesting point to note as in figure 1 of a balanced system is that the phase angle of any voltage phase with the corresponding current phase is the same. Whereas in the case of phase unbalanced system as in figure 2 the phase angles between the phases will be different. Therefore the neutral point will be shifted from the common ground and there will be a voltage of V_{LN} compared to ground at the neutral node. [2]

Unbalance voltages and unbalance currents go hand in hand. Which means unbalance current causes an unbalance voltage and this unbalance voltage causes an unbalance current. Unbalance loads and presence of non linear loads is the reason for unbalance irregular current waveforms. Unbalance phase currents causes a flow of neutral current. In an ideal system neutral current should be zero. But practically there exist a neutral current flow. The higher the imbalance the higher will be the neutral current. The plot below is typical case of a LV installation where the phases are unbalance and there is a considerable neutral current.

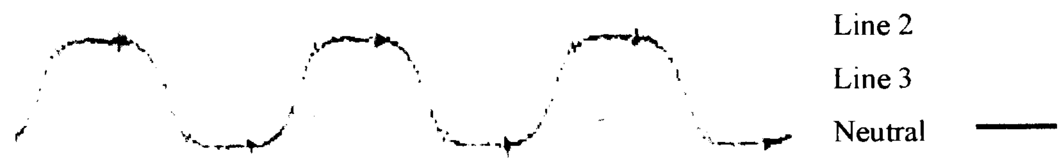


Figure 3 : Current waveforms of a load centre

The figure above is a very natural case of a waveform analysis. The figure shows one cycle each of each phase and the neutral plotted on a common time axis. The waveforms are totally distorted with unbalances and presence of harmonics in the system. Hence the resultant is a considerable neutral current showing a clear 3rd harmonic.

From the recent past this problem has raised due to the recent heavy use of electronic equipment. Switch mode power supplies that are very common in electronic devices is the main cause of the problem. In this case even if the load currents are balanced, there could be a neutral current due to the non linearity. This caused due to the generation of other frequency components higher than 50Hz, which reflects in the neutral. At times the neutral current can be more than the phase current. It is quite common in industry to have a neutral current twice as the phase current or at least one rating higher than the phase. This has been the practice by many electrical designers, installing contractors and consultants. It is no more a good practice with the rising cost of copper cables.

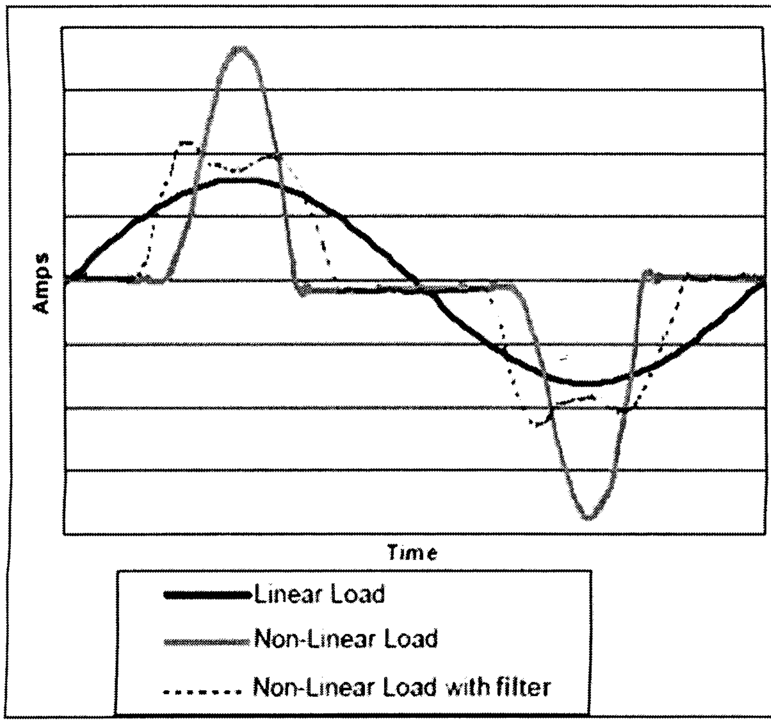


Figure 4 : Current waveforms of a linear, non linear and non linear with filtration system

The figure (Figure 4) above illustrates the behavior of a current waveform to linear, non linear and non linear with filtration loads. As per the figure a linear load will have a perfect sine wave with absolutely no distortion. In the case of a non linear load the waveform is entirely distorted having a very high peak to the original wave and the rise and fall is shifted from the zero crossings. The third waveform is a correction done to the distorted waveform by clipping the peak to reduce the unbalance and distortion. This filtration used has tried to match the non linearity to a close ideal sine waveform. But still the waveform is distorted.

This whole power quality problem is not something happening instantaneous nor for a short period. But the unbalances will remain in the system for considerable amount of time or even sometimes as long as it is rectified. It has always been the practice to blame the power supplier pointing the finger at unbalance voltage phase. But the bitter part is that the customer loads are not balanced nor harmonics is taken care of. Balancing current and reducing harmonics will be economic and energy efficient options rather than trying to balance phase voltages by variable transformers.

1.2 Motivation

The idea of this research is to find techniques and methodologies to keep the neutral current low. This will mean keeping the phase currents of the load balanced as well as keeping the harmonic levels at a tolerable value. Hence the voltage of the system will be balanced or more precisely the unbalance voltages will be reduced. The whole intention of this approach is to stop complaining electricity authorities over the issues related with loads. Ideally if all consumers can keep the currents balanced and harmonics reduced the distortion in the voltage waveform is minimized. While intending this concept the consumer also should not forget that the benefits he is going to achieve by fulfilling this criterion. Some of the major benefits are listed below, but not limited to those.[4] The benefits will be discussed in length in the later chapters.

- Reduction of energy losses from cable currents
- Overloading of cables
- Reduce on extra investment for cables
- Reduce losses due to heating
- Keep phase voltages balanced
- Reduced cost of maintenance
- Overheating or derating of transformer
- Overloading neutral conductors
- Excessive heating of wiring and connections
- Damaging of capacitor banks
- Resonance
- Malfunction of electronic equipment
- Communication interference
- Distorted supply voltage
- Increased power losses
- Logic faults in digital devices
- Errors in power metering
- Inadvertent thermal tripping of relays, circuit breakers and protective devices.

Chapter 2

2.0 Problems Faced Due To Heavy Neutral Currents

2.1 Introduction

The problems faced due to the unbalance issues are enormous across different type of industries, distribution systems, commercial and residential installations. The problems are faced mostly in operations by maintenance and operational staff. Most problems are detected only after engaging the system into operations, which is quite unprofessional. Some problems remain unsolvable due to the unplanned design and high investment required to change. Considerable amount of time, money and losses could have saved if proper initial design was done. However some common problems to a range of industries will be discussed in this chapter. Some of the cases are my personal experiences as an operational engineer and a consultant.

2.2 Voltage unbalance problems

2.2.1 Three phase motors

Voltage unbalance is extremely harmful to the proper operation and life of a three-phase motor. Probably the highest impacts ever recorded due to unbalance. When line voltages supplying an induction motor are not equal in magnitude several problems occur. These are AC asynchronous machines with internally induced rotating magnetic fields. The magnitude is proportional to the amplitude of the direct and/or inverse components. The rotational sense of the field of the inverse component is opposite to the field of the direct component. Hence, in the case of an unbalanced supply, the total rotating magnetic field becomes ‘elliptical’ instead of circular. Induction machines face three kinds of problems due to unbalance.

First, the machine cannot produce its full torque as the inversely rotating magnetic field of the negative-sequence system causes a negative braking torque that has to be subtracted from the base torque linked to the normal rotating magnetic field. [2]

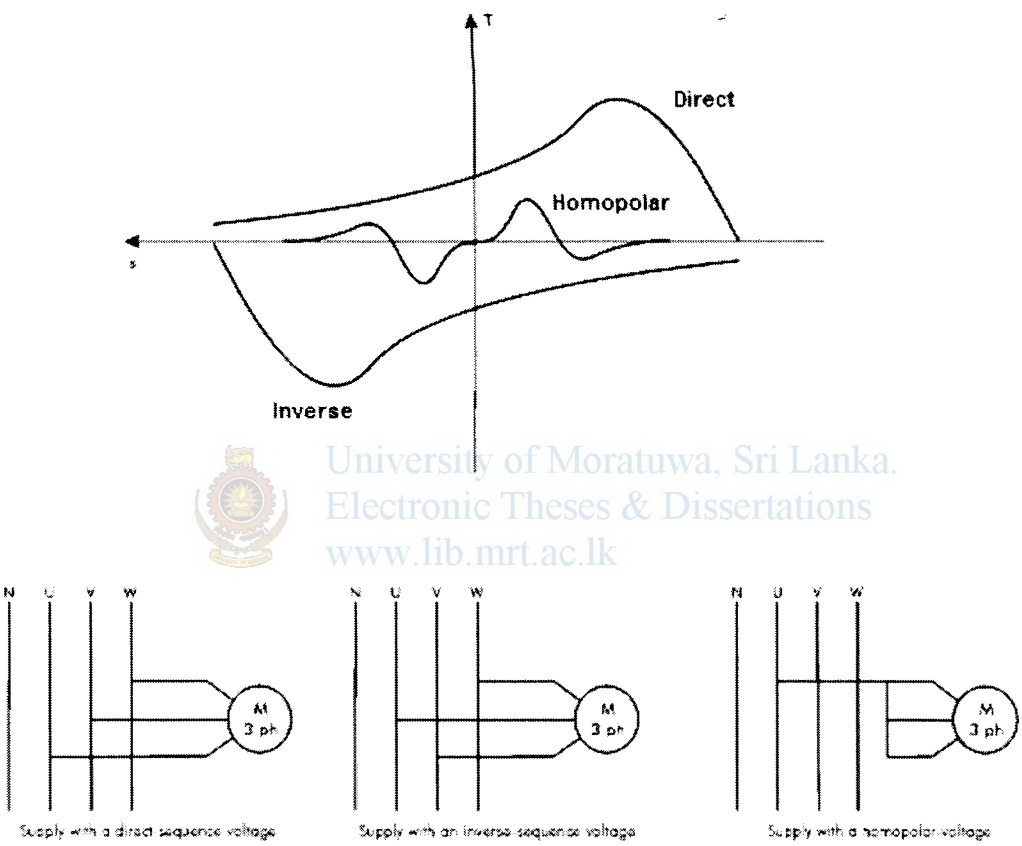


Figure 5 : Torque – speed curves under unbalance conditions

Figure 5 shows the different torque-speed characteristics of an induction machine under unbalanced supply. The actual steady-state curve is the weighted sum of these curves with the squared unbalance ratios as weights as the torque scales with the square of the load. It can be seen that in the normal operating region, being the almost straight line section of the 'Direct' curve (the part starting at the top of the curve, eventually crossing the horizontal axis at synchronous speed), 'Inverse' curve and 'Homopolar' curve are both negative.

Secondly, the bearings may suffer mechanical damage because of induced torque components at double system frequency.

Finally, the stator and, especially, the rotor are heated excessively, possibly leading to faster thermal ageing. This heat is caused by induction of significant currents by the fast rotating (in the relative sense) inverse magnetic field, as seen by the rotor. To be able to deal with this extra heating, the motor must be derated, which may require a machine of a larger power rating to be installed.

Unbalanced voltages on three-phase motors produce large unbalanced currents, overheating of the motor, shorter insulation life, excessive losses and wasted energy. Also, significantly unbalanced line currents make the problem of providing adequate overload protection more difficult.

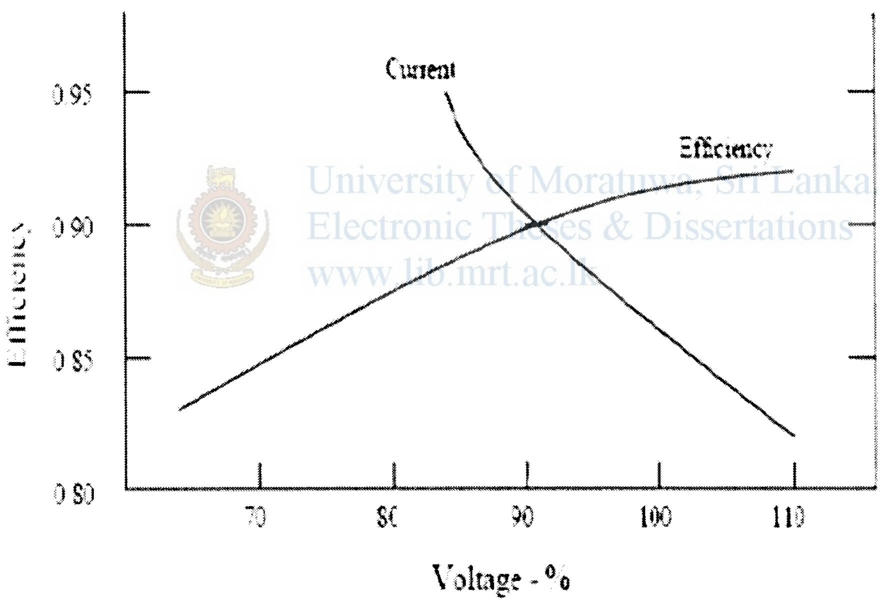


Figure 6 : Variation of current and efficiency of a motor with voltage unbalance [1]

The above graph in Figure 6 illustrates the variation of the current with the variation of the voltage unbalance. Unbalanced voltage produces a corresponding negative sequence flux causing unbalanced currents in excess of those under balanced voltage conditions. It is important to note that excessive current creates excessive heat, which in turn, shortens insulation life; insulation breakdown is permanent. In the phase with the highest current, the percentage increase in temperature rise will be approximately two times the square of the percentage voltage unbalance. Thus, a 3% voltage unbalance will increase temperature rise about 3×3×2 or 18%. Such an unbalance could also result in electromechanical vibration, leading to bearing failures. In addition, noise and vibration will be particularly severe on high rpm motors.

Also the graph describes how the efficiency of the motor drops with the variation of the imbalance. It is important to keep the voltages balanced to save on energy, whilst obtaining the maximum output from the motor.

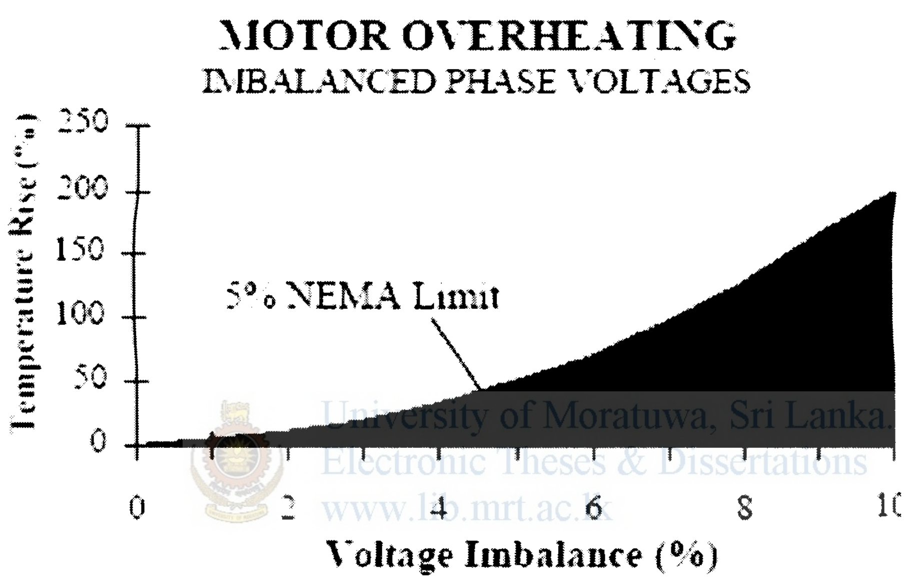


Figure 7 : Motor overheating with voltage imbalance [1]

The above graph in Figure 7 is a classic example of temperature rise with the voltage imbalance. A danger zone is marked to describe the risk of degradation of insulation due to the temperature rise. Higher the voltage imbalance higher will be the probability for an insulation failure. NEMA stands for National Electrical Manufacturers Association, which allows a voltage imbalance of 5% for safer operation.

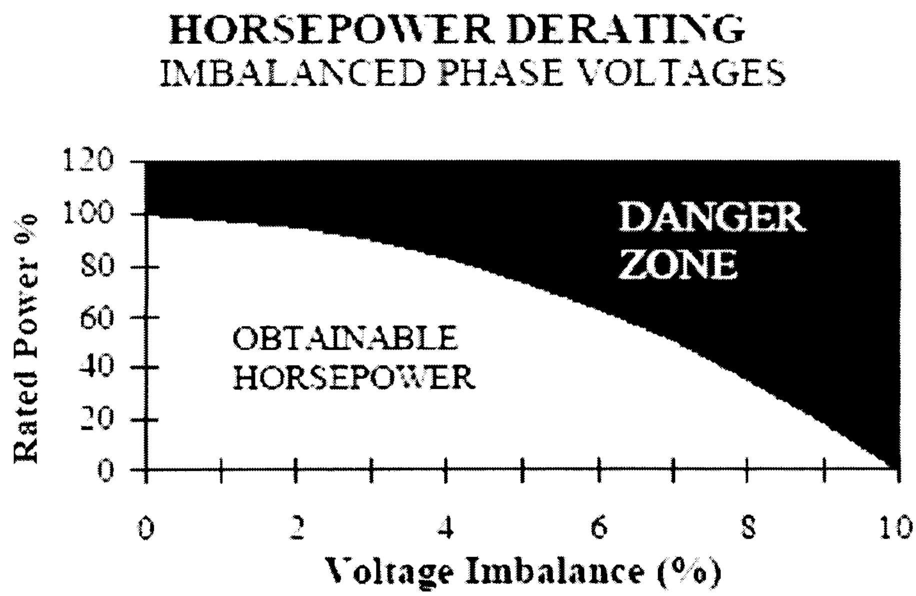


Figure 8 : Decrement of rated power with voltage imbalance [1]

The plot above in Figure 8 shows how the rated power output of a motor will reduce with the increase of the imbalance.

2.2.2 Electrical network

The capacity of transformers, cables and lines is reduced due to negative sequence components. The operational limit is in fact determined by the RMS rating of the total current, being partially made up of 'useless' non-direct sequence currents as well. This has to be considered when setting trigger points of protection devices, operating on the total current. The maximum capacity can be expressed by a derating factor, to be supplied by the manufacturer, which can be used to select a larger system, capable of handling the load.

Transformers subject to negative sequence voltages transform them in the same way as positive-sequence voltages. The behaviour with respect to homopolar voltages depends on the primary and secondary connections and, more particularly, the presence of a neutral conductor. If, for instance, one side has a three-phase four-wire connection, neutral currents can flow. If at the other side the winding is delta connected, the homopolar current is transformed into a circulating (and heat-causing) current in the delta. The associated homopolar magnetic flux passes through constructional parts of the transformer causing parasitic losses in parts such as the tank, sometimes requiring an additional derating.

2.3 Current unbalance problems

Current unbalance is seen much as a starting point for this whole problem. In a most common distribution system there will be a 4 wire system with a single set for each phase and a neutral wire. Some critical problems are listed below with regard to phase current unbalances.

- Overloading of single set of cables
- Heating of high current carrying cable
- Possible insulation failure of the high current carrying cable
- Neutral overloading
- Energy loss in neutral current
- Failures in breakers, contactors, terminals etc.

Current unbalance occurs with a bad design of load division. Special care has to be taken when multiple single phase loads are included in a load centre. The diversity and simultaneity of the single phase loads need to be considered. Following is a classic case in a Sri Lankan industrial installation. The current imbalance is more than 25%. The current RMS values logged over a period of time are given below.

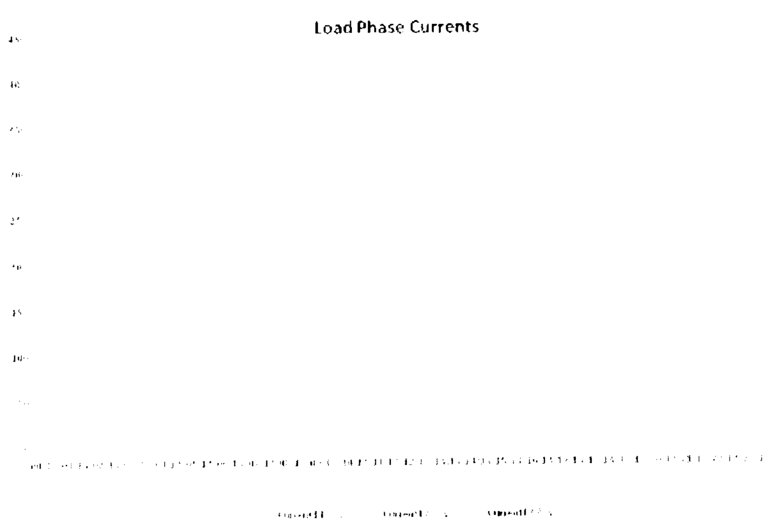


Figure 9 : Phase currents of an industrial installation

The problem raised concern over several parties due to a constant failure of the contactors of the change over switch. One phase contactor failed for the second time after two replacements of the change over switch which revealed a subsequent over loading in that phase. Previous change over switch was replaced by the client without proper investigation of the cause of the problem. The following is a picture (Figure 10) of the single phase burnt change over switch. The burnt phase is clearly visible with burnt marks.

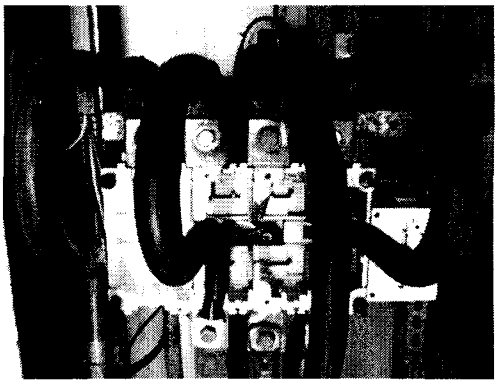


Figure 10 : Burnt change over switch of an installation

2.4 Harmonics problem

Harmonic currents generated by non linear mainly office equipment increase power system heat losses and the power bills of end users. Generally harmonic problems in office buildings are caused by nonlinear loads causing harmonic current injection[5]. The injected current is propagated to all distribution circuits and leads to harmonic voltage distortion on the system. Harmonic currents can cause such problems as

- Overloading neutral conductors
- Damaging of capacitor banks
- Resonance
- Malfunction of electronic equipment
- Communication interference
- Logic faults in digital devices
- Errors in power metering
- Inadvertent thermal tripping of relays, circuit breakers and protective devices.

The 3rd and other triplen harmonic currents are additive as they return in the neutral conductor. Because of this, neutral conductors will often carry very heavy currents when non-linear loads are present. These currents have been known to cause overheating and failures of the neutral conductor. In addition, harmonics will increase I^2R and eddy current losses in transformers and other distribution equipment such as UPS systems. These excessive losses can cause transformers to overheat even when they are relatively lightly loaded. This is further described in the following equations and the waveforms given below. As it is illustrated the third harmonic components present in the phase currents will not cancel out in the neutral but add up. Therefore at times the neutral current could be more than the phase current.

$$I_{N,rms} = \sqrt{(I^2_{a,rms} + I^2_{b,rms} + I^2_{c,rms})}$$

$$I_{N,rms} = \sqrt{3} * I_{phase,rms}$$

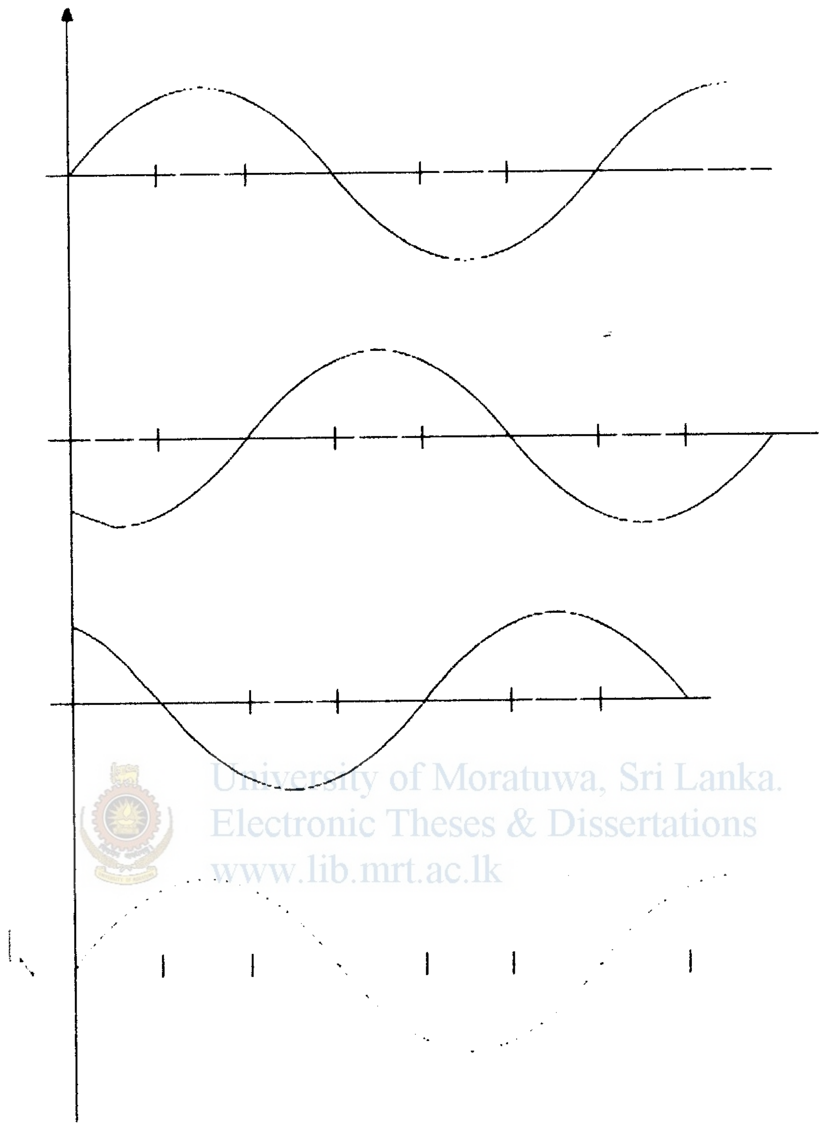
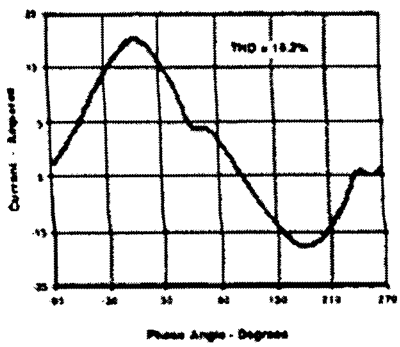


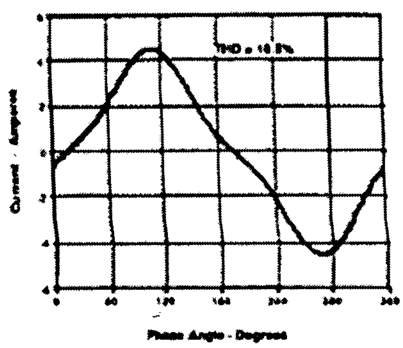
Figure 11: Effects of presence of harmonics in phases to the neutral

Non-linear loads, such as computers, emergency lighting, fluorescent lighting, etc, are becoming ever more present and create high levels of harmonic current which can add-up in the neutral, creating ever serious problems. Some plots of common equipment used in the day today life are given below in Figure 12. The distortion in these current waveforms will be seen due to harmonics. [6]

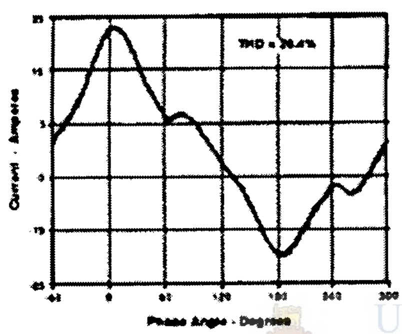
Microwave Oven Current Waveform #1



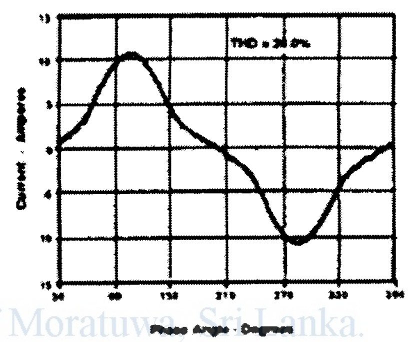
Weed Eater Current Waveform



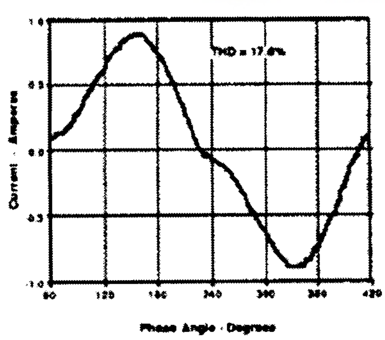
Microwave Oven Current Waveform #2



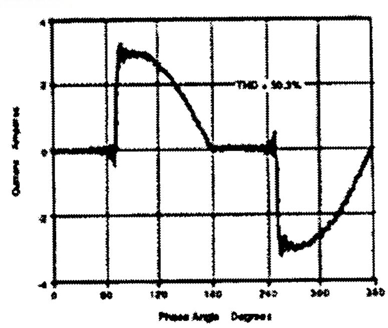
Vacuum Cleaner Current Waveform



Fluorescent Desk Lamp Current Waveform



Light Dimmer Current Waveform



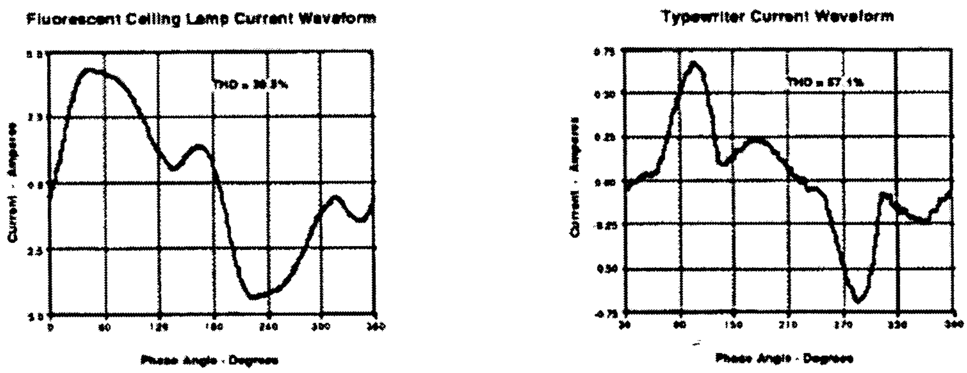


Figure 12 : Current waveforms of different loads

For fluorescent lighting fixtures with conventional magnetic ballasts, the third harmonic content is typically in the range of 13% to 20% of the fundamental 50 Hz frequency. Electronic ballasts generate an even higher third harmonic component, as high as 80%.

Overheated transformers (K Factor), motors, and standby generators that are exposed to significant levels of harmonic currents can suffer serious increases in operating temperature. In addition, excessive current in the neutral conductors not only overheats the conductors, possibly causing damage to insulation, but also can be reflected back into the 3-phase transformer winding as a circulating current, causing additional heat. Power Factor Correction Capacitors (PFCC's) can also overheat due to harmonic distortion on line voltage in the power system. Since the impedance of a capacitor decreases as the frequency of the applied voltage increases, excessive current can flow through the capacitor. Capacitors can also form a resonant circuit with inductive elements in the system, which will create a measurable increase in the voltage across the capacitor.
Lighting ballast capacitors are also susceptible to heat caused by high-frequency currents; frequent failures of this type are indicative of the presence of harmonics in the system. Harmonics can be cause of inefficient distribution of power, power line carrier (PLC), eg. Clocks and Energy Management Systems (EMS)

Chapter 3

3.0 Standards & Regulations

3.1 Why Standards?

This chapter will be concentrated on standards governing the problem of phase unbalances and neutral currents. This is the only way a restriction can be imposed on consumers to make sure power distribution quality is maintained. The levels are given only to maintain an acceptable power quality. But how much a large consumer is loosing due to not maintaining at least the levels when he can easily do is the main concern of this whole research study.

In a Sri Lankan context I have never come across a situation where the consumer is blamed of low power quality. The only charge which can be closest based on power quality issue is the maximum demand charge which in turn is the power factor of the load centre for large consumers. Therefore large consumers invest on power factor correction capacitor banks to keep the maximum demand low, because the financial payback is acceptable in this case. But other than that no other low power quality penalties exist in the tariff structure.

Due to the above fact that low power quality is not penalized, we could see many issues in the power system of Sri Lanka. Many power quality problems in the system are due to the load centres being of low quality concern. One side of the story is that consumers are not at all concern over balancing their power system. They are unaware of the losses due to unbalance system. Balancing is only during the design which the electrical design engineer will take care of and after that it has not been of concern to anyone. The system under operation is entirely different from what it was installed after few years.

On the other hand various non standardised components are used across different consumers. Low quality fluorescent ballasts, low quality drives and computers and other equipment manufactured without standards are flooding the market. The whole issue of importing low quality components has caused the power system of Sri Lanka to suffer.

For an example from my personal experience the feeder line reaching to Batticloa all the way through Polonnaruwa is full of power quality problems. Power sags, harmonics, voltage variations are just to name a few issues. This line is feeding rice mills with huge motors and the quality has not been anyone's concern.

3.2 Relevant Standards

Several standards of different international standard organizations and professional bodies were studied for this research. Unfortunately there exist neither Sri Lankan standard for power quality nor an adopted stringent rule for any international standard. Some of the major governing bodies of power quality standard are given below.

- International Electrotechnical Commission (IEC) of London, England
- Institute of Electrical and Electronics Engineers (IEEE) of USA
- British Standard (BS)
- European Standard (EN)
- National Electrical Manufacturers Association (NEMA)

I had visit to several libraries and standard organizations to study these standards. Unfortunately these are not available free of charge. These are sold not at a nominal price. This could be a reason for not adopting standard due to limitation in accessibility. A summary of standards is given below.

3.2.1 IEC

- The ratio of the negative or zero sequence to the positive sequence is given as the imbalance percentage.

$$U_u = (U_i / U_d) * 100 \%$$

$$U_u = (U_h / U_d) * 100 \%$$

$$I_u = (I_i / I_d) * 100 \%$$

$$I_u = (I_h / I_d) * 100 \%$$

Where,

U_u is the voltage unbalance

U_i is the voltage inverse(negative) sequence

U_d is the voltage direct(positive) sequence

U_h is the voltage homopolar(zero) sequence

I_u is the current unbalance

I_i is the current inverse (negative) sequence

I_d is the current direct (positive) sequence

I_h is the current homopolar (zero) sequence

- Limits for the unbalance ratio defined by above equation is less than 2 % for LV and MV systems and less than 1 % for HV, measured as 10-minute values, with an instantaneous maximum of 4 %.

- Standard 61000-3-2 and 61000-3-3 describes harmonics and their tolerable limits. Equipments are divided into different classes as class A, B, C and D. Following is the table for class D equipment.

Harmonic	Maximum permissible harmonic current per watt (mA/W)
3	3.4
5	1.9
7	1.0
9	0.5
13	0.35
Other odd up to 39	3.85/n

Table 1 : Harmonics regulations on IEC

3.2.2 BS EN 50160

- Imbalance standard is given as negative sequence RMS to be 2% of the positive sequence RMS as the described testing method in the standard.

- This standard also gives the limitations for the harmonics levels. The harmonic order is divided into multiple harmonic, odd and even harmonics. U_n is the RMS value of the harmonic as a percentage of the fundamental.

Odd Harmonic				Even Harmonic	
Not a multiple of 3		Multiple of 3			
Order	**U_n(%)**	**Order**	**U_n(%)**	**Order**	**U_n(%)**
5	6.0	3	5.0	2	2.0
7	5.0	9	1.5	4	1.0
11	3.5	15	0.5	6 to 24	0.5
13	3.0	21	0.5		
17	2.0				
19	1.5				
23	1.5				
25	1.5				

Table 2 : Harmonics regulations on BS EN

3.2.3 IEEE

In contrast IEEE describes the standards of the harmonic levels as below. This is a much simpler categorization and description of the similar standard. This is described in IEEE519 standard.

- The utility is responsible for maintaining quality of voltage waveform

- The customer is responsible for limiting harmonic currents injected onto the power system.

Bus voltage	Maximum individual harmonic component	Maximum THD (%)
69 kV and below	3.0%	5.0%

69 to 161kV	1.5%	2.5%
Above 161kV	1.0%	1.5%

Table 3 : Voltage regulations on IEEE

3.2.4 NEMA Standards

On NEMA standards maximum deviation of voltage is defined as below.

Voltage Unbalance = Maximum Deviation from mean of (Va,Vb,Vc)/Mean of Va,Vb,Vc

Realising that voltage unbalance causes extra losses, in order to safeguard motors from overloading NEMA has developed a derating curve as shown by Figure 13. This curve assumes that the motor is already delivering the rated load. According to this curve it is required that any motor should be built to handle 1% unbalance and thereafter it should be derated depending on the level of unbalance. For example if the unbalance is 3% a 10kW motor should be loaded up to only 9kW. If 10kW of power is to be developed with 3% unbalance the motor should be rated to about 12kW or should have a service factor of 1.15. Operation of an induction motor above 5% voltage unbalance is not recommended.

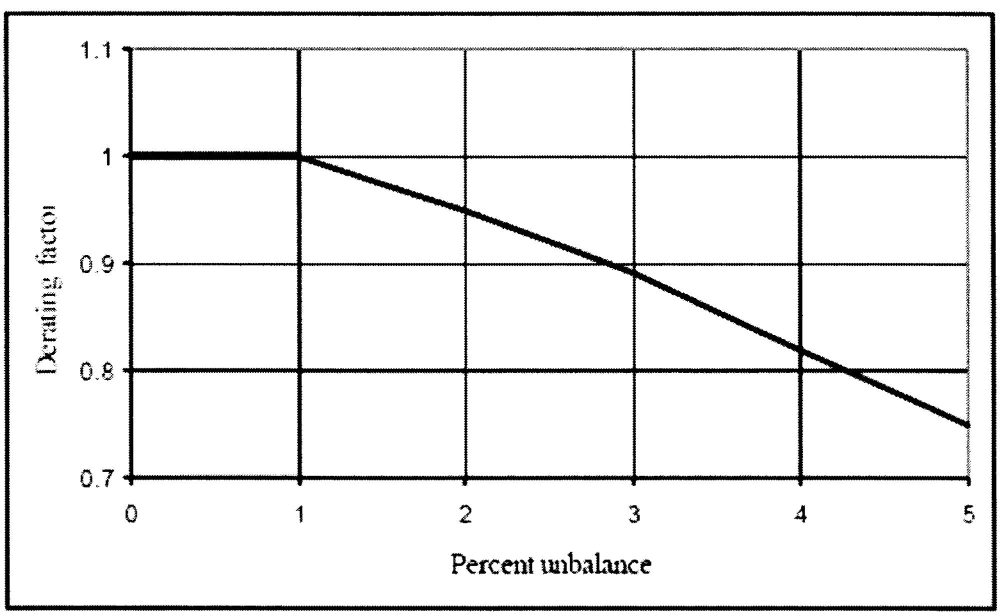


Figure 13 : Motor derating with percentage unbalance

Chapter 4

4.0 Prevention before Cure

4.1 Why prevention?

This power quality problem is not something new to the world. From the day of power distribution the problem is experienced. Different type of solutions is available in the industry from a range of brand names. Unfortunately industrial practice over this quality issue has been cure rather than prevention. Cost factor for harmonic filters can be named as one reason for a curing process rather than prevention in the initial stage.

What is forgotten by power consumers is that how much the facility is losing in terms of energy and process inefficiencies due to not incorporating a quality power system. The losses associated with this power quality problem were discussed in detail in the previous chapter and I will be discussing few remedial measures in this chapter.

4.2 Prevention of current imbalance

As already discussed unbalance in current will cause several problems in the system and is the cause for the unbalance in voltage. Heavy neutral current, cable overloading, breakers overloading, temperature rise of cables and components are to name a few. There is no complex current balancing method other than proper load distribution to phases and analysis of currents in phases in regular maintenance work. The most economical and viable methodologies is feeder swapping to balance load currents. This can be done during a maintenance program after identifying the correct swapping.

4.2.1 Electrical system designer's role in avoiding the problem

The discussions and interviews conducted with most junior and senior electrical installation designers prove that they have a major role to play in reducing the current imbalance and neutral current problems. Lot of issues arising after the installation during operation can be solved at the level of designing. As the installation designer is the first person who come into play of the distribution system it is important he plays a correct role. Some facilities encounter unsolvable problems due to bad designs. Common proposals are given below for the designer to follow.

- Design in a way that 3 phase power is supplied to all major load points, to the lowest point downstream of the network.

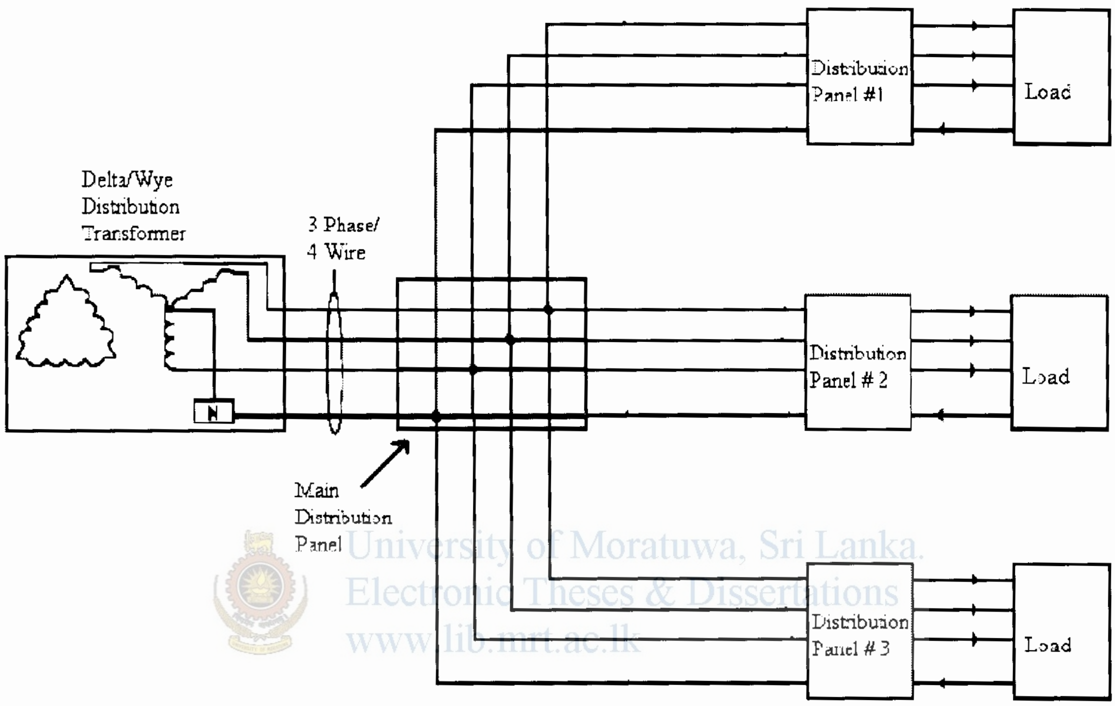


Figure 14 : A well designed network for easy phase balancing

- Take extra effort in dividing the loads to 3 phases. This will need a clear understanding of the loading patterns of the facility with the diversity and simultaneity of the loads.

4.2.2 Electrical maintenance engineer's role in avoiding the problem

Maintenance engineers of the electrical network are the persons who will be closest to this problem of phase unbalance. They will exactly know at what periods which phases of which feeder gets overloaded. Most of the time they will encounter the first glimpse of the problem either as an overheating or high neutral current. Sometimes unfortunately they will not realize until the problem worsens to a breaker failure or short circuit due to insulation damage.

Suggest maintenance engineers continuously monitor the present operating condition and collect as much as data by power analysis for possible swapping during the next maintenance. The criterion should be minimum energy loss or in other words lowest neutral current in the network. The saving in the system will be enormous in terms of energy loss, reduced maintenance costs and reduced nuisance tripping.

A logical unit is proposed in the next chapters for easy guidance to solve the above problem. If correct data can be inserted to the system a suggestion for load transfer is given as an output.

4.3 Prevention of voltage imbalance

Establishment of zero voltage unbalance on a distribution system is clearly impossible due to the randomness of the connection and disconnection of single phase loads, uneven distribution of single-phase loads on the three phases and inherent asymmetry of the power system. However, there are utility system level mitigation techniques as well as plant level mitigation techniques that can be used to improve the voltage unbalance and its effects.

Utility level techniques:

- Redistribution of single-phase loads equally to all phases.
- Reduction of the system unbalance that arise due to system impedances such as those due to transformers and lines.
- Single-phase regulators have been suggested as devices that can be used to correct the unbalance but care must be exercised to ensure that they are controlled carefully not to introduce further unbalance.
- Passive network systems and active power electronic systems such as static var compensators and line conditioners also have been suggested for unbalance correction. Compared to passive systems, active systems are able to dynamically correct the unbalance.

Plant level techniques:

- Load balancing.
- Use of passive networks and static var compensators.
- Equipment that is sensitive to voltage unbalance should not be connected to systems which supply single-phase loads.
- For certain applications, there is a possibility of reducing unbalance by changing the operating parameters. In order to reduce the influence of negative sequence currents, causing negative sequence voltage drops, on the supply voltage, low internal system impedance is required. This may be achieved by connecting the unbalanced loads at points with higher short circuit level, or by other system measures to reduce the internal impedance.
- Effect of voltage unbalance on ac variable speed drives can be reduced by properly sizing ac side and dc link reactors.

4.4 Prevention of harmonic problems

There are a number of approaches to avoiding harmonic problems. These include:

1. Specifying equipment that does not create harmonics
2. Correcting harmonics
3. Oversizing neutral wiring
4. K-rated transformers

Specifying equipment that does not create harmonics

In the case of networking equipment, the problem is solved because of the IEC regulations. In the case of PCs, it is more difficult since a large amount of the harmonic contribution comes from the monitor. One approach is to use PCs and monitors with lower power draw overall, such as the use of LCD monitors or laptop PCs. This avoids both building wiring and transformer problems.

If a UPS is used in conjunction with the equipment, then in some cases the UPS can correct or eliminate the harmonics. Some single phase UPS like the APC Symmetra eliminates neutral current entirely. If a power factor correcting UPS is used to power clusters of PCs, the harmonics problem cannot pass upstream to the building wiring or power transformers. This approach has the advantage that it can be retrofit to an existing building, and used with existing loads. It also corrects both the wiring and the transformer issues. For other types of loads, such as large industrial motor drives which are not covered by the harmonic regulations, specialized products are available that can absorb harmonics near the source.

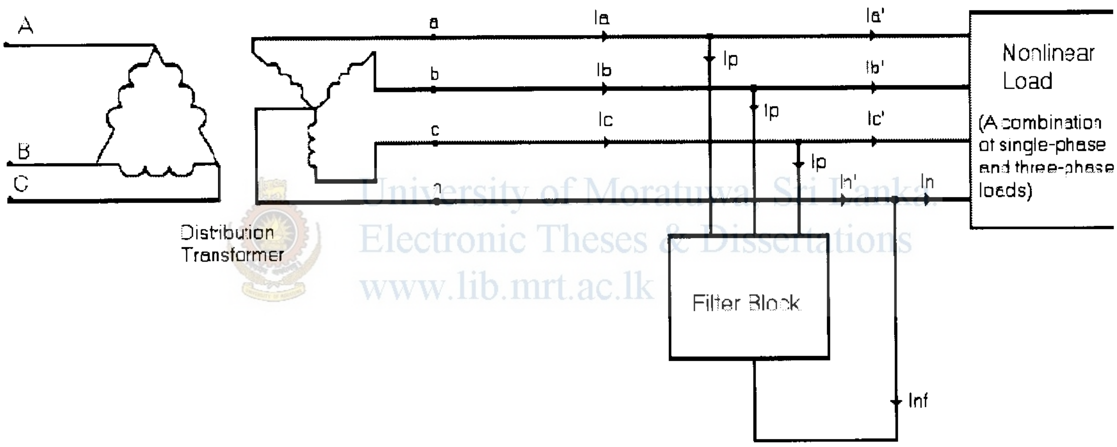
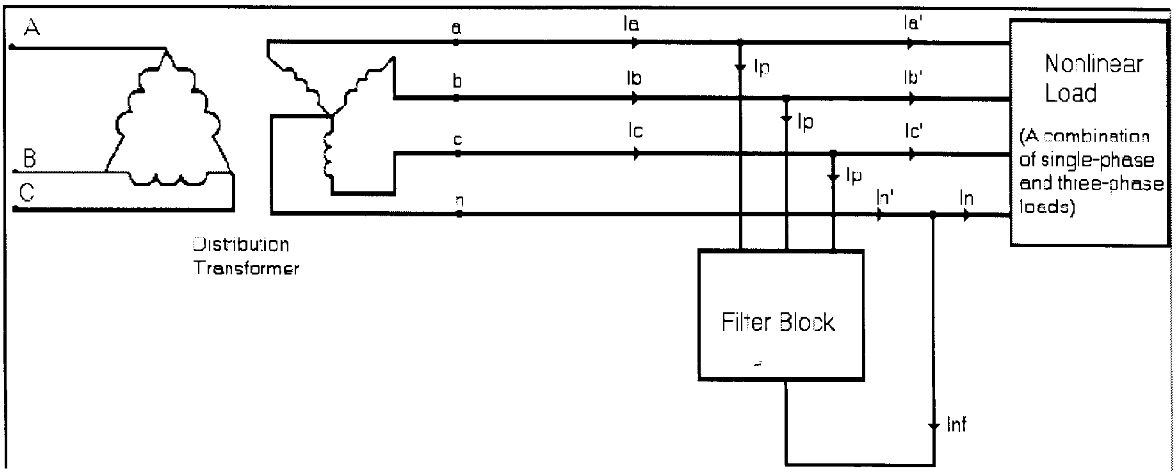


Figure 15 : Filtration for non linear loads

- Select all equipment which conforms to international standards in harmonics levels. These equipments are labelled with the “CE” marking.
- Segregate loads producing high harmonics in such a way that a filtering mechanism can be easily incorporated.
- As a standard practice estimate the possible harmonics levels of sub panels and use filters for eliminating harmonics.



Passive approach for neutral current reduction

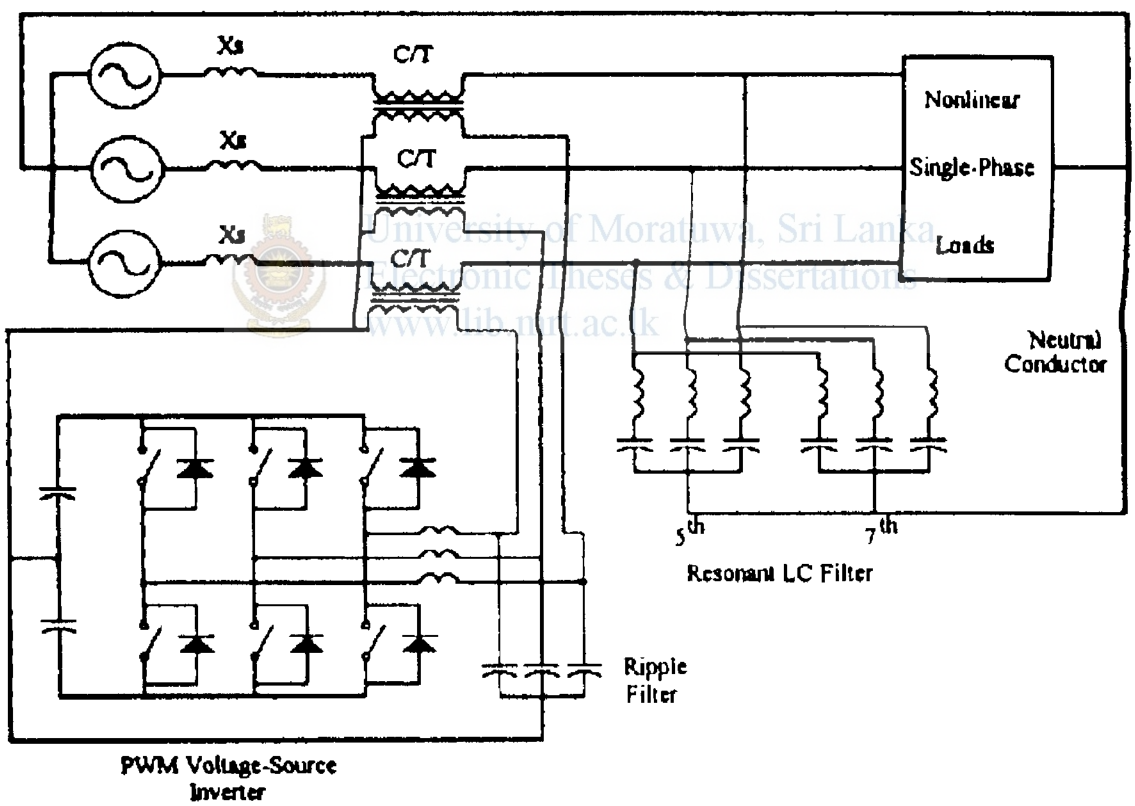


Figure 16 : An active power filter used to eliminate negative and zero sequence

Chapter 5

5.0 Case Studies for Existing Installations

5.1 Background

This chapter will present few case studies of existing building electrical installations on how above methodologies can be used to save operational and maintenance costs. At the time of proposal they did not have any issue over the unbalance. Hence the whole idea of the research could be achieved by suggesting changes to the existing system to save the losses and possible future unexpected maintenance costs.

5.2 Data collection from various facilities

Data was collected from varying large LV installations. The purpose was to analyze how different consumers face the problem of phase unbalance and how different solutions will be implemented. The following different types of facilities were included for the study.

- Apparel facility – Located in the Kaluthara area producing children's wear for export to US & Europe. The maximum demand is 260 kVA and the facility is mostly 450W single phase sewing machines of 350 numbers and fluorescent lighting with magnetic ballasts.

- Hospital facility – Located in Malaysia a 225 bed hospital equipped with modern theatres and laboratories. The maximum demand is 4MVA. Central air conditioning and fluorescent lighting with magnetic ballasts are the largest power consumers. Bio medical equipment such as scanners, x-ray machines is used widely.

- Mobile base station – a GSM base station of a leading mobile operator in Sri Lanka, located in the Rathmalana area. The maximum demand is 15kVA. A GSM BTS station is present with split type air conditioning to keep the temperature inside the room.

- Data Centre – a data processing facility with over 3000 computers serving for an international bank. The maximum demand is 1.2 MVA. Computers are provided with large screen monitors of both CRT and LCD. Lighting is provided via T5 fluorescent fittings. Air conditioning is central air cooled chiller system.

5.3 Equipment used

The study required several meters to be used to collect data and to be recorded at the installation. The following equipment was used for the data recording and harmonics analysis of the above locations.

Detail of Equipment		
Name and model	**Description**	**Serial No.**
Fluke 1735 Power Logger	3 phase power analyzer with logger	S082701051B6

Table 4 : Equipment used for testing

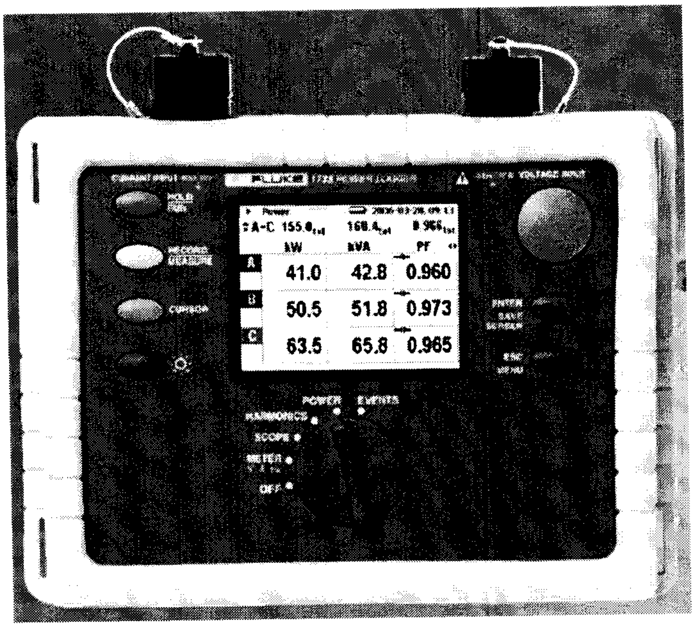


Figure 17 : Power analyzer used for data collection

5.4 Study results

Study results with problem definition are presented below as cases. Possible solutions are suggested with estimated savings and investment required to justify an economic solution.

5.4.1 Case 1 – Apparel facility

Analysis

- Phase Currents during peak – 322A, 321A, 378A
- Average current – 340A
- Maximum Unbalance – 11%
- Phase voltages during peak – 233V, 231V, 226V
- Average voltage – 230V
- Voltage unbalance – 1.7%
- Neutral current – 60A
- Neutral cable – 2runs of 120mm^2, 55m
- Inappropriate single phase load distribution

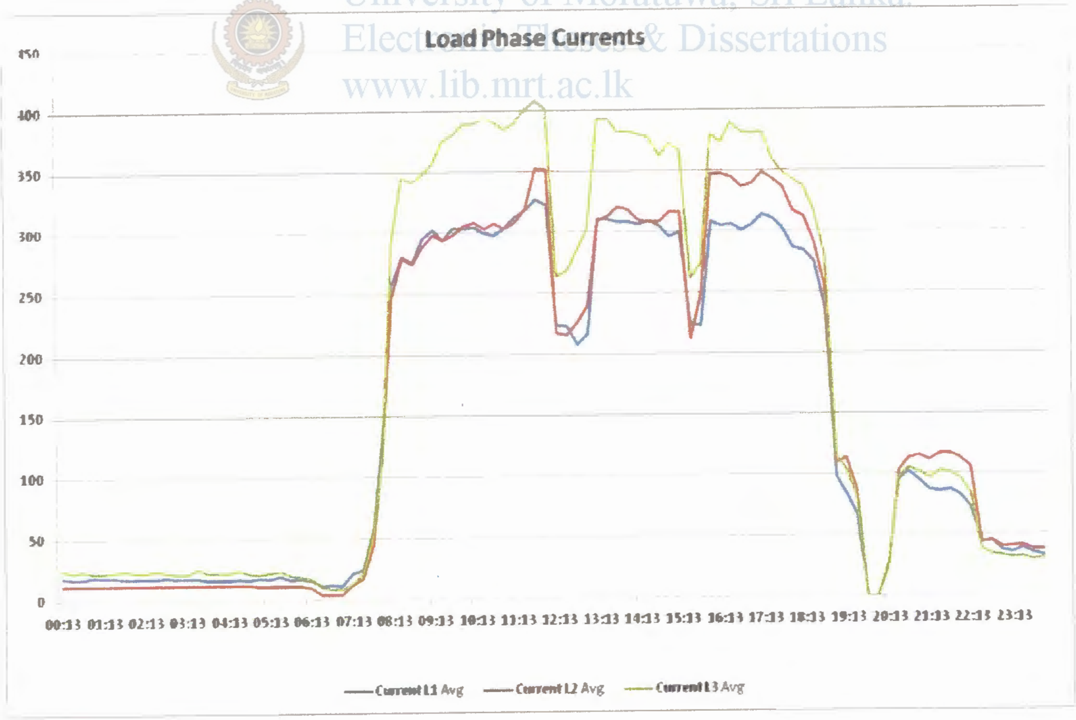


Figure 18 : Logged data of the facility

Suggestion for improvements

Almost all the loads of the facility were single phase loads and the load distribution was bad. This is a classic example of a bad design. The design was by a designer who doesn't have an idea of simultaneity of loads at this type of facility. The problem remains permanent to a certain extend making it difficult to solve as a proper load balancing will cost an entire rewiring. I did a feeder rearrangement of the facility to reduce neutral current by about 60%. This facility is an ideal place where a half neutral cable could be used. There are no major harmonic distortions in the network. It is in vain to use a cable that can carry over 500A when the actual is only 20A.

Benefits to the facility

- Load balancing – Neutral current reduced to 20A
- Cable loss reduction – 1,634 kWh/annum
- Saving – 16,000 LKR/annum
- Investment – negligible (phase swapping at breakers by technicians)
- If ½ neutral cable used – 150,000 LKR saving
- Change over switch heating rectified

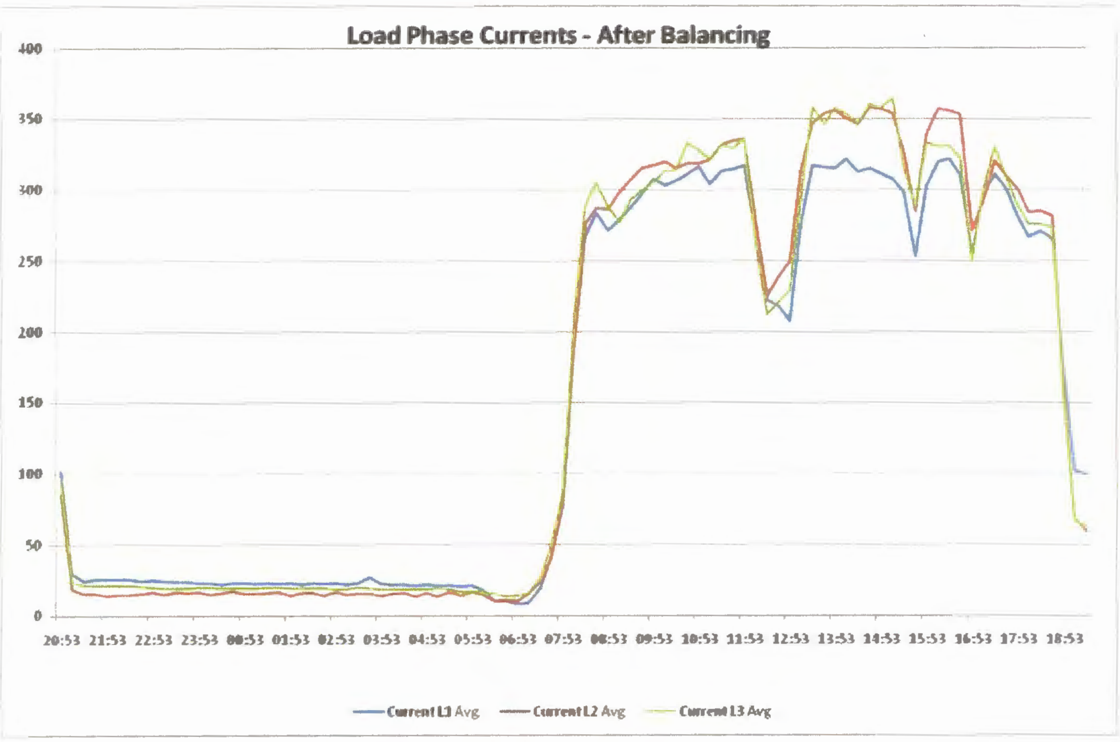


Figure 19 : Logged data after balancing

5.4.2 Case 2 – Hospital facility

Analysis

- Currents balanced – but, high neutral current
- Unbalance – <10%, Neutral current – 20% of phase current
- Non-linear loads not segregated
- Feeder for bio medical equipment with high neutral current and harmonics level.
- Poor quality electronic ballast not conforming IEC'

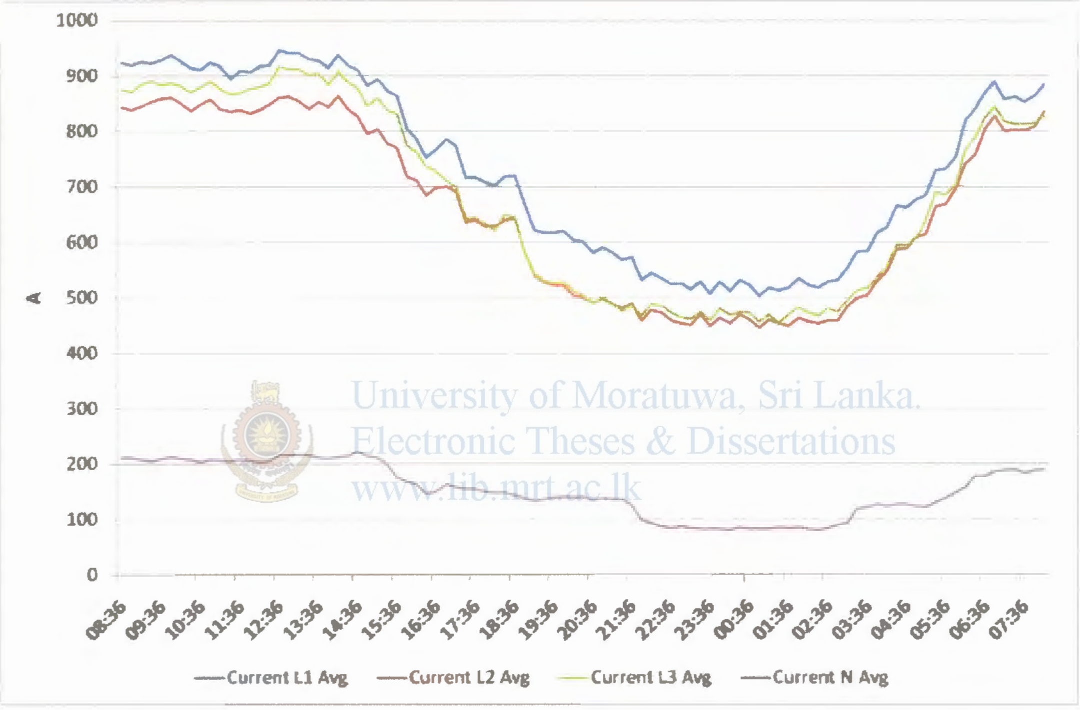


Figure 20 : Logged data of the facility

Suggestion for improvement

This is a bad design due to non-segregation of possible harmonic producing equipment to a single feeder. Then filtration of harmonics is much easier. No filtration was used at this facility and transformer overloading was experienced by operational staff.

Benefits

- Harmonic filtering – Neutral current reduced to 20A
- Cable loss reduction – 10,100 kWh/annum

- Saving – 100,000 LKR/annum
- If ½ neutral cable used – 1,300,000 LKR saving
- Transformer overloading solved
- Investment – 2,500,000 LKR

5.4.3 Case 3 – Mobile base station

Analysis

- Currents unbalanced – different phases carrying different loads, heavy neutral current
- Unbalance – >25%, Neutral current – 90% of average phase current
- Non-linear loads such as switches and switch mode power supplies used
- No filtration of harmonics

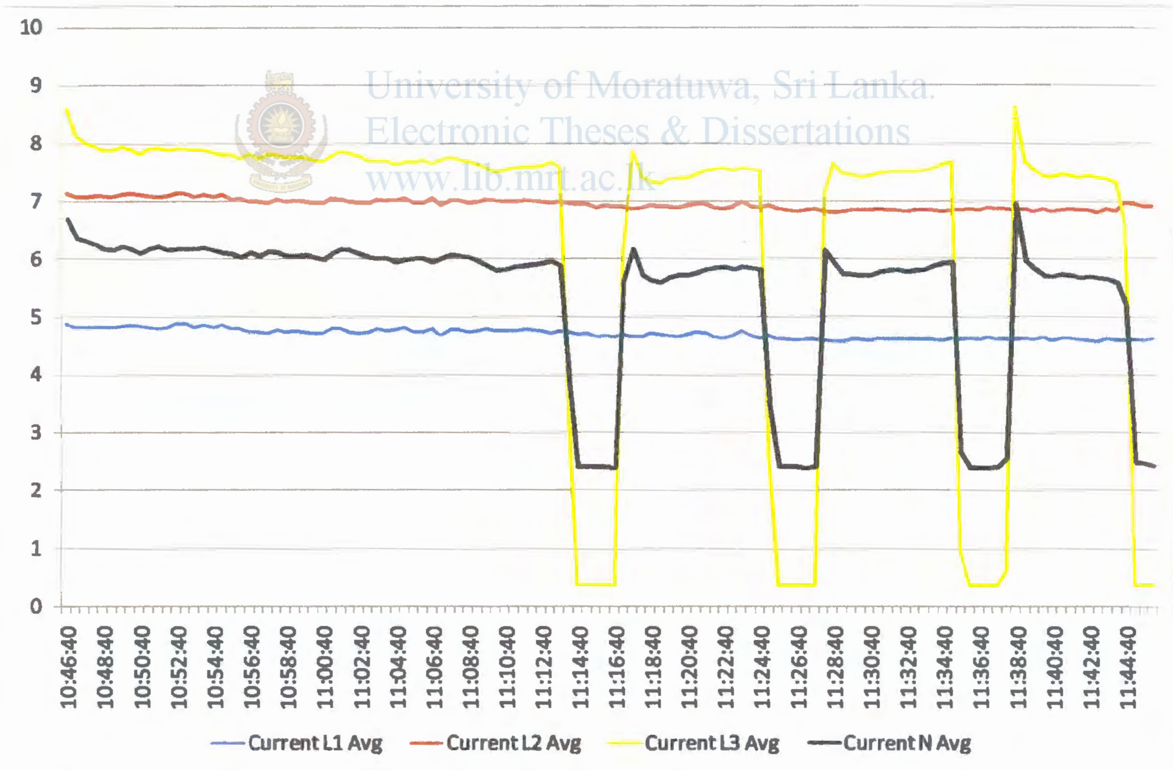


Figure 21: Logged data of a mobile base station

Suggestion for improvement

This is a typical carelessness of the consultants. Most will think this is a very low load, but these range in thousands for each operator. They absorb power from the national grid u dand inject harmonics into the system. No filtration was used at this facility which can be easily incorporated at the inception.

Benefits

- Harmonic filtering – Neutral current can be reduced to 2A
- Cable loss reduction – 3,000 kWh/annum
- Saving – 45,000 LKR/annum
- Investment – 50,000 LKR

5.4.4 Case 4 – Data centre

Analysis

- Currents unbalanced – different phases carrying different loads, heavy neutral current
- Unbalance – <5%, Neutral current – 10% of average phase current
- Non-linear loads such as computers, data servers, UPS, emergency power systems and network switches used extensively.
- Some amount of filtration of harmonics from central UPS.

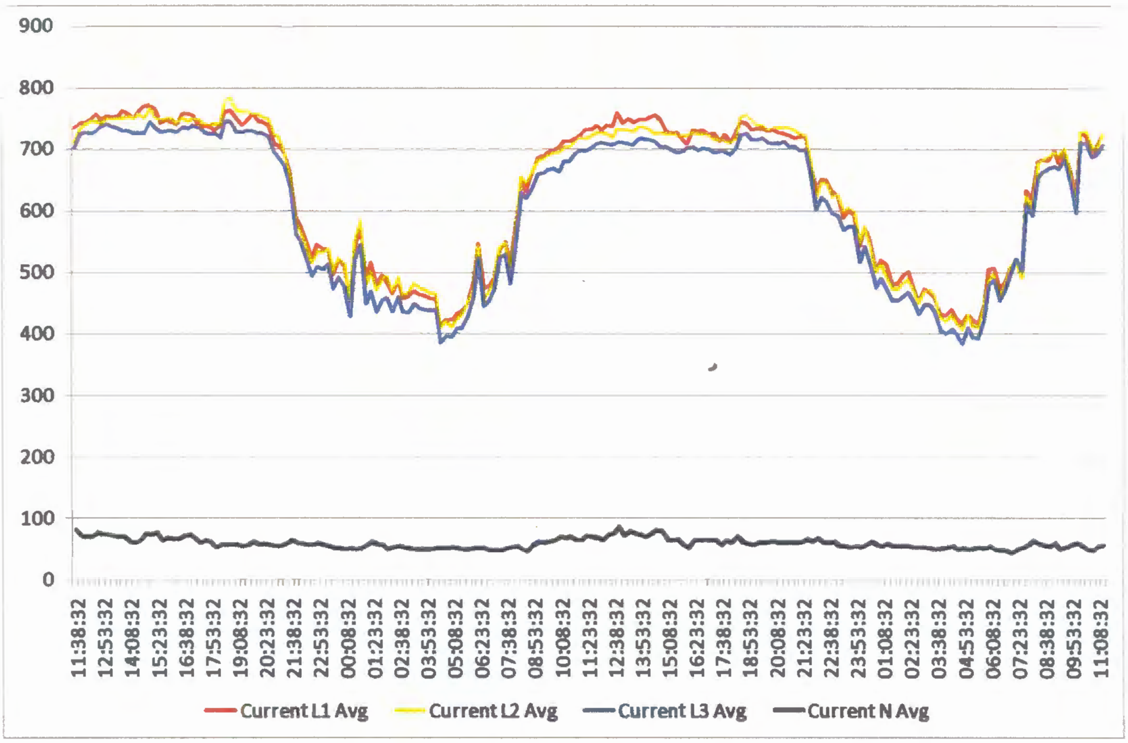


Figure 22: Logged data of a computer data centre

Suggestion for improvement

This is a somewhat better designed facility. Consultants have acted early for the heavy non linear loads that will be added to the system. This has led them to a lot of saving from the distribution network. However further reduction can be recommended to keep the network losses low. Main requirement is to analyze existing harmonic filtrations and to recommend improvements to the existing system.

Benefits

- Harmonic filtering – Neutral current can be reduced to 20A
- Cable loss reduction – 26,000 kWh/annum
- Saving – 260,000 LKR/annum
- Investment – 300,000 LKR

Chapter 6

6.0 An Automated Solution

6.1 Introduction

In this chapter I would like to describe an effort by me to develop a solution for a much complicated electrical distribution network suffering from network inefficiencies and losses. The necessity arises as I found a manual phase swapping or load balancing is not practical when it comes to a complicated distribution system like a large installation of the range of 4-5 MVA or above. This type of an installation will have several transformers with several Main Switch Boards making the process complex. The number of feeders incorporated will be high and finding a manual solution will not be the most feasible thing to do.

Another problem I encountered was that most equipment such as power analyzers used for analysis of an electrical network is purely for data collection purposes. There were very few software facilities to analyze the collected data. Therefore I tried to develop a program to get a solution for this problem.

I have used MATLAB as the software for developing this solution as I found it easy to develop a solution using matrix operations. A 'm file' is developed for each and every feature of the program and is available for further development on the same platform.

I intend this software to be used by operations and maintenance managers for the process of load balancing and harmonic detection in an electrical network. The system will give suggestions for phase swapping on a instantaneous or long term basis. The recommendations can be incorporated at the next maintenance program as these require power interruptions.

Objective of the program

- Reduce neutral current by reducing phase current unbalance
- Reduce network losses over a period of operation

Input to the system

- Average current readings of the feeders to find out best combination to reduce neutral current and voltage unbalance
- Current logs over period to find out best solution to reduce neutral current losses and reduce voltage unbalance

Output of the system

- Best combination of feeder phase arrangement to reduce the losses and improve efficiency.

6.2 Phase combinations

If you are trying to connect up a feeder to a main or sub panel, there are several combinations of connection. It is not necessary on technical terms to connect phase 1 of the feeder to phase 1 of the incomer. But depending on the types of machines on the load side like three phase machines, it is important to connect up so that the phase rotation is not changed. Given that the incoming is L1, L2 and L3, and if the feeder to be connected is L4, L5 and L6 the following combinations are possible.

If load includes 3phase loads

- L1-L4, L2-L5, L3-L6
- L1-L5, L2-L6, L3-L4
- L1-L6, L2-L4, L3-L5

However we will not consider a feeder to be connected in a reverse phase rotation due to safety regulations and compatibility to standards.

6.3 Logical processes of the system

6.3.1 Solving current unbalance problem

The idea of this feature is to make sure the phase currents of a distribution system is balanced and hence the voltage unbalance problem is sorted to a certain extent. The program will consider how the phases can be swapped to arrive at the minimum neutral current and minimum phase unbalance level.

For the phase swapping option feeders are considered from each panel. Say panel no. 1 is taken first and the outgoing feeders of the panel to the load side are identified. Feeder data of each feeder is inserted to the software first. Then this will do a load flow analysis for all combinations of the connections. Then the best combination to reduce the resultant neutral current is selected. This is a very basic process where the current of each phase of each feeder is input manually to the system and the system will advise on the best combination for that feeder.

User will need to identify the rms currents of the 3 phases and the power factors to input to the system. Harmonics currents need to be eliminated first and only the fundamental is to be inserted for calculations. High harmonics will reduce the accuracy of the output.

Input to the system

Feeder No.	Feeder Name	Phase 1 current (A)	PF	Phase 2 current (A)	PF	Phase 3 current (A)	PF	3 phase
1								
2								
3								
...								

Table 5 : Sample data entry table

Phase unbalance

$$\text{Current Unbalance Ratio} = \frac{\text{Maximum difference of a phase current to average}}{\text{Average phase current}}$$

$$= \frac{\text{Max}\{\,|Ia - Iavg|,\ |Ib - Iavg|,\ |Ic - Iavg|\,\}}{Iavg}$$

Where

$$I_{avg} = (I_a + I_b + I_c) / 3$$

Where Ia, Ib and Ic are fundamental phase rms currents.

Neutral current is estimated assuming the fundamental phase currents are balanced with equal phasor differences of 120°.

$$\text{Neutral current } I_n = \sqrt{2}\, I_a \sin \omega t + \sqrt{2}\, I_b \sin (\omega t + 2\Pi/3) + \sqrt{2}\, I_a \sin (\omega t + 4\,\Pi/3)$$

This feature will require only the instantaneous values of the phases, which can be easily measured using a clip on meter. It is important that a true rms value ammeter is used to measure as other meters will not give the correct value. The power factor level will need a power factor meter or a power analyzer to be used for measurement. If PF cannot be measured it is recommended to insert average assumed power factors to enable calculations.

The following process flow diagram is what will be used in the logical components in finding a solution for this problem.

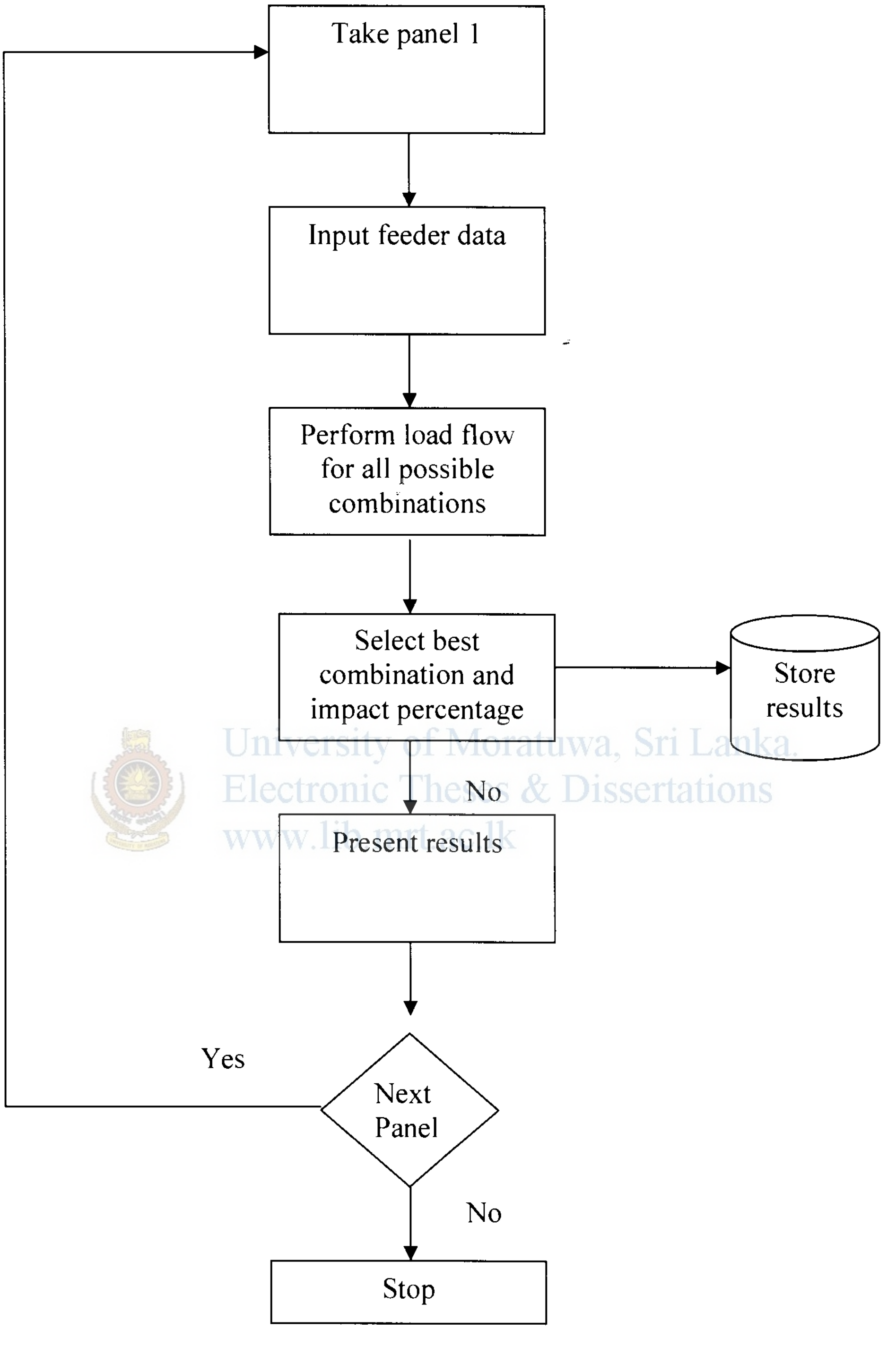


Figure 23 : Flow chart for instantaneous phase balancing

Matrix operation description

If feeder 1 currents a, b & c and if feeder 2 currents are d, e & f, where currents are written in complex numbers for active and reactive components in the form of x + jy. The following combinations can be achieved as the resultant.

	Phases		
Combinations	a + d	b + e	c + f
	a + e	b + f	c + d
	a + f	b + d	c + e

Table 6 : Matrix after the first step

If another feeder is to be added as feeder 3 of currents g, h & l, the resultant will be increased to 9 * 3 matrix as below.

	Phases		
Combinations	a + d + g	b + e + h	c + f + i
	a + d + h	b + e + i	c + f + g
	a + d + i	b + e + g	c + f + h
	a + e + g	b + f + h	c + d + i
	a + e + h	b + f + i	c + d + g
	a + e + i	b + f + g	c + d + h
	a + f + g	b + d + h	c + e + i
	a + f + h	b + d + i	c + e + g
	a + f + i	b + d + g	c + e + h

Table 7 : matrix after the second step

The diagram above is the matrix operation for the current phase unbalance solution finder. The process is iterative in finding the best combination for the network. Higher the number of feeders, higher will be the size of the matrix. However for panel with a large number of feeders, the process time will be considerably longer.

The graphical user interface for entering the data of each feeder of each panel is given below. Entry to the system is manual and results will be shown at the end of the process.

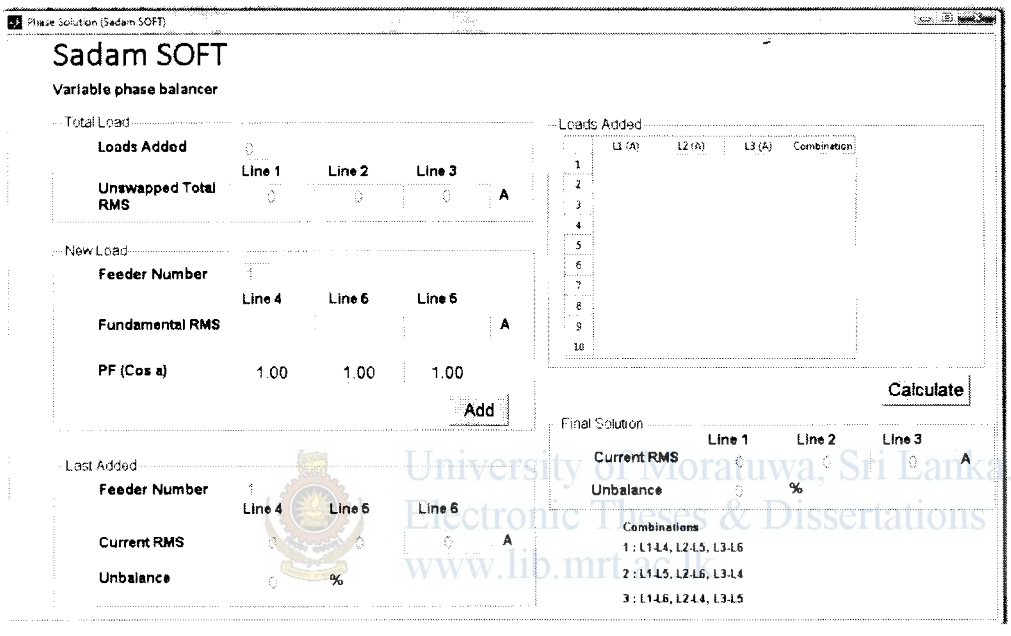


Figure 24 : User interface for data entry for instantaneous phase balancing

In the first frame of "Total Load" displays the present status of the iterative load addition process. This will get updated when each feeder is added to the system. The second frame of "New Load" is where the user enters the next feeder and adds it up to the existing system. The button "Add" will convert phase currents to complex numbers using the power factor and store it for calculations.

The frame "Last Added" will display the feeder added last to the system. It will display the unbalance of the last added feeder.

Once the additions of the feeders are done, next step is to calculate the load flows for each combination. This will be done by clicking the "Calculate" button. This will calculate the maximum unbalances of each combination first. Then it will select the minimum unbalance combination as the best solution.

The results will be displayed on the "Loads Added" frame under combination column. The table will display recommended combination for each feeder. The combinations are given at the bottom of the panel. The frame "Final Solution" will display final phase currents after phase swapping and the respective unbalance level. The user can decide whether the required level of unbalance is reached.

6.3.2 Solving minimum network losses over a period of time

This feature was introduced to the process to overcome some problems in the above system. The previous system can receive only instantaneous data. In a practical load flow the currents in each phase will not be constant. It can even be the case that the overloaded phase at one time is a minimum loaded at another time. Therefore the requirement arises to find a solution for a whole period of time. This could be a day or week as appropriate to the load centre.

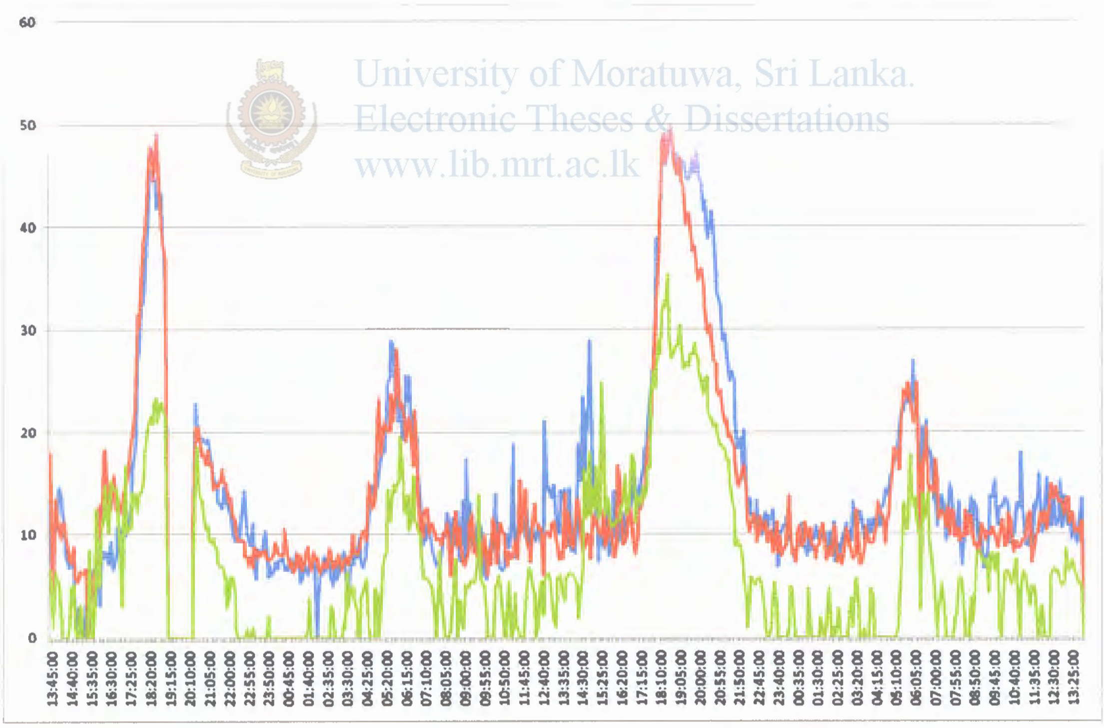


Figure 25 : Logged data with high current variations

System will receive data as logged data over the period as averaged decided by the user. The logged data will be in a table format with the time and average current as columns. Each nodes data will be added to the system and at the end of the input the system will start processing the data to find out the best solution for the load flow.

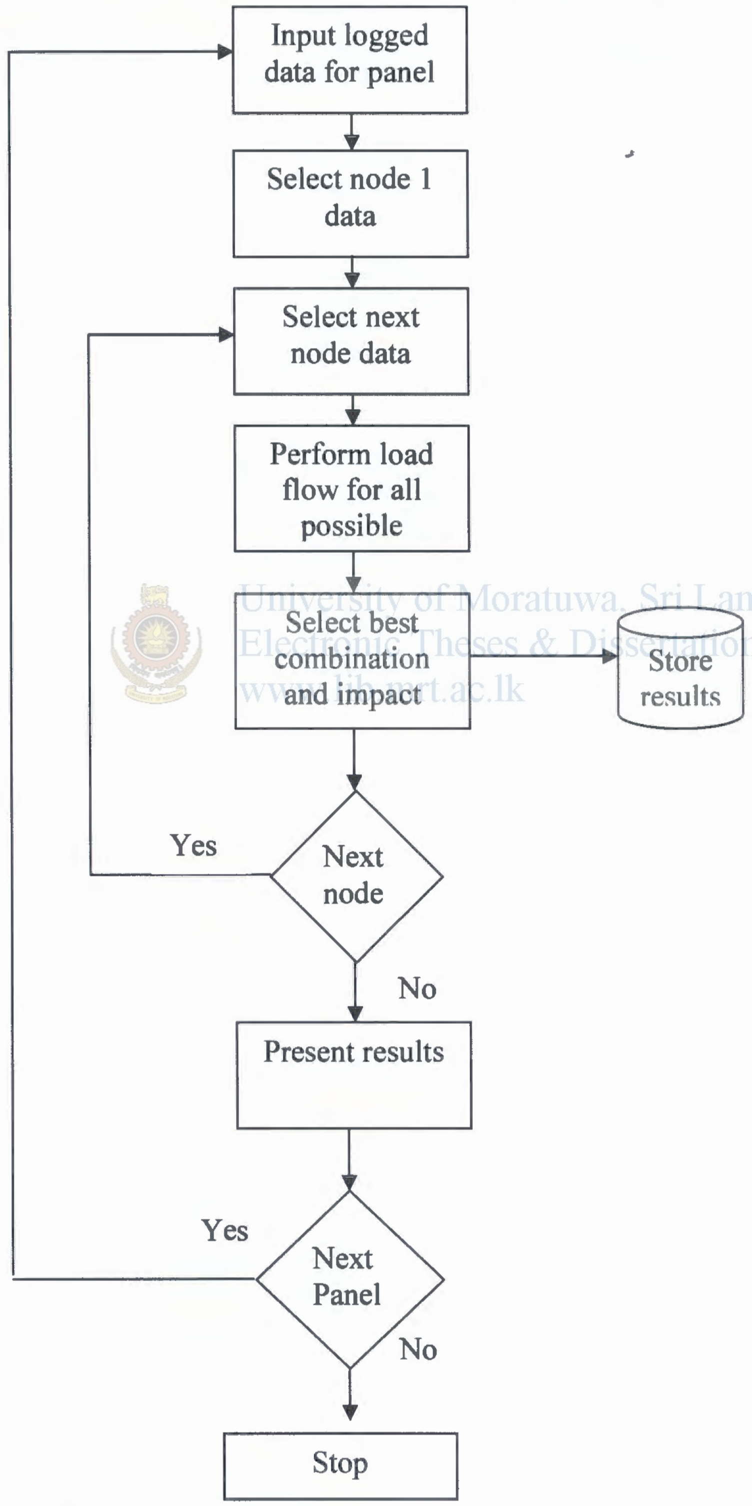


Figure 24 : Flow chart for phase balancing over a period

An example table of a logged data is given below.

Record	Chan 1
End Time	Avg. Amp
13:45:00	13.04
13:50:00	4.52
13:55:00	3.2
14:00:00	13.56
14:05:00	10.53
14:10:00	14.59
14:15:00	13.73
14:20:00	12.59
14:25:00	10.81
14:30:00	7.84
14:35:00	7.38
14:40:00	6.75
14:45:00	7.95
14:50:00	6.64
14:55:00	1.32
15:00:00	0
15:05:00	2.92
15:10:00	1.89
15:15:00	0
15:20:00	0
15:25:00	3.32
15:30:00	4.75
15:35:00	5.84
15:40:00	6.46
15:45:00	5.84

Table 8 : Sample data entry format for phase balancing over a period

The above table is only for Line 1, which is tabulated as “chan 1” as downloaded from common power data loggers. Therefore it is convenient to transfer downloaded data directly to the program for finding a solution. Similarly the data for “Line 2” and “Line 3” need to be inserted for the calculation.

The report generated from the input will be displayed in the same format as of the above computation.

6.4 Case study done using the program

The program was executed for a few sample data collected at different facilities. These data was collected by measurement of existing load flow in the particular installation.

Case study

Data was collected from a main distribution panel of a hospital facility which was also used for the previous unbalance analysis. The outgoing breakers were measured for phase currents and tabulated as below.

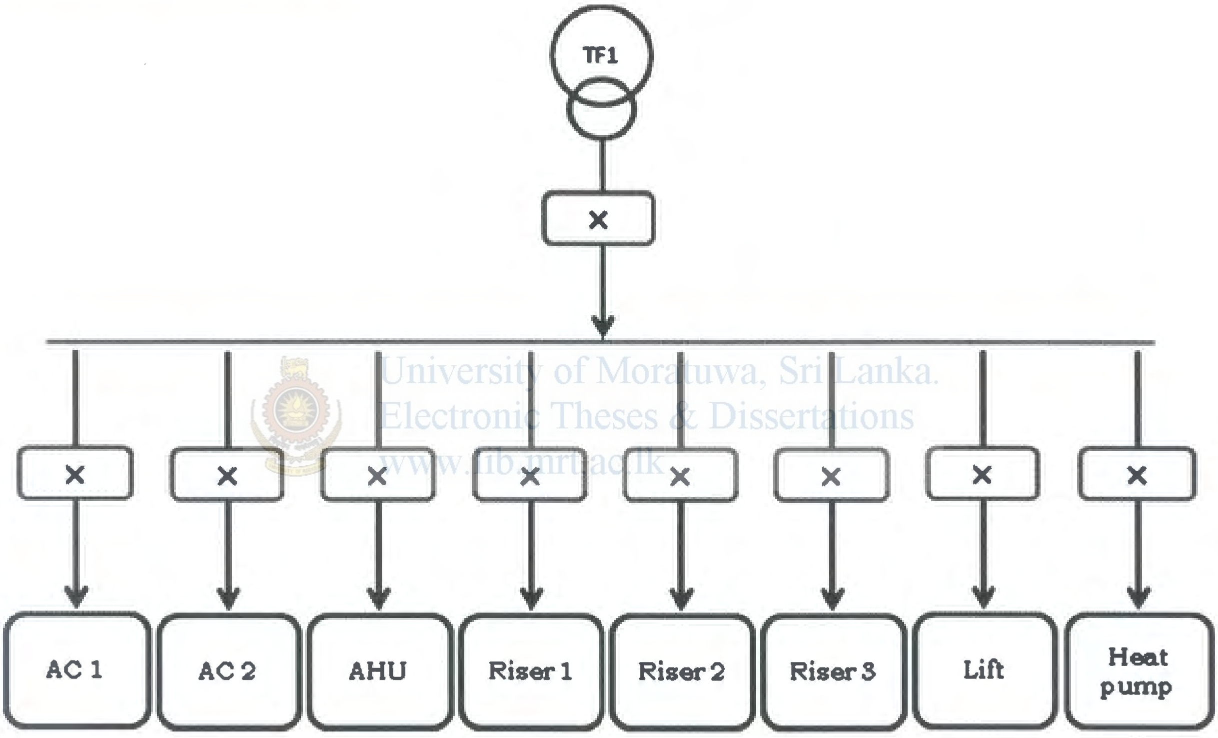


Figure 25 : Sample network configuration

Feeder No.	Feeder Name	Phase 1 current (A)	PF	Phase 2 current (A)	PF	Phase 3 current (A)	PF
1	AC 1	165	0.74	120	0.73	130	0.75
2	AC 2	125	0.68	130	0.68	92	0.69
3	AHU	175	0.80	140	0.79	150	0.81

4	Riser 1	130	0.85	120	0.86	130	0.85
5	Riser 2	140	0.65	120	0.67	120	.60
6	Riser 3	111	0.78	110	0.75	107	0.77
7	Lift	115	0.68	115	0.68	116	0.69
8	Heat pump	54	0.93	53	0.92	54	0.94

Table 9 : Input data to the software

Input to the system

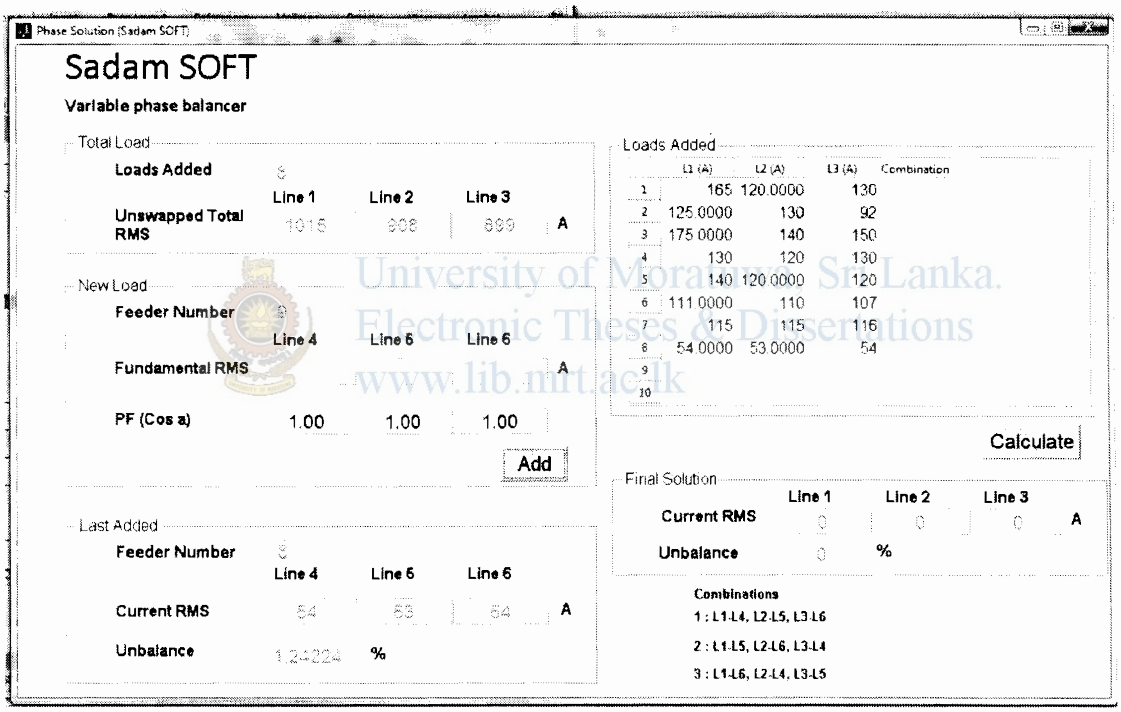


Figure 26 : Screen after data entry

Output of the system

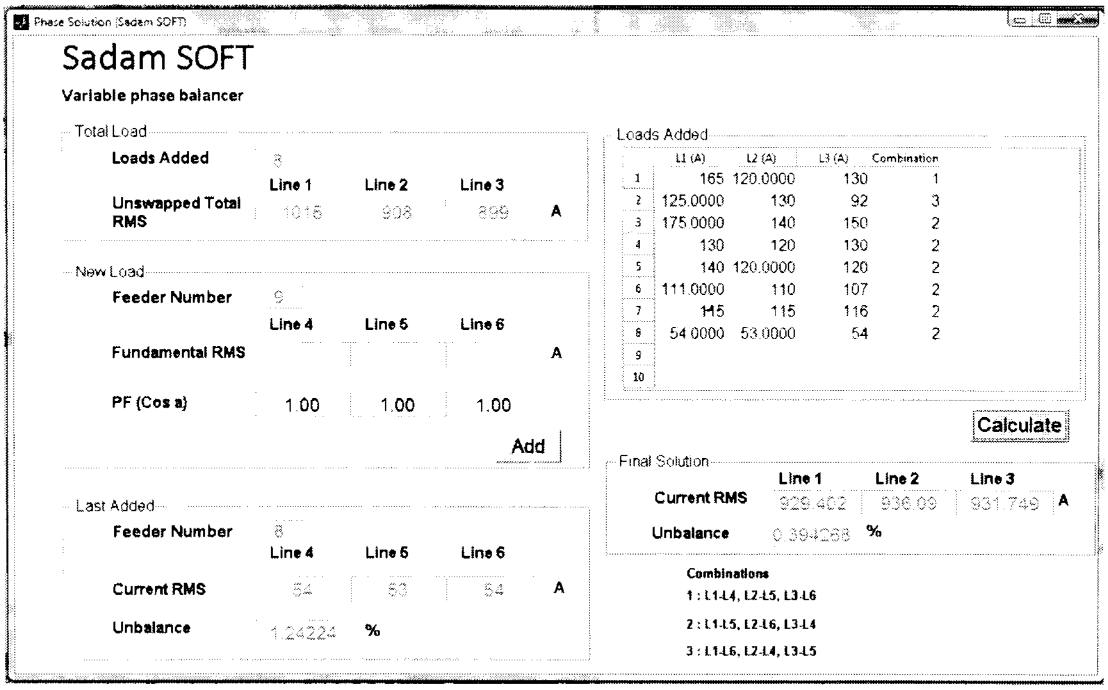


Figure 27 : Output screen

Chapter 7

7.0 Conclusion

The idea of the project was to be an eye opener for-this careless mistake of loosing energy on the electrical network. Millions of units energy would have lost and being lost even today due to this carelessness. Hope this research will reach all concern of designing and operating electrical networks to incorporate into future projects or minimize in the existing facilities.

I have discussed the background for the project and the lengthy problems occurring due to the unbalances in the electrical network. The list is not limited to those but ever increasing as the demand for electricity gets expanded and more loads and electronic equipment is added to the system.

Some typical solutions was discussed that can be easily adapted to the facilities. Even these are not limited to those solution but any other methodologies can be used to keep the unbalances and neutral currents low.

Case studies presented gave a good indication of the saving potential each facility has, which can be a motivation for engineers considering modifications. It was proved that the problem is not limited to particular consumer type or set of consumers, but widely spread over all consumer categories consuming 3 phase power. The problem is reflected for the single phase consumers in large scale.

Ability of data collection by electronic energy meters is not being practiced for the purpose of concentrating on the savings as above. It is proposed that the power supply authorities should give the day to day data collection access to the consumer from energy meters and let the consumer be aware about his own power quality problems and to initiate remedial action for his problems. As proposed by the paper the consumer can use load balancing and to select the correct equipment so that the harmonics are minimized back on the system could be practiced.

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