

**NETWORK OPTIMIZATION BASED LOAD  
BALANCING TECHNIQUE FOR LV ELECTRICITY  
DISTRIBUTION NETWORK**

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DISTRIBUTION NETWORK**

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Dissertation submitted in partial fulfillment of the requirements for the degree Master  
of Science in Electrical Engineering

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May 2017

## Declaration

“I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Date:

(Dr. P.S.N. de Silva)

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Signature of the supervisor

Date:

(Dr. K.T.M. Udayanga Hemapala)

## **Dedication**

I dedicate this work to my loving parents and to teachers

## **Acknowledgement**

First, I pay my sincere gratitude to Dr. K.T.M. Udayanga Hemapala and Dr. P.S.N. de Silva who encouraged and guided me to conduct this investigation and on perpetration of final dissertation. Without their encouragement and help, this research will not be a success.

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## **Abstract**

### **Network Optimization Based Load Balancing Technique for LV Electricity Distribution Network**

Network optimization is vital requirement for all the electricity distribution companies. Energy loss reduction, fulfill the statutory requirements, lifetime improvements of the network accessories and healthy operation of network are some of benefits of network optimization. Load arrangement within the network is one of key factor influence for network condition. Proper load balancing mechanism among phases is based on the appropriate positioning of consumers within the electricity distribution network which empowers network optimization. So load balancing can be referred as way of consumer arrangement within the context of electricity distribution.

Ceylon Electricity Board (CEB) and Lanka Electricity Company (LECO) are the utilities responsible for electricity distribution within Sri Lanka. Presently there is not proper methodology used for load balancing by Sri Lankan electricity utilities. According to the electricity demand growth and increasing sensitivity to network by consumers, better network planning methodology will be required to cater their requirements.

In order to address this issue, this dissertation focuses on development of network optimization based load balancing technique for LV electricity distribution network. Actual features enriched distribution network model and appropriate power flow analysis method are essential infrastructure for accurate determination network condition. Such kind of platform can be used to evaluate different consumer arrangement patterns along low voltage feeders using their load profiles to find network optimized arrangement. Consumer load profiles can be represented by characteristic curves which illustrate their electrical behavior. Evaluation of network status generated due to combined effect throughout each and every point of consumer load profiles for all consumer arrangement patterns provide better result rather than just consideration of particular set of values.

Three phase four wire neutral grounded systems are using for electricity distribution in Sri Lanka. Incorporation of ground return path in to network model is considered within this research work. Applicability of forward backward load flow techniques is validated for proposed distribution network model. Proposed an algorithm for network optimization based load balancing which provide consumer arrangement plan at nodes for a certain low voltage feeder of distribution network.

Generally, this study provides the platform for network planners to find best arrangement of consumers at the network to achieve optimum network condition. This can be used for existing network evaluation as well as future planning of the distribution networks.

Key words: Network optimization, load balancing, Consumer assignment

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## **List of Abbreviations**

LECO	Lanka Electricity Company
CEB	Ceylon Electricity Board
PUCSL	Public utilities commission of Sri Lanka
CT	Current Transformer
ABC	Arial Bundle Conductor

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# 1 INTRODUCTION

## 1.1 Background

Electricity is becoming as fundamental need for recent society. So electrification is the one of increasingly popular term all over the world. Most of the countries are benchmarking their electrification target to maximum. Sri Lanka also conducting 100% electrification program and improving accessibility to distribution network .Ceylon Electricity Board (CEB) and Lanka Electricity Company (LECO) are in the process of successfully reaching to these targets [1], [2]. Usages of sensitive electrical devices are raised requirement for improvement of quality of electricity distribution.

Electrical vehicle charging and distributed generation entity addition in to low voltage electricity distribution network are shifting the electrical behavior of low voltage feeder in to complex pattern. Sri Lankan government encourages domestic consumers to integrate solar system to increase renewable energy usage [3].Attached loads are one of the decision makers for corresponding network. Different types of consumers are rapidly attaching to the distribution network and their consumption patterns exist within considerable range. Electricity consumption patterns are varying from consumer to consumer and accurate prediction will be difficult. This will create unpredictable electricity behavior within the low voltage feeder. Sometimes electrical parameters such as voltage, current can be deviate from pre-defined limits which influence healthy operation of the power distribution system. Unequal current distribution among phases is reason for increase the electrical energy loss as well as sometimes exceeds the current carrying capacity of the cable where the large loads are connected. These unbalance currents are returned through neutral conductor path to source and again create energy loss within the system. Also voltage drop is created

through neutral conductor and consumer end voltage can be affected. Especially single phase consumers are the major contributors for neutral current existence.

So maintaining network at optimum condition will be huge challenge in the future for Sri Lankan utilities. Public Utilities Commission of Sri Lanka (PUCSL) is the regulatory body for electricity utilities. They defined stipulated margins for electricity distribution network [4] (such as voltage level at +/- 6% of defined value, transformer loading at rated values...). To maintain network performance at considerable level, utilities are monitoring feeder end voltages, feeder currents, per phase customer count and instantaneous current measurement based load balancing and conducting energy loss reduction programs as present practices.

Proper load balancing mechanism among phases is based on the appropriate positioning of consumers within the electricity distribution network which empowers network optimization. So load balancing can be referred as way of consumer arrangement within the context of electricity distribution.

There are number of possible phase allocation combinations for set of consumers belong certain feeder. Different network statuses are generated for each arrangement throughout their electrical load profiles. Consumer load profiles can be represented by characteristic curves which show their electrical behavior. Results of each connection arrangement must be evaluate to find best arrangement which facilitate to maintain most optimum condition within the network. But there is no such methodology practicing by utilities for consumer allocation to their network. So network optimization based consumer allocation technique will be essential requirement for all electricity distribution utilities to provide better service.

Different utilities are using different type of distribution network configurations according to their requirement. So network model is typical to their requirement. Inclusion of inherent features of particular network during network modeling will be facilitating for better analysis. Three phase four wire neutral grounded overhead electricity distribution systems are using for electricity distribution in Sri Lanka. Different methods are used in the world to model such type of networks [5],[6],[7],

[8],[9],[10]. Suitable load flow analysis method will be help to obtain results with sufficient accuracy [11],[12],[13],[14]. Different techniques are used in the world for arrange loads among phases which is commonly known as load balancing. Consumers are referred by loads in aforesaid context and consumer connections are changed among phase within the distribution network. Nowadays automatic phase changing methods are also used by some of the utilities in the world. Most of the networks are in the transition stage from traditional electricity distribution network to smart grids. This will take considerable time for developing countries like Sri Lanka and within that period, utilities need to use proper network optimization methods which cater for present requirements as well as preliminary arrangement for automated network.

## **1.2 Motivation**

Network statuses are varying according to the load attachments and de attachments to network. Different statuses are generated within the network throughout load profile of each consumer attached to network. This create more complex situation within the feeder especially consumer electricity consumptions are varying considerable range. There may be situations like some consumers are receiving voltages below or above from stipulated margins, conductor current exceed their current carrying capacity or high losses. So question arise about traditional per phase customer count and instantaneous current measurement based load balancing techniques are sufficient for present situation. Sometimes incorrect addition of new consumer in to network will be affected to existing customers when network at critical status. So evaluating correlation between different customer arrangement and their effect to the network parameters are important for electricity utilities.

If there is proper method to maintain network at optimum condition, that is important for better utilization of available distribution network infrastructure as well as help to provide high quality service to consumers. Results of such evaluation technique will

indicate ability of the network to cater the loads and requirements about network infrastructure expansion.

### **1.3 Objective of the Study**

The objective of this study is to develop a network optimization based load balancing technique for low voltage electricity distribution network to provide solution for issues addressed in the aforesaid sections. Validated simplified power flow algorithm is used as platform for evaluating proposed algorithm.

### **1.4 Methodology**

A literature survey was conducted to study about neutral grounded overhead distribution network models, power flow algorithms and methods for electricity distribution network optimization. Following steps are followed to reach the objective of this research.

- 1) Proposed a impedance model for electricity distribution network with ground return
- 2) Select appropriate power flow algorithm
- 3) Validate applicability of selected power flow algorithm for three phase four wire neutral grounded overhead radial distribution feeder
- 4) Develop algorithm for network optimization based load balancing
- 5) Application of proposed load balancing technique for low voltage feeder
- 6) Evaluate the performance of the proposed method



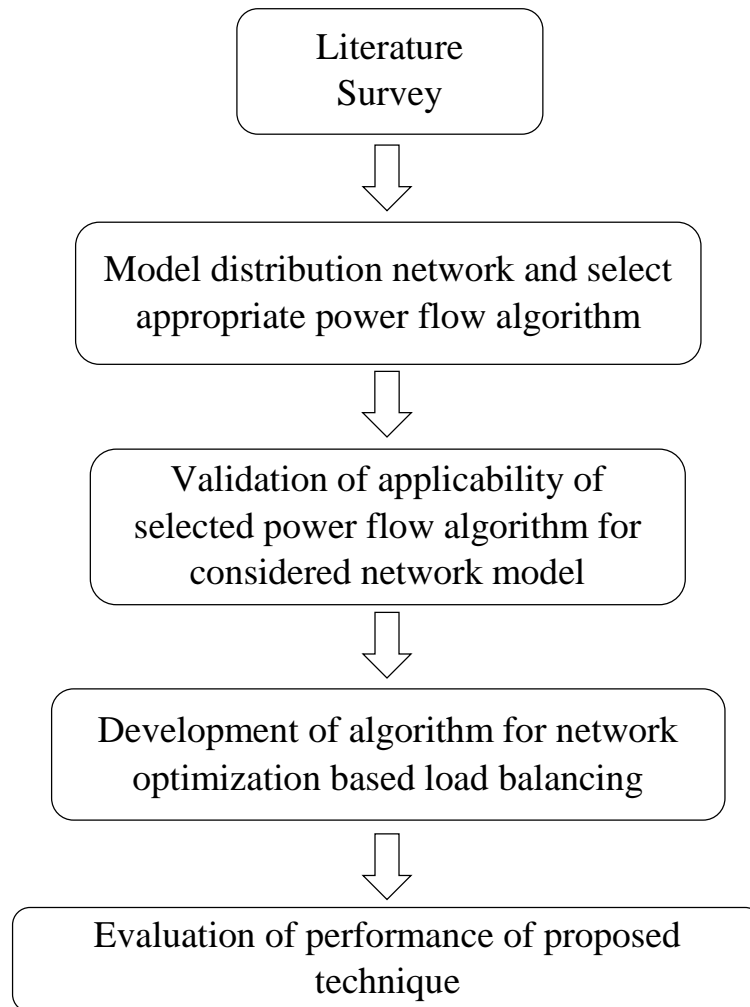


Figure 1.1: Thesis Organization

## 1.5 Thesis Organization

Figure 1.1 shows the thesis organization. Chapter 2 discuss about the fundamentals of modeling of overhead electricity distribution system with ground return, Power flow algorithms and electricity distribution network optimization. Chapter 3 propose model for neutral grounded three phase four wire radial overhead distribution system and customized power flow algorithm. Chapter 4 describe the validation procedure for proposed power flow algorithm developed for three phase four wire neutral grounded radial overhead distribution feeder model. Chapter 5 includes algorithm development for network optimization based load balancing. Chapter 6 includes application of proposed technique and the performance evaluation. Final chapter presents the conclusions, recommendations and future works.

## 2 LITERATURE SURVEY

### 2.1 Modeling Methods for Low Voltage Overhead Distribution System with Ground Return

Accuracy of steady state analysis of low voltage electricity distribution system is depend on the network model which represent by impedances matrix and algorithm used for power flow simulation. There are some inherent properties for each electricity distribution system according to the standards maintained by certain companies/countries as per their objectives. As example, three phase four wire overhead networks are used by LECO which consists of neutral conductor grounded at feeder start (transformer) and feeder end using earth rods. CEB is using three phase four wire overhead network with neutral grounded only at transformer. So incorporation of such kind of inherent properties during calculation of line impedance matrix and power flow analysis is helpful to provide more realistic results. Precision of line impedance matrix is subjected on such properties and the assumptions made during the modeling.

Neutral grounded electricity distribution systems are facilitated with return path through ground additional to the neutral conductor for loads which are highly unbalanced or include considerable harmonic current. So self and mutual impedances of conductors in such systems are needed to incorporate the effect of ground. In 1926 John Carson developed equations to find impedances of the conductors including ground effect of such networks which can be used to model the system [7]. Neutral to earth voltage can be exists due to the different grounding techniques except assumption of solidly grounded condition. Such systems can be modeled based on the different assumptions and approximations. Simulation results like voltages, currents can be vary depend on the way that distribution line and grounded systems are modeled [9]. Line impedance matrix is one of most important component of such distribution system. Modified Carson and a full Carson approach are commonly used methods for impedance matrix calculation.

### 2.1.1 Carson's equation

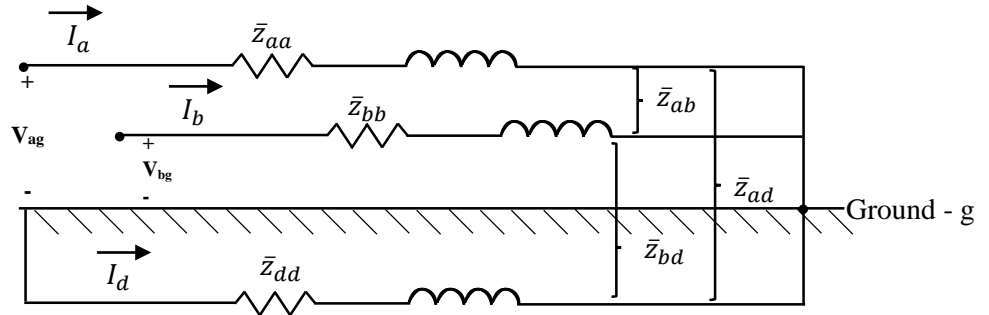


Figure 2.1: Two conductors with ground return

Figure 2.1 shows overhead conductors with ground return. Ground path is represented by fictitious conductor. Voltage between conductor “a” and ground can be written using Kirchhoff's voltage law (KVL), [5]

$$V_{ag} = \bar{z}_{aa} * I_a + \bar{z}_{ab} * I_b + \bar{z}_{ad} * I_d - (\bar{z}_{dd} * I_d + \bar{z}_{da} * I_a + \bar{z}_{db} * I_b) \quad (2.1)$$

From Kirchhoff's current law:

$$I_a + I_b + I_d = 0$$

$$I_d = -I_a - I_b \quad (2.2)$$

Substitute Equation (2.2) into Equation (2.1)

$$V_{ag} = (\bar{z}_{aa} + \bar{z}_{dd} - \bar{z}_{da} - \bar{z}_{ad}) * I_a + (\bar{z}_{ab} + \bar{z}_{dd} - \bar{z}_{db} - \bar{z}_{ad}) * I_b \quad (2.3)$$

Equation (2.3) can be written as:

$$V_{ag} = \hat{z}_{aa} * I_a + \hat{z}_{ab} * I_b \quad (2.4)$$

Where,

$$\hat{z}_{aa} = \bar{z}_{aa} + \bar{z}_{dd} - \bar{z}_{da} - \bar{z}_{ad} \quad (2.5)$$

$$\hat{z}_{ab} = \bar{z}_{ab} + \bar{z}_{dd} - \bar{z}_{db} - \bar{z}_{ad} \quad (2.6)$$

$\hat{z}_{aa}$  &  $\hat{z}_{ab}$  are called as primitive self and mutual impedance of the conductor.

Over bar impedances (series and mutual impedances) can be calculated using (2.7) & (2.8) equations.

$$\bar{z}_{aa} = r_a + j\omega \frac{\mu_0}{2\pi} * \ln\left(\frac{1}{D_{aa}}\right) \quad (2.7)$$

$$\bar{z}_{ab} = j\omega \frac{\mu_0}{2\pi} * \ln\left(\frac{1}{D_{ab}}\right) \quad (2.8)$$

Other terms in the equations (2.5) & (2.6) can be calculated same manner using equation (2.7) & (2.8).

Where,

$r_a$  - Resistance of conductor "a"

$$\omega = 2. \pi. f$$

$\mu_0$  –permeability of free space  $4\pi * 10^{-7}$ H

$D_{aa}$  - Geometric Mean Radius

$D_{ab}$  - Geometric Mean Distance

$f$  – Frequency

When calculating terms in the (2.5) & (2.6), equation (2.7) & (2.8) need to be used. Calculation issue arises due to unknown GMR and GMD of ground conductor within the equation. These issues are addressed through Carson's equation.

Carson made several assumptions during the model development for overhead conductors with ground return. Assumptions regarding the properties of earth are important to derive fictitious type of conductor for ground return path.

Some of the assumptions are,

- Earth is an infinite, uniform solid with a flat uniform upper surface.
- Constant resistivity.
- Current entering point end effects are negligible at power frequencies.
- Current distribution in the ground and the cable is same all along the cable.
- Conductor images are used to model ground return systems.

Figure 2.2 shows arrangement of two conductors  $i$  and  $j$ , which have common grounding system [5], [16], [11].

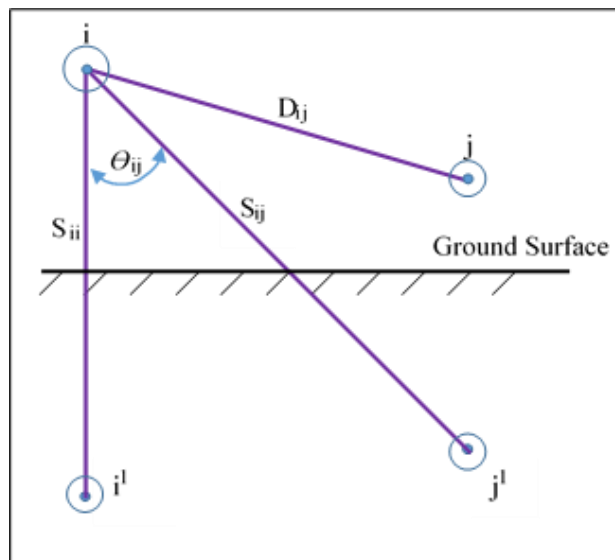


Figure 2.2: Conductors with earth return

$$\hat{z}_{ii} = (r_i + 4 \cdot \omega \cdot P_{ii} \cdot G) + j 2 \cdot \omega \cdot G \left( x_i + \ln \frac{S_{ii}}{R_i} + 2 \cdot Q_{ii} \right) \quad (2.9)$$

$$\hat{z}_{ij} = 4 \cdot \omega \cdot P_{ij} \cdot G + j 2 \cdot \omega \cdot G \left( \ln \frac{S_{ij}}{D_{ij}} + 2 \cdot Q_{ij} \right) \quad (2.10)$$

Equation (2.9) & (2.10) give the impedances in  $\Omega/\text{mile}$ .

Where,

$$i = j = 1, 2 \text{ ---- } N_{\text{cond}}$$

$N_{\text{cond}}$  = number of conductors

$$P_{ij} = \frac{\pi}{8} - \frac{1}{3\sqrt{2}} \cdot k_{ij} \cdot \cos(\theta_{ij}) + \frac{k_{ij}^2 \cdot \cos(2\theta_{ij})}{16} \cdot \left( 0.6728 + \ln \frac{2}{k_{ij}} \right) + \frac{k_{ij}^3}{16} \cdot \theta_{ij} \cdot \sin(\theta_{ij}) + \frac{k_{ij}^3}{\sqrt{2.45}} \cdot \cos(3\theta_{ij}) - \frac{\pi k_{ij}^4}{1536} \cdot \cos(4\theta_{ij}) \quad (2.11)$$

$$Q_{ij} = -0.0386 + \frac{1}{2} \cdot \ln \frac{2}{k_{ij}} + \frac{1}{3\sqrt{2}} \cdot k_{ij} \cdot \theta_{ij} - \frac{\pi \cdot k_{ij}^2}{64} \cdot \cos(2\theta_{ij}) + \frac{k_{ij}^3}{45\sqrt{2}} \cdot \cos(3\theta_{ij}) - \frac{k_{ij}^4}{384} \cdot \theta_{ij} \cdot \sin(4\theta_{ij}) - \frac{k_{ij}^4 \cdot \cos(4\theta_{ij})}{384} \cdot \left( \ln \frac{2}{k_{ij}} + 1.0895 \right) \quad (2.12)$$

$\theta_{ij}$  = Angle between image  $i$  and image  $j$  of the conductors reference to conductor  $i$

$$k_{ij} = 8.565 * 10^{-4} \cdot S_{ij} \cdot \sqrt{\frac{f}{\rho}}$$

$f$  = frequency

$\rho$  = resistivity of earth in Ohm-meter

$$G = 0.1609344 * 10^{-3} \Omega/\text{mile}$$

$$\omega = 2 \cdot \pi \cdot f$$

$R_i$  = Radius of the conductor  $i$

$D_{ij}$ = Distance between conductors  $i$  and  $j$  in feet.

$S_{ij}$ = Distance between conductor  $i$  and image  $j$  in feet

$S_{ii}$ = Distance between conductor  $i$  and image  $i$  in feet

$$x_i = \ln \left[ \frac{R_i}{GMR_i} \right] \quad (2.13)$$

$D_{ii} = GMR_i$  = Geometric mean radius of conductor  $i$  in feet.

Substitute Equation (2.13) into Equations (2.9) and simplify (2.9) & (2.10):

$$\hat{z}_{ii} = (r_i + 4. \omega. P_{ii}. G) + j2. \omega. G \left( \ln \frac{1}{GMR_i} + \ln(S_{ii}) + 2. Q_{ii} \right) \quad (2.14)$$

$$\hat{z}_{ij} = 4. \omega. P_{ij}. G + j2. \omega. G \left( \ln \frac{1}{D_{ij}} + \ln(S_{ij}) + 2. Q_{ij} \right) \quad (2.15)$$

Above equations are referred as full Carson's equations.

### 2.1.2 Modified Carson's equations

Due to complexity of calculating P and Q in original equations, limit the number of terms used and new equation is called as Modified Carson's equations.

$$P_{ij} = \frac{\pi}{8} \quad (2.16)$$

$$Q_{ij} = -0.0386 + \frac{1}{2} * \ln \frac{2}{k_{ij}} \quad (2.17)$$

According to Carson's equation, distance from conductors to relevant fictitious ground conductors must be known to calculate ground effect incorporated impedance for certain conductor. For circuit with ground return path when this distance unknown, modified equations can be used in SI units [12] which can be derived substituting terms for G,P,Q and  $\mu_0$  in equations (2.14) & (2.15).

The unit conversion in to SI units ( $\Omega/m$ ) of equations (2.14) & (2.15) can be done substituting,

$$S_{ij,ft} = S_{ij} * 1000 / (25.4 * 12) \quad (2.18)$$

$$\hat{z}_{ii} = r_i + \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} \left( \ln \frac{S_{ii}}{D_{ii}} - 0.0386 * 2 + \ln \frac{2}{8.565 * 10^{-4} * S_{ii} * 1000 / (25.4 * 12) \sqrt{f/\rho}} \right) \quad (2.19)$$

$$\hat{z}_{ij} = \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} \left( \ln \frac{S_{ij}}{D_{ij}} - 0.0386 * 2 + \ln \frac{2}{8.565 * 10^{-4} * S_{ij} * 1000 / (25.4 * 12) \sqrt{f/\rho}} \right) \quad (2.20)$$

Simplifying the equations (2.19) & (2.20), the modified Carson's equations can be written in SI units:

$$\hat{z}_{ii} = r_i + \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{ii} \sqrt{f/\rho}} \right) \quad (2.21)$$

$$\hat{z}_{ij} = \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{ij} \sqrt{f/\rho}} \right) \quad (2.22)$$

Where,

$\rho$  is the ground resistivity in  $\Omega m$

$D_{ii}$ - Geometric Mean Radius (GMR), for circular conductor

$$D_{ii} = e^{-1/4} R$$

$R$  is the physical radius

$D_{ij}$  - Geometric Mean Distance (GMD)



Primitive impedance matrix for certain set of conductors can be developed using equation (2.21) and (2.22).

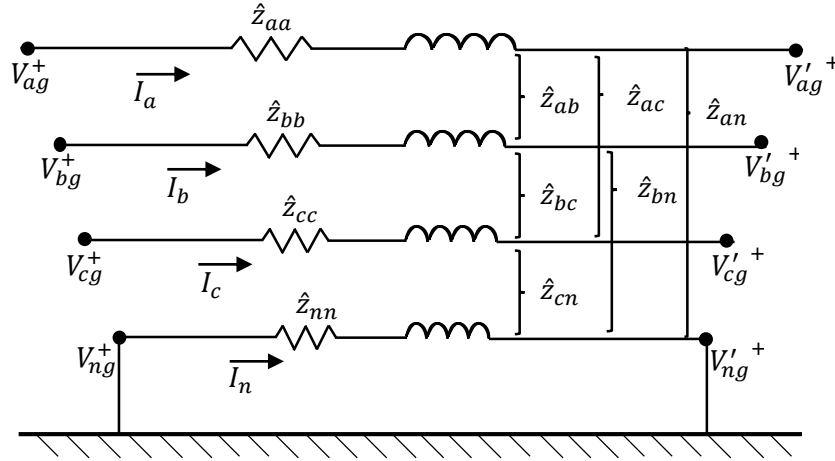


Figure 2.3: Neutral grounded line segment

Figure 2.3 shows segment of three phase four wire conductors system with grounded neutral. Primitive impedance matrix can be written as;

$$[Z_{abcn}] = \begin{bmatrix} \hat{Z}_{aa} & \hat{Z}_{ab} & \hat{Z}_{ac} & \hat{Z}_{an} \\ \hat{Z}_{ba} & \hat{Z}_{bb} & \hat{Z}_{bc} & \hat{Z}_{bn} \\ \hat{Z}_{ca} & \hat{Z}_{cb} & \hat{Z}_{cc} & \hat{Z}_{cn} \\ \hat{Z}_{na} & \hat{Z}_{nb} & \hat{Z}_{nc} & \hat{Z}_{nn} \end{bmatrix} \quad (2.23)$$

Line to ground voltage difference in each conductor segment can be written as [12],

$$\begin{bmatrix} V_{drop_a} \\ V_{drop_b} \\ V_{drop_c} \\ V_{drop_n} \end{bmatrix} = \begin{bmatrix} \hat{Z}_{aa} & \hat{Z}_{ab} & \hat{Z}_{ac} & \hat{Z}_{an} \\ \hat{Z}_{ba} & \hat{Z}_{bb} & \hat{Z}_{bc} & \hat{Z}_{bn} \\ \hat{Z}_{ca} & \hat{Z}_{cb} & \hat{Z}_{cc} & \hat{Z}_{cn} \\ \hat{Z}_{na} & \hat{Z}_{nb} & \hat{Z}_{nc} & \hat{Z}_{nn} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \\ I_n \end{bmatrix} \quad (2.24)$$

Line to Neutral voltage can be written as,

$$\begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = \begin{bmatrix} V'_{an} \\ V'_{bn} \\ V'_{cn} \end{bmatrix} + \begin{bmatrix} V_{drop\_a} \\ V_{drop\_b} \\ V_{drop\_c} \end{bmatrix} - \begin{bmatrix} V_{drop\_n} \\ V_{drop\_n} \\ V_{drop\_n} \end{bmatrix} \quad (2.25)$$

Difference between impedance matrixes developed using Full Carson's equation and Modified Carson's equations is not significant according to the sample calculation done in [16]. As per the assumptions made deriving above equations, resistance existing between ground and line are ignored. Most distribution system overhead line models follow the same assumption. Based on that assumption, further simplification can be done for primitive impedance matrix to calculate primitive phase impedance matrix where method called as Kron reduction. But resistance between neutral and ground is needed to incorporate for accurate analysis [10], [11]. So voltage can be exists between neutral to ground.

Authors of [9] discussed about the application of Deri (Dubanton), Modified Carson and a full Carson approach for line impedance calculations for particular line segment. They discussed results variation at different frequencies and impact of different assumptions made for the internal impedance calculation of the conductors and handling of the conductor GMR. Most of the distribution systems are using stranded conductors for their network. As per the [12], Authors justified that negligible difference in the impedance matrix for stranded conductors (with gaps) compared to the conductor consisting uniform solid material with the same average conductivity.

So influence of modeling assumptions related to low voltage overhead distribution network is dependent on the application. Modified Carson's equation is proposed to apply for this research to calculate conductor impedance including ground effect. Also grounding impedance is considered without making assumption of solidly grounding at grounding positions. Ground path self-impedance approximated only for resistive component during the unbalance current division

calculation between neutral and ground path and justified sufficiency for the scope during this research as per described in the Chapter-3.

## **2.2 Power Flow Analysis Methods for Steady State Analysis**

There are several load flow analysis methods available and selection of appropriate method for particular application is a challenge. Most of the commercially available softwares are not developed for unbalance power flow analysis and customization for integrating applications is restricted due to their proprietary nature. Some of the three phase four wire systems are simplified in to three wire system with assumptions during software development. So requirement is raised to select load flow method and need to modify appropriate for neutral grounded distribution system during this research scope to evaluate consumer connection patterns which are generated by proposed consumer connection pattern generation algorithm at chapter-5.

Generally active and reactive power flow in the power system is interpreted as power flow or load flow of the system. Load flow analysis is important activity related to power system. These analyses provide network voltages, phase angle, branch current... etc. under steady state condition. Determination procedure comprises of mathematical approach with non-linear equations. So iterative techniques are used during such analysis [17], [18].

Forward/ Backward sweep method is commonly used most applicable method for radial distribution networks. Association of ground return path in to the distribution system creates some modification requirement for traditional Forward/ Backward sweep method. Convergence problems are common for most iterative methods like forward/backward sweep and that will be depend on the algorithm specified. Ground and neutral path current division is questionable in grounded distribution systems. If the ground to neutral voltages are used for calculation of ground current during Forward/ Backward sweep method, then that will create convergence problem as mentioned in some case studies [12] .Unknown self-impedance of ground path is influenced for determination of current division between the ground and neutral

paths using impedance ratio method. There are different proposals to separate ground impedance from Carson's equation to incorporate the current division calculation [13]. These methods are based on some assumptions. Self-impedance of the ground path is approximated in to resistive component during load flow analysis within this research and accuracy is sufficient due to large resistance existence in the grounding path including grounding rod resistance compare to reactive component. So Forward/ Backward sweep method is proposed to use incorporation with this current division method during this research.

Method	Applicability & requirements
Backward/Forward Sweep	<ul style="list-style-type: none"> <li>• High R/X Ratio</li> <li>• Radial Or Weekly Meshed Networks</li> </ul>
Newton Raphson	<ul style="list-style-type: none"> <li>• Need Jacobian Matrix</li> <li>• Not successes when Jacobian Matrix becomes singular</li> <li>• Not Suitable For High R/X Ratio</li> <li>• Developed Specially For Transmission Systems</li> </ul>
Gauss-Seidel method admittance matrix(YGS)	<ul style="list-style-type: none"> <li>• Need admittance matrix</li> <li>• Not suitable for High R/X Ratio</li> <li>• Not suitable for Higher loading level</li> </ul>

Table 2.1: Power flow methods and applicability

### 2.3 Methods for Electricity Distribution Network Optimization

Load balancing among different phases is one of most important factor for network optimization. Loads in the electricity distribution network can be represented by consumer connections at nodes. Load arrangement among phases is correspondent to consumer connection arrangement. So appropriate consumer connection arrangement is prime requirement for distribution sector. Traditional load balancing technique is

based on the number of connections equally divide between phases. Sometimes current measurements at peak demand are considered. Consumers are not equally demand at all. Consumer load profiles are most important input for consumer allocation. So possible consumer connection patterns are need to evaluate using appropriate network model, accurate load profiles and load flow analysis method for better network optimization. Presently such kinds of methods are not used by the Sri Lankan distribution network operators.

### 3 IMPEDANCE MODEL FOR RADIAL DISTRIBUTION FEEDER WITH GROUND RETURN

Three phase four wire neutral grounded overhead radial distribution systems are considered for evaluation of proposed optimization technique within this research scope. Neutral grounded system modeling is somewhat complex comparing to the ungrounded systems. Neutral conductor start and end grounded configurations are used for analysis. Series Impedances and shunt capacitance represent the cable in the electrical circuit. Effect of Shunt capacitance can be neglected in the low voltage distribution systems [13]. Normally feeder starts from transformer bushing and transformer is represented by voltage source during analysis. Unbalance current divided between neutral conductor and ground path at each node in such distribution system. Ground current at each node flows to source through ground return path. Modified Carson's equation is applicable to calculate primitive impedance matrix which provides better accuracy by simple calculation as discussed in the previous chapter for this network. Stranded aerial bundle conductors are used in considered network. GMR calculation is done for stranded conductors same as conductor consisting uniform solid material as justified at [12]. Figure 3.1 shows the physical arrangement of considered feeder.

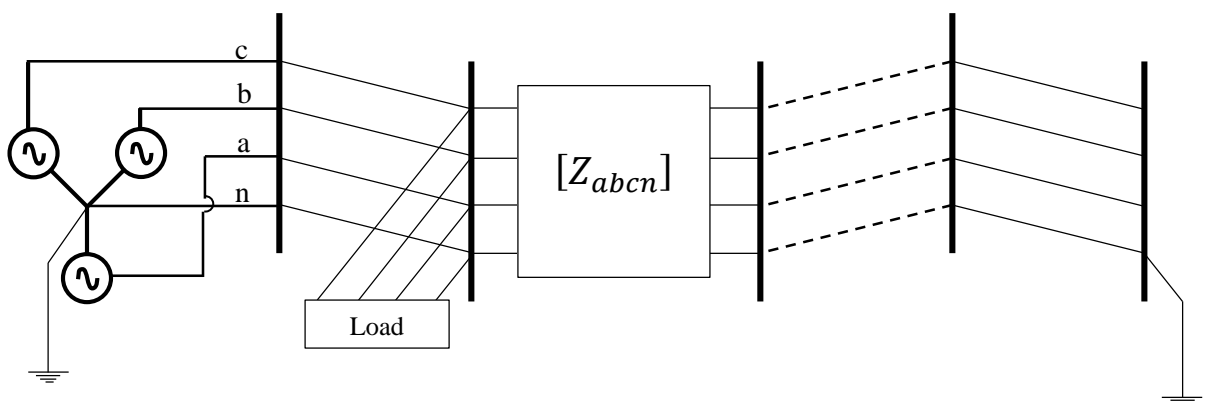


Figure 3.1: Physical arrangement of considered feeder.

### 3.1 Development of Power Flow Algorithm for Considered Network Model

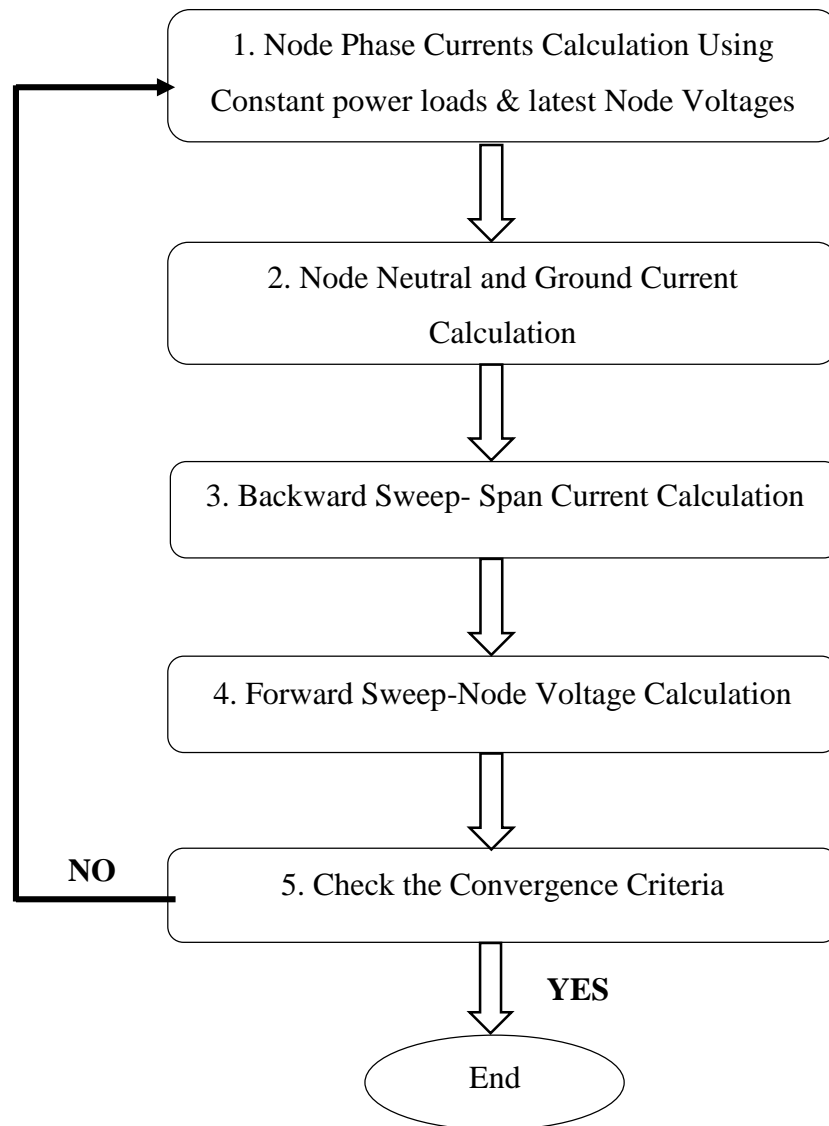


Figure 3.2: Power flow analysis algorithm

Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) is directly applied on forward backward sweep iterative method [14]. Modification is proposed for traditional forward backward sweep iterative method to include ground return path effect for steady state analysis of considered three phase four wire overhead distribution feeder. Ground return path effect is associated in to primitive impedance matrix and node unbalance current division. Ground path current of each node is included at each iteration step of backward sweep.

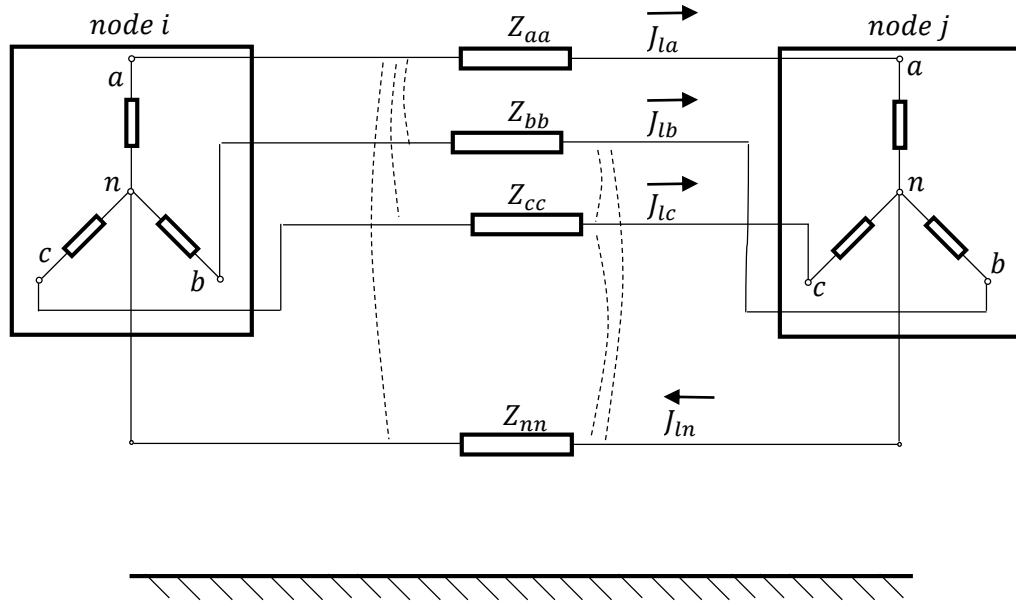


Figure 3.3: Model of the three-phase four-wire distribution line

**Step 1: Node current calculation:**

Figure 3.2 shows algorithm proposed for power flow analysis. Figure 3.3 presents model for intermediate span of considered feeder. Root node is assumed as slack node which has known voltage and phase angle. Iteration process can be start by assigning root node voltage for all nodes.

The current flowing outward from root node is considered as positive direction as convention. The current drawn at node-i from phase “x” at  $k^{th}$  iteration can be calculated by,

$$I_{i,x}^{(k)} = \left( S_{i,x} / V_{i,x}^{(k-1)} \right)^* + y_{i,x} * V_{i,x}^{(k-1)} \quad (3.1)$$

Where,

$$i = 1, 2, 3 \dots N$$

$$x = a, b, c$$

$S_{i,x}$  = constant real and reactive power load (PQ load) connected to phase x



$V_{i,x}^{(k-1)}$  is the voltage at node- $i$  of phase  $x$  reference to neutral which calculated at  $(k - 1)^{th}$  iteration.

$y_{i,x}$  is shunt capacitance element of node  $i$  of phase  $x$ . Shunt capacitance can be ignored for low voltage distribution systems as mentioned earlier chapter.

Using equation (3.1), node phase current matrix can be calculated as follows.

$$\begin{bmatrix} I_{i,a} \\ I_{i,b} \\ I_{i,c} \end{bmatrix}^k = \begin{bmatrix} (S_{i,a}/V_{i,a}^{(k-1)})^* \\ (S_{i,b}/V_{i,b}^{(k-1)})^* \\ (S_{i,c}/V_{i,c}^{(k-1)})^* \end{bmatrix} \quad (3.2)$$

**Step 2: Node neutral and ground current calculation:**

Unbalance current of node  $i$  at  $k^{th}$  iteration can be calculated

$$I_{i,u}^{(k)} = I_{i,a}^{(k)} + I_{i,b}^{(k)} + I_{i,c}^{(k)} \quad (3.3)$$

Representing loads as current sources, Unbalance current division between neutral conductor and ground path at  $k^{th}$  iteration can be illustrated as Figure 3.4.

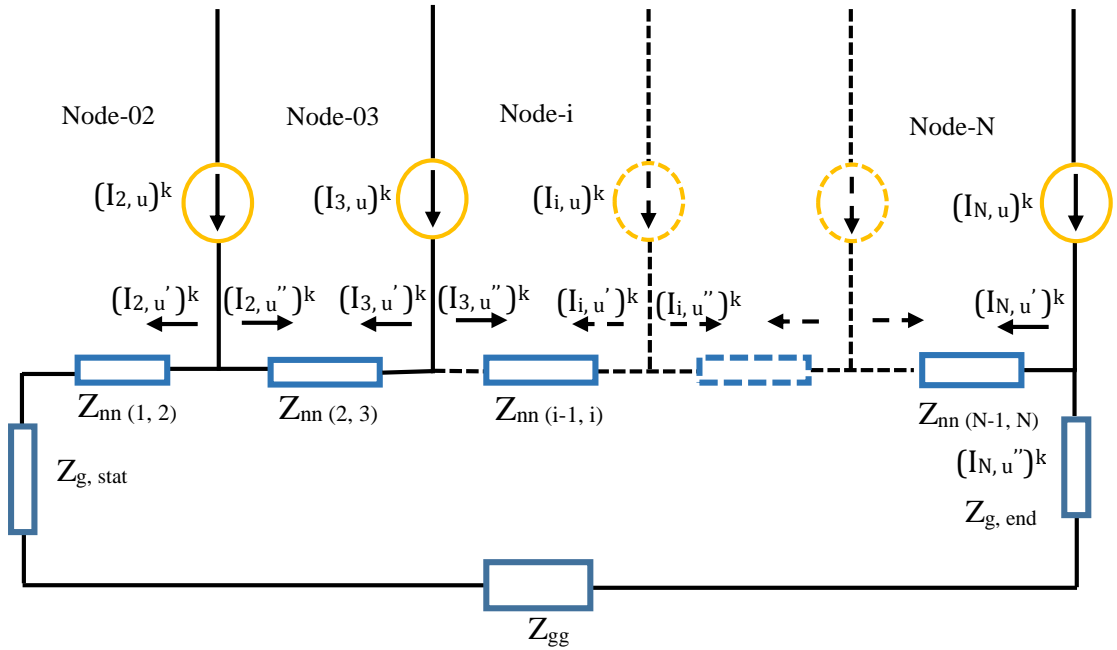


Figure 3.4: Unbalance current division

Unbalance current division between neutral and ground path can be calculated using following equation except first node. There will not be ground current component at first node due to direct connection to the source [13].

Neutral current at node i,

$$(I_{i,n})^k = (I_{i,u})^k * (Z_{back\_i} / (Z_{front\_i} + Z_{back\_i})) \quad (3.4)$$

Ground current at node i,

$$(I_{i,g})^k = (I_{i,u})^k * (Z_{front\_i} / (Z_{front\_i} + Z_{back\_i})) \quad (3.5)$$

Where:

$$Z_{back\_i} = [Z_{nn(i,i+1)} + Z_{nn(i+1,i+2)} + \dots + Z_{nn(N-1,N)}] + Z_{g,end} + Z_{gg} + Z_{g,start} \quad (3.6)$$

$$Z_{front\_i} = [Z_{nn(1,2)} + Z_{nn(2,3)} + \dots + Z_{nn(i-1,i)}] \quad (3.7)$$

$Z_{nn(i+1,i+2)}$  = self-impedance of neutral conductor between node (i+1) to node (i+2)

$Z_{g,end}$  = Neutral grounding impedance at feeder end

$Z_{g,start}$  = Neutral grounding impedance at feeder start

$Z_{gg}$  = Ground path self-impedance

Above current division procedure is applicable to nodes where unbalance current is available. So this indicates unbalance current return from neutral conductor as well as ground path according to the impedance ratio. But ground path self-impedance determination is questionable. As per the [13], proposed method to separate terms related self-impedance of ground path from Carson's equation. That is only valid for certain assumptions [12].

Reconsidering terms included in the equations (2.5) & (2.6) and modified Carson's equations (2.21) & (2.22) for phase "a" and neutral conductor "n",

$$\hat{Z}_{aa} = \bar{z}_{aa} + \bar{z}_{gg} - \bar{z}_{ga} - \bar{z}_{ag}$$

$$\hat{Z}_{an} = \bar{z}_{an} + \bar{z}_{gg} - \bar{z}_{gn} - \bar{z}_{ag}$$

$$\hat{z}_{aa} = r_a + \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{aa}\sqrt{f/\rho}} \right)$$

$$\hat{z}_{an} = \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{an}\sqrt{f/\rho}} \right)$$

Primitive self-impedance consists of self-impedance of conductor, self-impedance of the ground path and mutual impedance between conductors and ground path.

Primitive mutual-impedance consists of self-impedance of the ground path and mutual impedance between conductors and ground path.

Equating above equation

$$\bar{z}_{aa} + \bar{z}_{gg} - \bar{z}_{ga} - \bar{z}_{ag} = r_a + \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{aa}\sqrt{f/\rho}} \right) \quad (3.8)$$

$$\bar{z}_{an} + \bar{z}_{gg} - \bar{z}_{gn} - \bar{z}_{ag} = \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{an}\sqrt{f/\rho}} \right) \quad (3.9)$$

Equation (2.21) is the simplified version of Equation (2.5). Resistance of the overhead conductor and ground path can be clearly distinguishable according to the simplified equations (3.8) & (3.9). Considering reactance part of (2.21), includes self- reactance of phase conductor “a”, self- reactance of ground path and mutual reactance between conductors “a” and ground. Self-reactance of phase conductor “a” can be determined using following equation.

$$\bar{z}_{aa} = r_a + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{1}{D_{aa}} \right)$$

Calculated self-reactance of phase “a” for considered feeder is 0.00036278  $\Omega/m$ . calculation details are attached in Appendix A.

But mutual and self-inductance of ground cannot be clearly separated from the inductance term of Equation (3.8). But value of total reactance for all three types of inductance at frequency of 50Hz is,

Total reactance = 0.00079237  $\Omega/m$ .

Calculation details are attached in Appendix A.

So reactance except conductor “a” can be written as

$$(\bar{Z}_{gg} - \bar{Z}_{ga} - \bar{Z}_{ag})_{reactance} = 0.00042959 \Omega/m \quad (3.10)$$

Measured grounding resistance at feeder start for considered feeder is 63  $\Omega$  .

Measured grounding resistance at feeder end for considered feeder is 63  $\Omega$  .

Calculated per meter resistance of fictitious ground conductor is 0.000049345  $\Omega/m$ . Calculation details are attached in Appendix A.

Total ground path resistive components of considered feeder including grounding resistance at feeder start, end and per meter resistance of fictitious ground conductor is,

$$R_{g,end} + R_{g,start} + R_g = 63 + 63 + 0.000049345 = 126.0000493$$

Reactance of ground conductor cannot be clearly distinguishable from equation (3.10) and value is negligible compare to total resistance of ground path.

So that will not heavily influence for power flow calculation.  $\bar{Z}_{gg}$  can be approximated only for resistive component as follows during this research scope.

$$\bar{Z}_{gg} = \frac{\mu_0 \omega}{8} \quad (3.11)$$

### ***Step 3: Backward sweep- Span current calculation***

Span current calculation start from the last ordered span for phase and neutral conductors. Phase span currents of segment “l” referring to Figure 3.3 can be calculated by,

$$\begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \end{bmatrix}^{(k)} = \begin{bmatrix} I_{j,a} \\ I_{j,b} \\ I_{j,c} \end{bmatrix}^{(k)} + \sum_{m \in M} \begin{bmatrix} J_{ma} \\ J_{mb} \\ J_{mc} \end{bmatrix}^{(k)} \quad (3.12)$$

M is the set of spur lines connected downstream to node-j.

Resultant current at neutral conductor for considered span can be calculated by ground current return from node close to upstream direction and neutral current belong to successive downstream node. Ground currents return to considered span from upstream node,

$$(J_{lg})^k = (I_{i,g})^k + \sum_{u \in Z} (J_{u,g})^k \quad (3.13)$$

Z is the set of spur lines connected upstream to node-i. “i” and “j” are consecutive nodes belong to same span.

Phase currents, neutral current and ground return current within neutral conductor for a particular span can be written as,

$$\begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \\ J_{ln} \\ J_{lg} \end{bmatrix}^{(k)} = \begin{bmatrix} I_{j,a} \\ I_{j,b} \\ I_{j,c} \\ -(I_{j,n}) \\ I_{i,g} \end{bmatrix}^{(k)} + \begin{bmatrix} \sum_{m \in M} J_{m,a} \\ \sum_{m \in M} J_{m,b} \\ \sum_{m \in M} J_{m,c} \\ \sum_{m \in M} J_{m,n} \\ \sum_{u \in Z} J_{u,g} \end{bmatrix}^{(k)} \quad (3.14)$$

“i” and “j” are successive nodes and Z is the set of spur lines connected to upstream node-i. M is the set of spur lines connected to downstream node-j.

Span current matrix including resultant neutral conductor current can be written as,

$$\begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \\ J_{lnR} \end{bmatrix} = \begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \\ J_{lg} + J_{ln} \end{bmatrix} \quad (3.15)$$

**Step 4: Forward sweep:-Nodal voltage calculation**

$$\begin{bmatrix} V_{drop_{(l,a)}} \\ V_{drop_{(l,b)}} \\ V_{drop_{(l,c)}} \\ V_{drop_{(l,n)}} \end{bmatrix} = \begin{bmatrix} \hat{z}_{aa} & \hat{z}_{ab} & \hat{z}_{ac} & \hat{z}_{an} \\ \hat{z}_{ba} & \hat{z}_{bb} & \hat{z}_{bc} & \hat{z}_{bn} \\ \hat{z}_{ca} & \hat{z}_{cb} & \hat{z}_{cc} & \hat{z}_{cn} \\ \hat{z}_{na} & \hat{z}_{nb} & \hat{z}_{nc} & \hat{z}_{nn} \end{bmatrix} * \begin{bmatrix} J_{la} \\ J_{lb} \\ J_{lc} \\ J_{lnR} \end{bmatrix}$$

Each of the primitive impedance elements can be computed using equation (2.21) & (2.22). Starting from the root node, remaining node voltages can be updated using equation (2.25)

$$\begin{bmatrix} V_{j,an} \\ V_{j,bn} \\ V_{j,cn} \end{bmatrix}^{(k)} = \begin{bmatrix} V_{i,an} \\ V_{i,bn} \\ V_{i,cn} \end{bmatrix}^{(k)} - \left[ \begin{bmatrix} V_{drop_{(l,a)}} \\ V_{drop_{(l,b)}} \\ V_{drop_{(l,c)}} \end{bmatrix} - \begin{bmatrix} V_{drop_{(l,n)}} \\ V_{drop_{(l,n)}} \end{bmatrix} \right]^{(k)}$$

**Step 5: Check the convergence criteria**

After completion of each iteration, check the power mismatch comparing to the defined threshold.

$$\Delta S_{ia}^{(k)} = V_{ia}^{(k)} \left( I_{ia}^{(k)} \right)^* - S_{ia} \quad (3.16)$$

$$\Delta S_{ib}^{(k)} = V_{ib}^{(k)} \left( I_{ib}^{(k)} \right)^* - S_{ib} \quad (3.17)$$

$$\Delta S_{ic}^{(k)} = V_{ic}^{(k)} \left( I_{ic}^{(k)} \right)^* - S_{ic} \quad (3.18)$$

## 4 VALIDATION OF PROPOSED POWER FLOW ALGORITHM

### 4.1 Introduction

Applicability of proposed power flow algorithm for considered feeder model is depend on the closeness of results of steady state analysis to corresponding field measurements. Proposed power flow algorithm was implemented using MATLAB R2008a software. Source voltage, constant real and reactive power load consumed at each node, primitive impedance matrix and span lengths are inputs for this program. Node voltages, node currents, calculated power and span currents are output after the completion of iteration process. Radial distribution feeder belongs to Lanka Electricity Company is selected for this analysis. This feeder is attached to distribution transformer number AZ-0043 located at Dalugama customer service center area.

### 4.2 Primitive Impedance Matrix for Considered Feeder

LECO is used Aerial Bundle Conductor (ABC) for low voltage electricity distribution system. Cable parameters, span lengths and calculation details of primitive impedance matrix are included in the Appendix A.

**Primitive impedance Matrix**  $[Z_{abcn}]$

$$\begin{bmatrix} 0.00065934 + 0.00079237i & 4.9345e-005 + 0.00067703i & 4.9345e-005 + 0.00067703i & 4.9345e-005 + 0.00071154i \\ 4.9345e-005 + 0.00067703i & 0.00065934 + 0.00079237i & 4.9345e-005 + 0.00067703i & 4.9345e-005 + 0.00071154i \\ 4.9345e-005 + 0.00067703i & 4.9345e-005 + 0.00067703i & 0.00065934 + 0.00079237i & 4.9345e-005 + 0.00071154i \\ 4.9345e-005 + 0.00071154i & 4.9345e-005 + 0.00071154i & 4.9345e-005 + 0.00071154i & 0.0010293 + 0.00080054i \end{bmatrix} \quad (4.1)$$

#### 4.2.1 Consumer arrangement details

Table 4.1 shows arrangement of nine consumers connected to considered feeder.

Phase	Node-01	Node-02	Node-03	Node-04	Node-05	Node-06	Node-07	Node-08
R		C1,C2			C7,C8		C9	
Y			C3,C4	C5,C6				
B								

Table 4.1: Consumer connection arrangement

Where,

$C_i$  – Consumer connection of  $i^{th}$  domestic consumer  $i=1, 2, 3, \dots, 9$

Data recordable meters are installed for considered feeder and all the measurements are taken as average values at each 15 minute time interval. Installed meters are 2W three element meters and compatible with IEC 62053 part-11. Reactive power calculated using measured parameters. Same symbolic representation is used for energy meters and consumer connections ( $C_i$ ) within this research scope. Measured parameters and other related details are listed in the Table 4.2. Figure 4.1 Shows energy meter arrangement in the site. Figure 4.2, Figure 4.3, Figure 4.4 and Figure 4.5 are sample of photos of transformer and installed energy meters.



### 4.3 Field Measurements Taken for Validation Process

Location	Application	Meter type	Quantity of meter installed	Measured parameters
Node-02 Node-03 Node-04 Node-05 Node-07	single phase domestic consumer information collection	Direct connected	9	<ul style="list-style-type: none"> <li>• Neutral to phase voltages (V)</li> <li>• Phase current (A)</li> <li>• Active power (kW)</li> <li>• Energy consumption (kWh)</li> <li>• Demand (kVA)</li> <li>• Power factor</li> </ul>
Node-08	LV Feeder information collection(at end)	Direct connected	1	<ul style="list-style-type: none"> <li>• Neutral to phase voltages (V)</li> </ul>
Node-01	LV Feeder information collection (at start - source)	Direct connected	1	<ul style="list-style-type: none"> <li>• Neutral to phase voltages (V)</li> <li>• Phase current (A)</li> <li>• Active power (kW)</li> <li>• Energy consumption (kWh)</li> <li>• Demand (kVA)</li> <li>• Power factor</li> </ul>
Node-01	Neutral conductor information collection(at start -source)	External CT connected	1	<ul style="list-style-type: none"> <li>• Neutral current(A)</li> </ul>

Table 4.2: Details of installed data recordable meters and their application

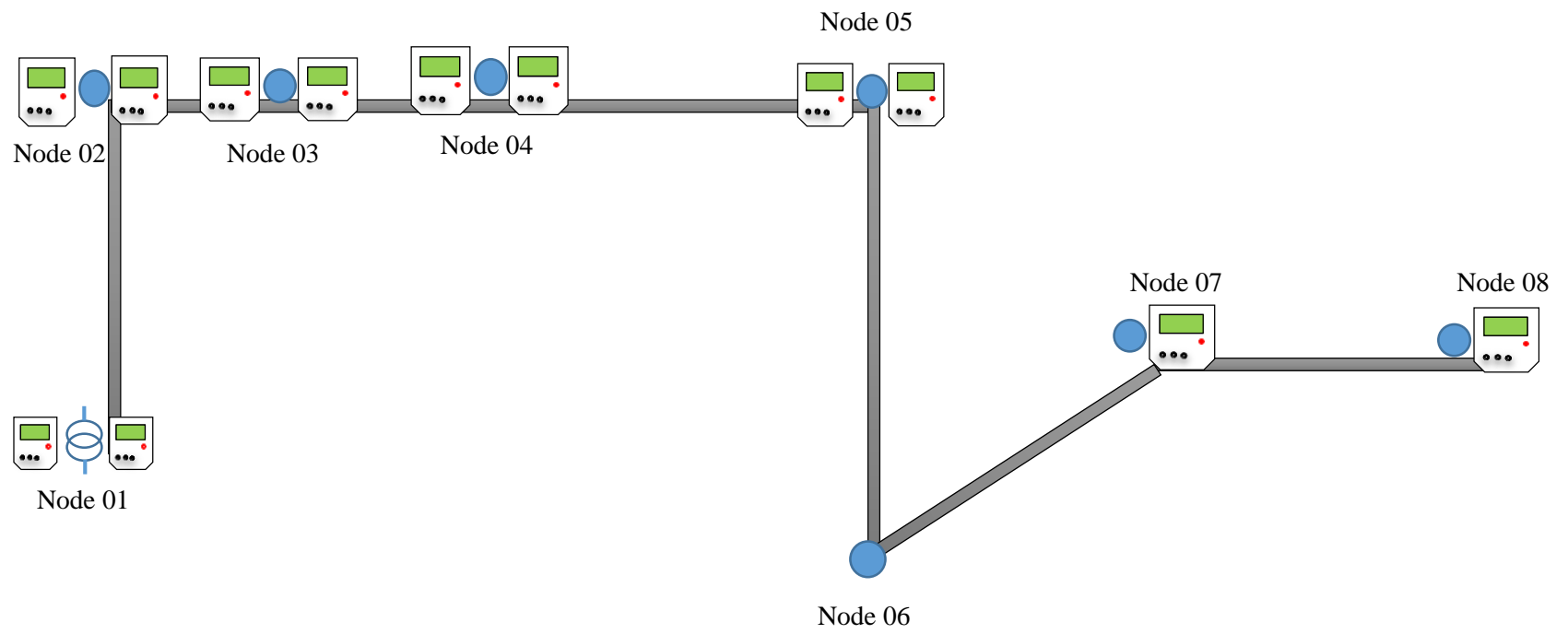


Figure 4.1: Meter arrangement in the field



Figure 4.2: Transformer AZ-0043



Figure 4.3: Energy meters installed at transformer for source detail collection



Figure 4.4: Energy meter installed for domestic consumer



Figure 4.5: Energy meter installed at feeder end

#### 4.4 Method of Validation

Calculated and measured values are compared to check the validity about proposed power flow algorithm. Above procedure is repeated for data set taken for the date of 2016-12-18. Figure 4.6 shows profile of measured and calculated total current drawn at node-02 from phase R. Figure 4.7 shows profile of measured and calculated voltage at node-02 of phase R.

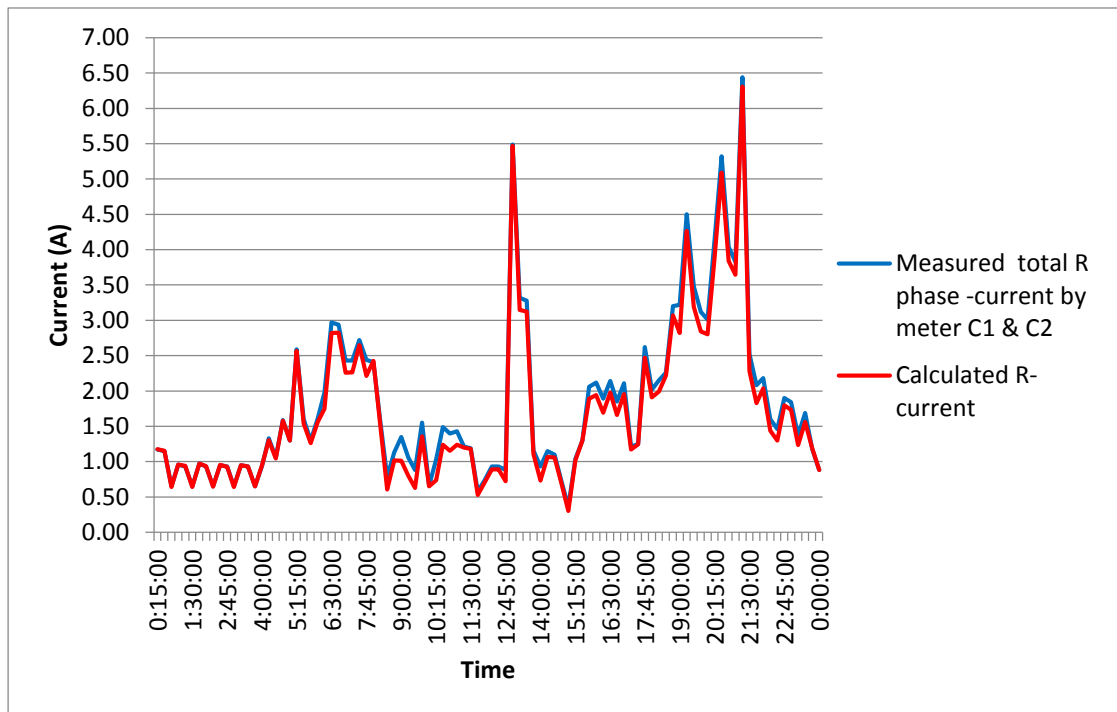


Figure 4.6: Node-02 current profiles taken on 2016-12-18



Figure 4.7: Node-02 voltage profiles taken on 2016-12-18

Measured and calculated parameters are slightly deviated and that can be happen due to many reasons. Figure 4.7 shows voltage measurements taken by two energy meters installed closely at node -02 for two customers connected to phase R. That indicate different voltage values for particular time slot from two energy meters. one possible reason is time synchronization issue of energy meters. Slight time shifting among energy meters can be possible after installation. Calculated Impedance matrix values can be differ from what actually available in conductor. Figure 4.8, Figure 4.9 and Figure 4.10 show how voltage errors vary throughout the day. Voltage errors are defined as difference between calculated and measured values. Figure 4.11 show how current errors vary throughout the day. Current errors are also defined as difference between calculated and measured values.

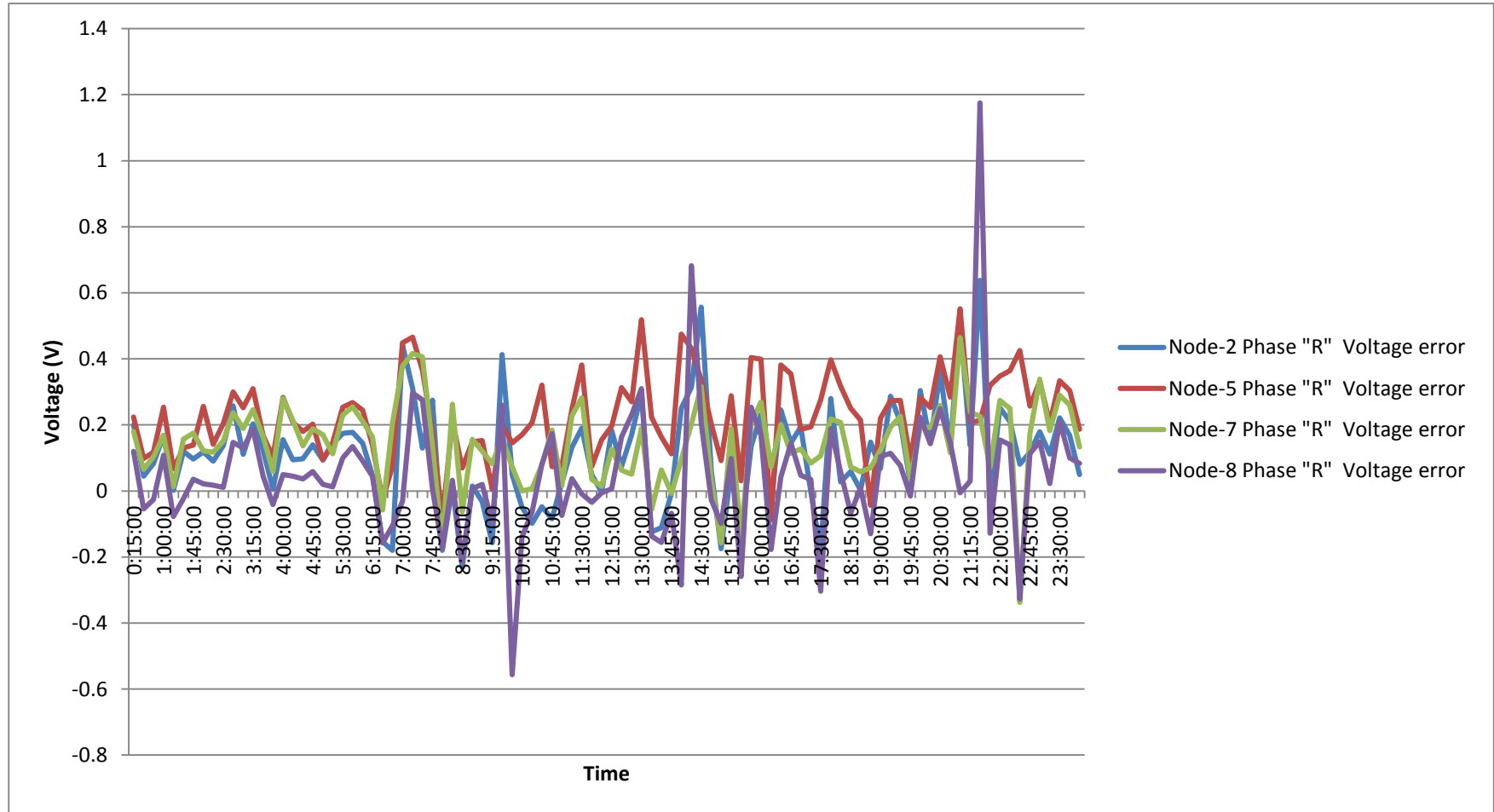


Figure 4.8: Phase "R" voltage error variation



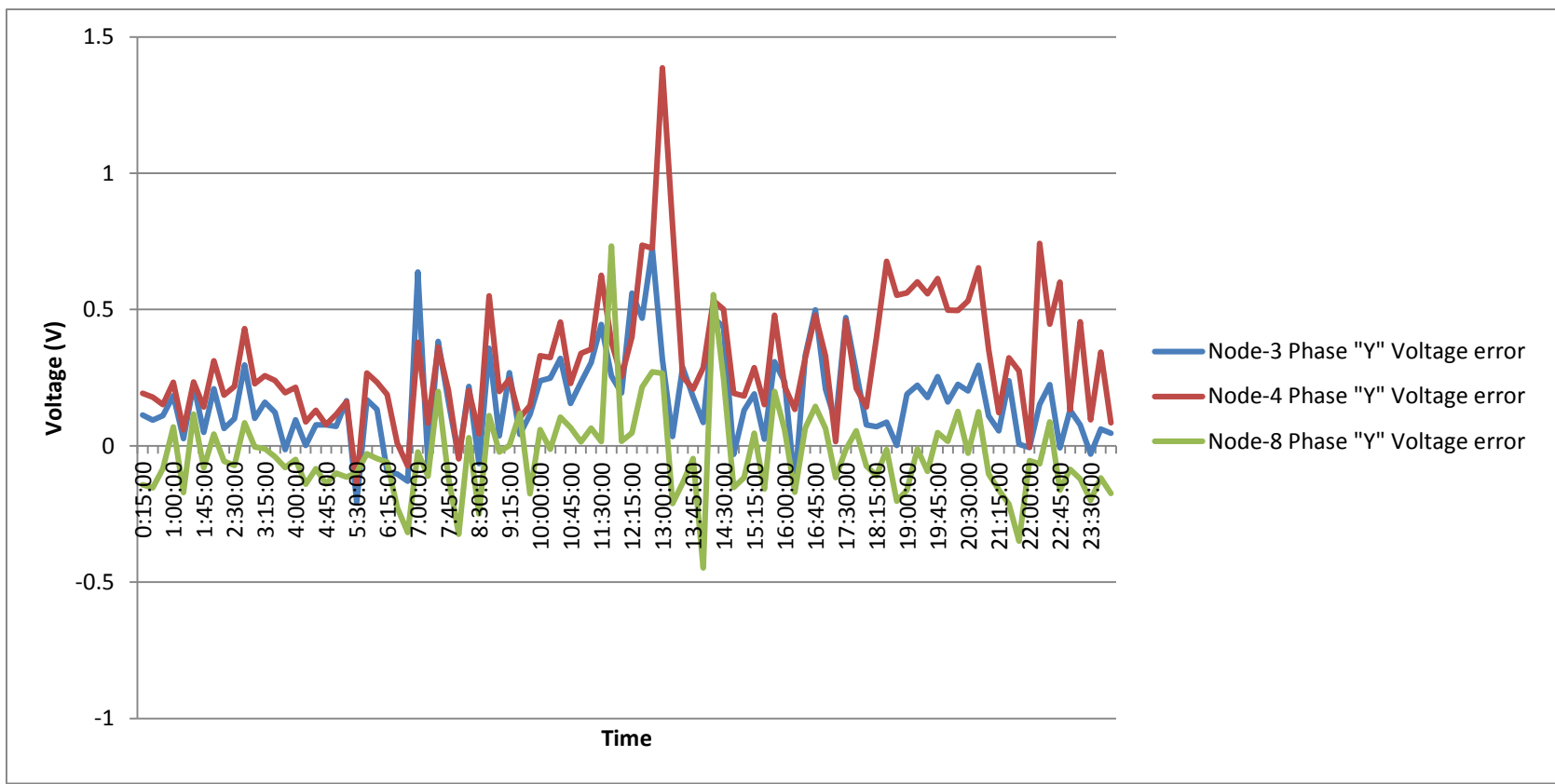


Figure 4.9: Phase "Y" voltage error variation.

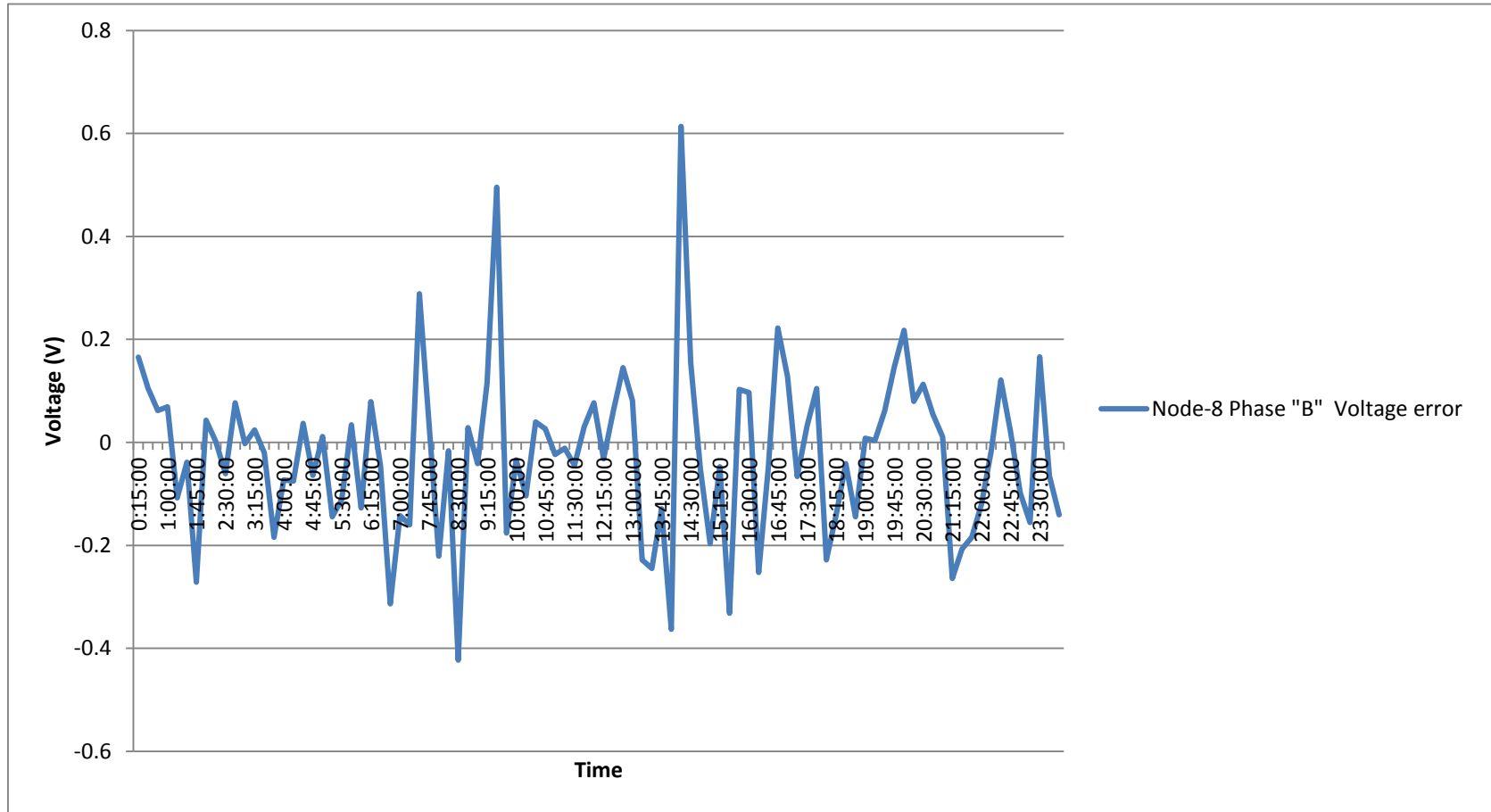


Figure 4.10: Phase "B" voltage error variation.

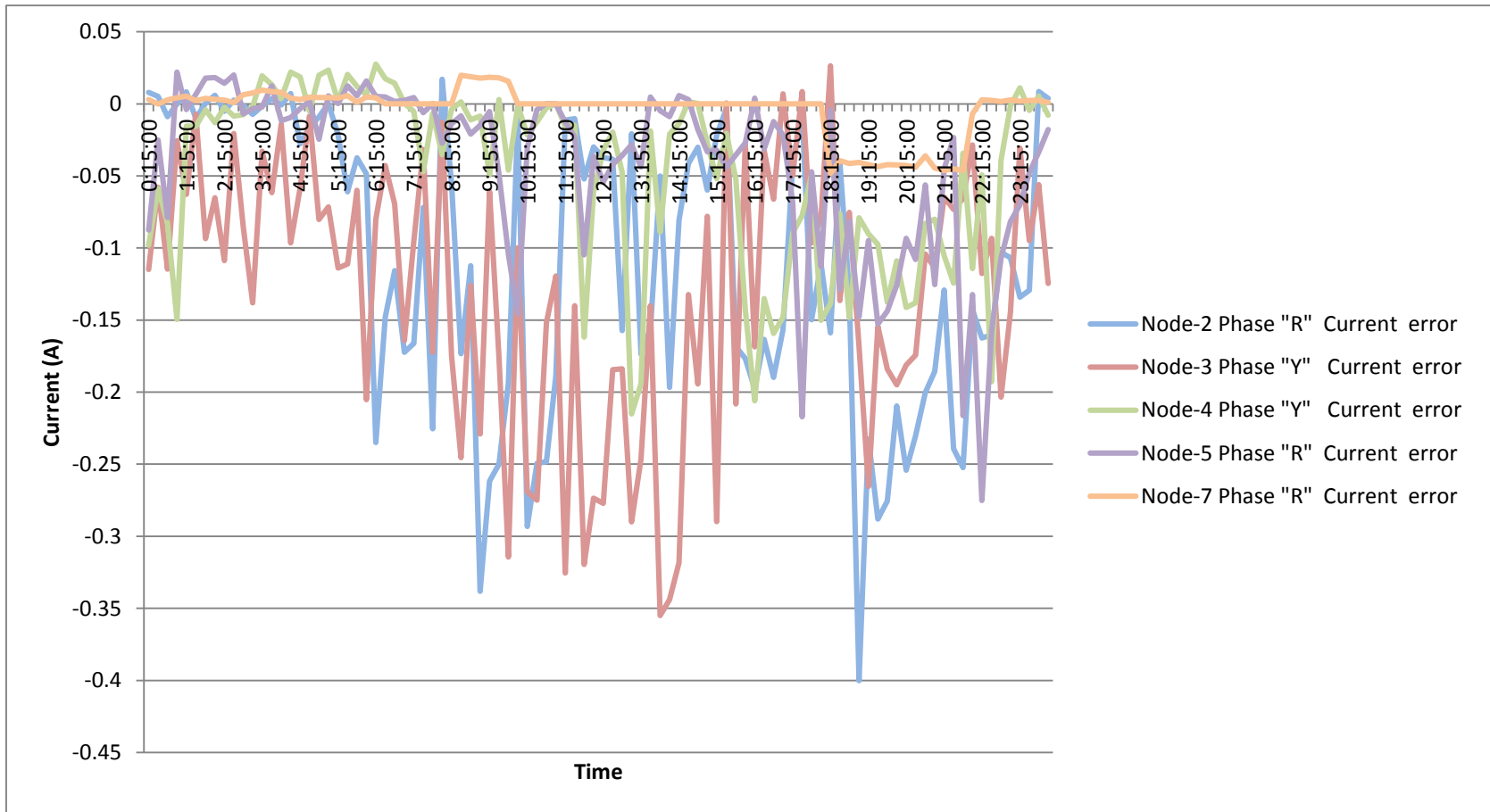


Figure 4.11: Current error variation.

According to the observations from voltage error variation graphs, most of the values are fallen between  $-0.5V$  &  $+0.5$ . Table 4.3 is a summary of number of errors distributed in the observed range. According to the observations from current error variation graphs, most of the values are fallen between  $-0.2V$  &  $+0.2V$ . Table 4.4 is a summary of number of errors distributed in the observed range.

Number of measurements taken	Percentage of number of error values less than $-0.5V$	Percentage of number of error values between $-0.5V$ and $+0.5V$	Percentage of number of error values more than $+0.5V$
768	0.1302	95.8333	4.0365

Table 4.3: Summary of number of Voltage error distribution.

Number of measurements taken	Percentage of number of error values less than $-0.2A$	Percentage of number of error values between $-0.2A$ and $+0.2A$	Percentage of number of error values more than $+0.2A$
480	8.75	91.25	0

Table 4.4: Summary of number of Current error distribution.

So based on the above analysis, conclusion can be made about proposed network model and power flow algorithm provides acceptable accuracy for network status evaluation at next chapters. Program used for validation is included in the Appendix B.

## 5 DEVELOPMENT OF ALGORITHM FOR NETWORK OPTIMIZATION BASED LOAD BALANCING TECHNIQUE

### 5.1 Introduction

Voltages, currents and network losses within feeder are varied throughout the day based on consumer connections arrangement among phases at nodes and their consumption. Network statuses are differed according to the consumer connected pattern although consumption pattern following same style. There are number of possible patterns for assign certain set of consumers among phases along low voltage feeder. Consumer connected pattern is combination of consumer arrangement at each node. But consumers cannot be interchanged between nodes according to practical limitation during combination generation. Network status is depending on aggregated result of individual consumer electricity consumption at certain pattern. So results generated from each consumer connected pattern should be evaluate individually and need to identify most appropriate pattern which create optimum condition for the network. Figure 5.1 shows the proposed algorithm for network optimization based load balancing.

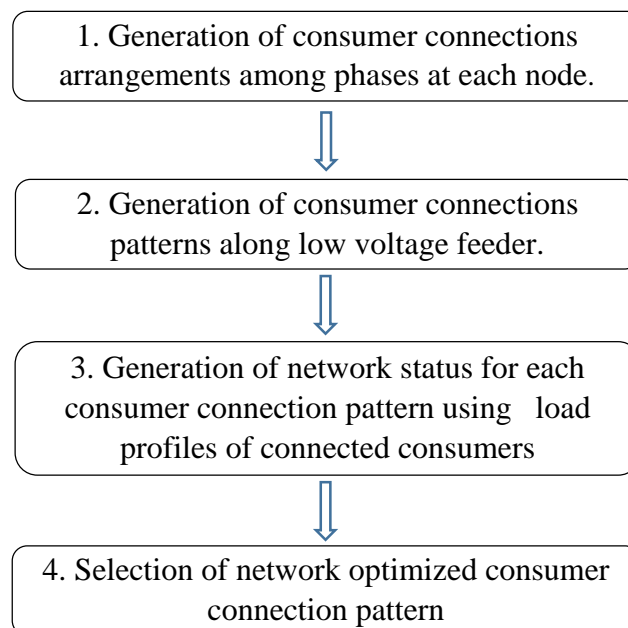


Figure 5.1: Algorithm for Network Optimization Based Load Balancing Technique

## 5.2 Generation of Consumer Connections Arrangements among Phases at a Node

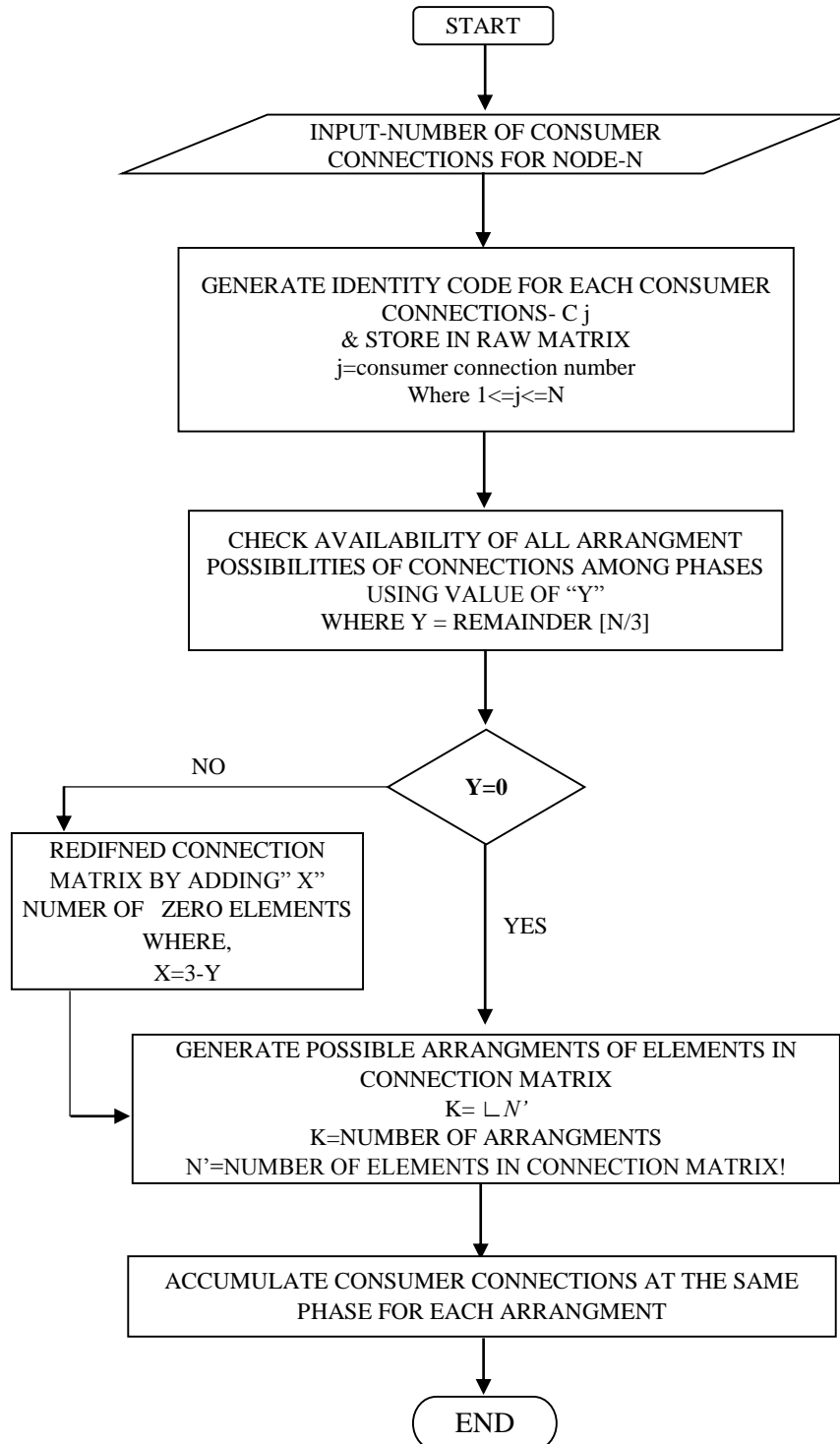


Figure 5.2: Algorithm for Generation of possible consumer arrangements among phases at a node

### 5.2.1 Consumer connections arrangements

Figure 5.2 shows proposed algorithm for generation of consumer connection arrangements. Set of consumer connections belong to certain node can be arranged among phases “R”, “Y” or “B” in different ways. Each consumer connection belongs to certain node is need to have opportunity for placing at all the phases during possible consumer connection arrangements generation within the node. Proposed to store consumer connections in to row matrix and number of consumer connections needed to be triple value to generate all possible arrangements among phase “R”, “Y” and “B”. Zero elements are added to complete number of connections to be as triple value if not match with criteria. Elements of such re defined data set can be ordered in different way and mathematically known as permutations. For “n” number of items per data set, there are  $(n) \times (n-1) \times (n-2) \times (n-3) \dots \times (1) = n!$  permutations will be generated (Factorial of “n”). Each zero element is identified as unique element during data ordering and some of arrangements can be duplicated due to that. Consumer connections at the same phase for certain arrangement will be accumulated to corresponding phase before completion of generating possible consumer arrangements at each node.

Following example described about the possible consumer connections arrangements at node-i using proposed algorithm at section 5.2 for four consumer connections.

**Step-01;**

Node - i			
$C_1$	$C_2$	$C_3$	$C_4$

Table 5.1: Symbolic representations of four consumer connection at Node-i

**Step-02;**

Check the value of  $Y = \text{Remainder}(N/3)$  where  $N=4$  for given case.

$Y=1$

$X=3-Y$

So,  $X=2$

Two numbers of zero elements must be added to connection matrix.

**Step-03;**

Table 5.2 shows redefined consumer connections matrix by adding number of zero elements equal to  $X$ .

R	Y	B	R	Y	B
$C_1$	$C_2$	$C_3$	$C_4$	0	0

Table 5.2: Redefined set of consumer connections

**Step-04;**

Possible arrangements for consumer connections are generated by implementing above algorithm using MATLAB R2008a. Table 5.3 shows sample of arrangements.

Possible arrangement =  $6! = 720$

R	Y	B	R	Y	B
$C_1$	$C_2$	$C_3$	$C_4$	0	0
$C_1$	$C_2$	$C_3$	0	$C_4$	0

Table 5.3: Sample of generated connection arrangements

**Step-05;**

Accumulated consumer connections for sample arrangements are shown in Table 5.4.

R	Y	B
$C_1 + C_4$	$C_2$	$C_3$
$C_1$	$C_2 + C_4$	$C_3$

Table 5.4: Accumulated connection arrangements



### 5.3 Generation of Consumer Connection Patterns along the Low Voltage Feeder

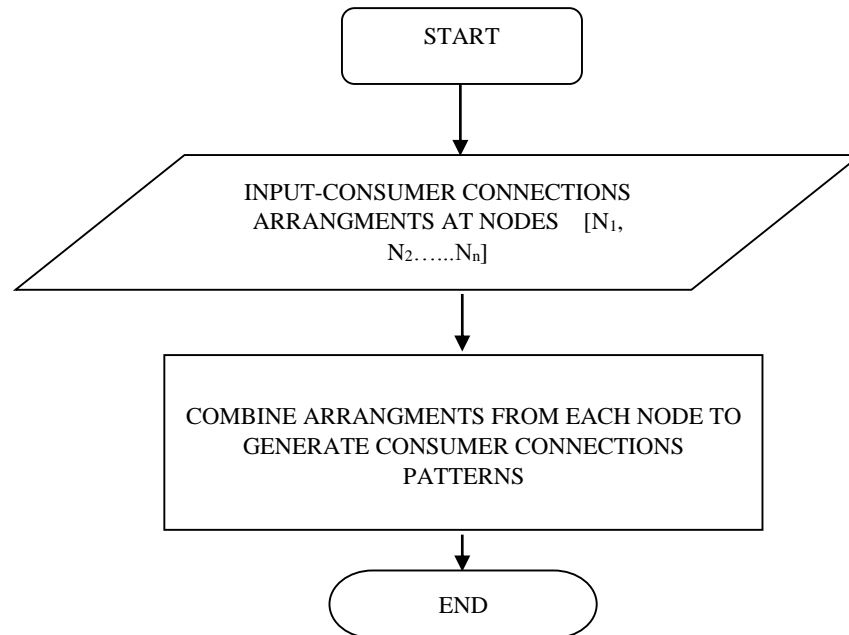


Figure 5.3: Algorithm for consumer connection pattern generation

Possible consumer connection patterns are generated by combining one consumer arrangement from each node at a time. This process continues until all the combinations are generated. Connections are not allowed to swap between poles which originally reserved. Total number of generated combinations is the multiplication of number of phase arrangements at each node.

$$\text{Number of patterns} = (N_1) \times (N_2) \times \dots \times (N_n)$$

Where,

$N_1, N_2, \dots, N_n$  - Number of possible arrangements at nodes.

1, 2... n-Node number

As example, three nodes network consist of one consumer per each and can be generate  $3 \times 3 \times 3 = 27$  of consumer connection patterns. Possible patterns for consumer connections relevant to considered example are generated by implementing above algorithm using MATLAB R2008a.

Node-1			Node-2			Node-3		
R	Y	R	R	Y	B	R	Y	B
$C_1$	0	0	$C_2$	0	0	$C_3$	0	0
0	$C_1$	0	0	0	$C_2$	0	$C_3$	0

Table 5.5: Sample of patterns generated from algorithm

#### 5.4 Generation of Network Status for Each Consumer Connection Pattern Using Load Profiles of Connected Consumer

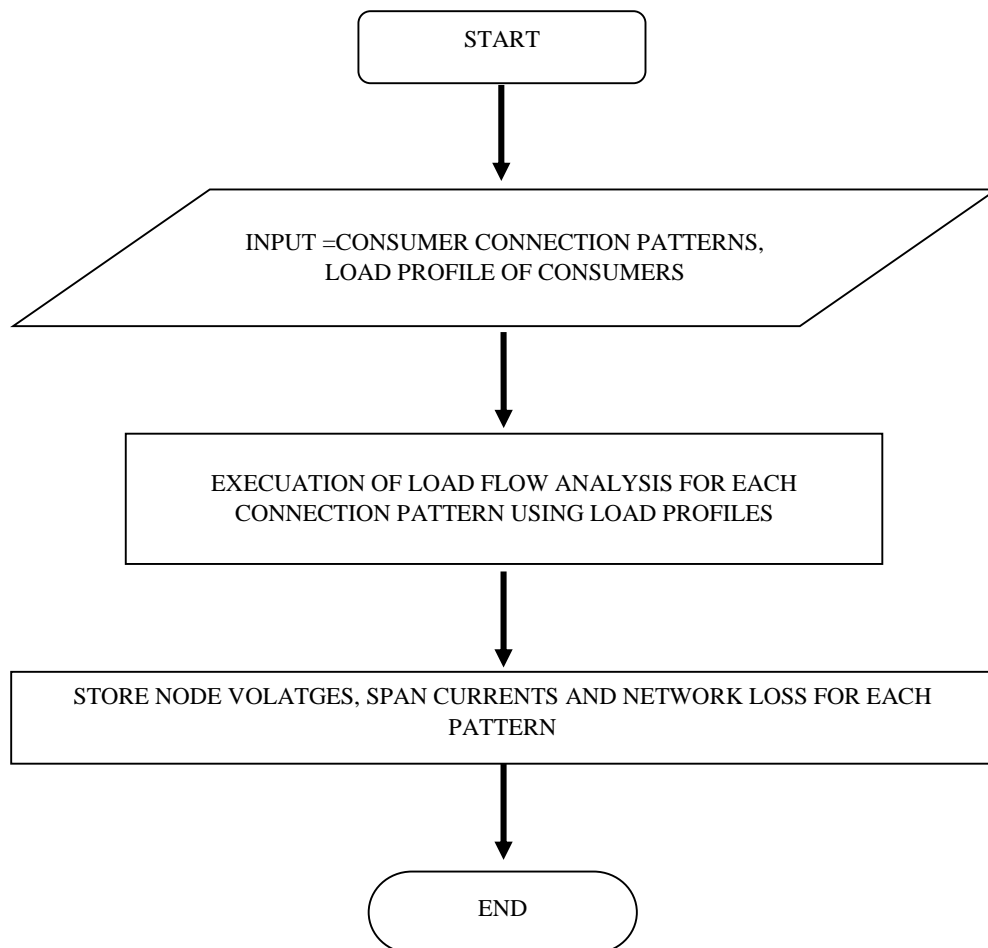


Figure 5.4: Algorithm for network status generation

Load profiles are feed in to load flow program to generate network status for each consumer connection pattern. Load profile is indication of electricity consumption of particular consumer. Time synchronized load profiles of consumers belong to certain feeder can be used to generate network status for the period related to load profile is defined. Load profiles which show similar or approximately similar behaviors of consumers can be grouped and they can be represented by a certain characteristic curve. However characteristic curves used for network status generation to represent each consumer must derive from similar time frame.

### 5.5 Selection of Network Optimized Consumer Connection Pattern

Selection of consumer connection pattern is depending on the evaluation of network status generated for each consumer connection pattern for particular time frame. Objective of distribution network optimization is defined as minimize the total feeder loss generated through conductors and satisfying constraints of maintaining node voltages to fulfill the statutory requirements and span currents below current carrying capacities of the conductors within this research scope.

Load profiles belong to same time frame must be used to select consumer connection pattern which create optimum condition for network. Cross evaluation is needed to conduct for different time frames to find best consumer assignment. Optimum status generated pattern will be selected which highly satisfy the objective function and its constraints.

$$\text{Minimize } \sum_{x=a,b,c,n} \left[ \sum_{t=1}^T \left[ \sum_{i=1}^n (I_{t,i,x})^2 R_{i,x} \right] \right] \quad (5.1)$$

Subjected to,

$$I_{t,i,x} \leq I_x'$$

$$V_{min} \leq V_{t,k,y} \leq V_{max}$$

Where,

$I_x'$  = maximum allowed current at conductor of phase  $x$

$I_{t,i,x}$  = Current at conductor of  $i^{\text{th}}$  span of phase  $x$  at time  $t$

$t = 1, 2, 3 \dots \dots T$

$x = a, b, c, n$

$R_{i,x}$  = Resistance of conductor of  $i^{\text{th}}$  span of phase  $x$

$i$  = span number

$i = 1, 2, 3 \dots \dots, n$

$V_{t,k,y}$  = Voltage at  $k^{\text{th}}$  node of phase  $y$  at time  $t$

$y = a, b, c$

$k$  = node number

$V_{max}$  = Maximum allowed voltage

$V_{min}$  = Minimum allowed voltage

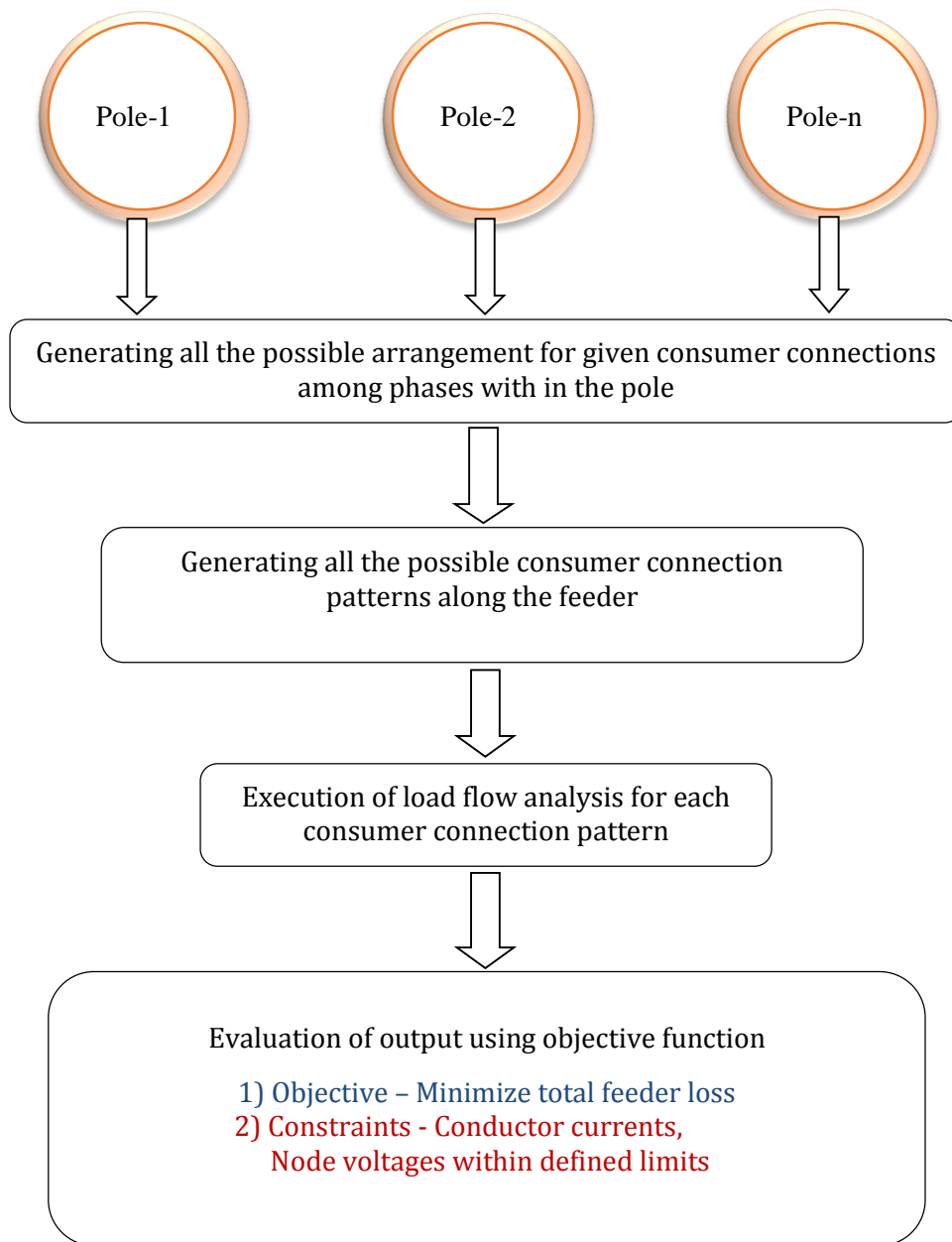


Figure 5.5: Summary of network optimization based load balancing algorithm

## 6 APPLICATION OF PROPOSED LOAD BALANCING TECHNIQUE FOR LOW VOLTAGE FEEDER

### 6.1 Existing Status Analysis of Sample Feeder

Low voltage feeder used for power flow algorithm validation at chapter-4 was selected to analyze the performance of proposed load balancing algorithm at chapter-5. Voltages, currents and power consumptions for the connected consumers and status of the feeder are recorded for the period of 2016-12-18 to 2017-01-11. Electrical characteristic of the considered feeder is needed to be analyzed for understanding the existing status before further improvement. Variation of phase current drawn from source and neutral current return provide indication about the load arrangement within the feeder.

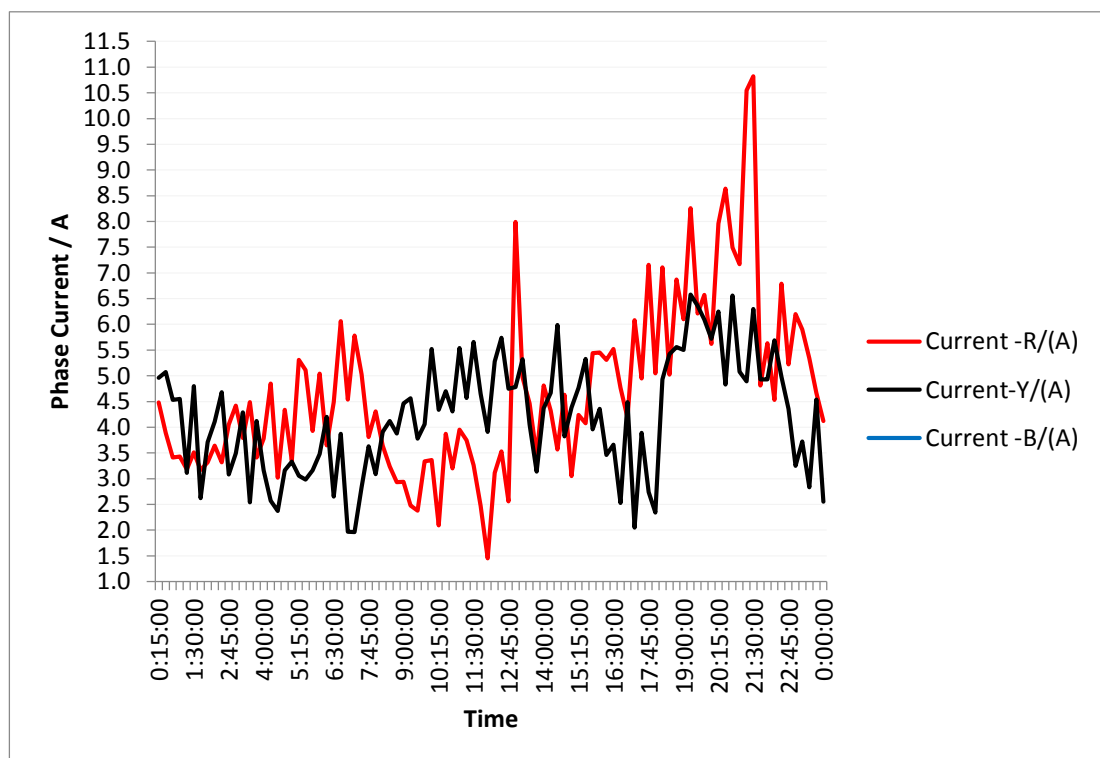


Figure 6.1: Phase Current Variation of Feeder start taken on 2016.12.18

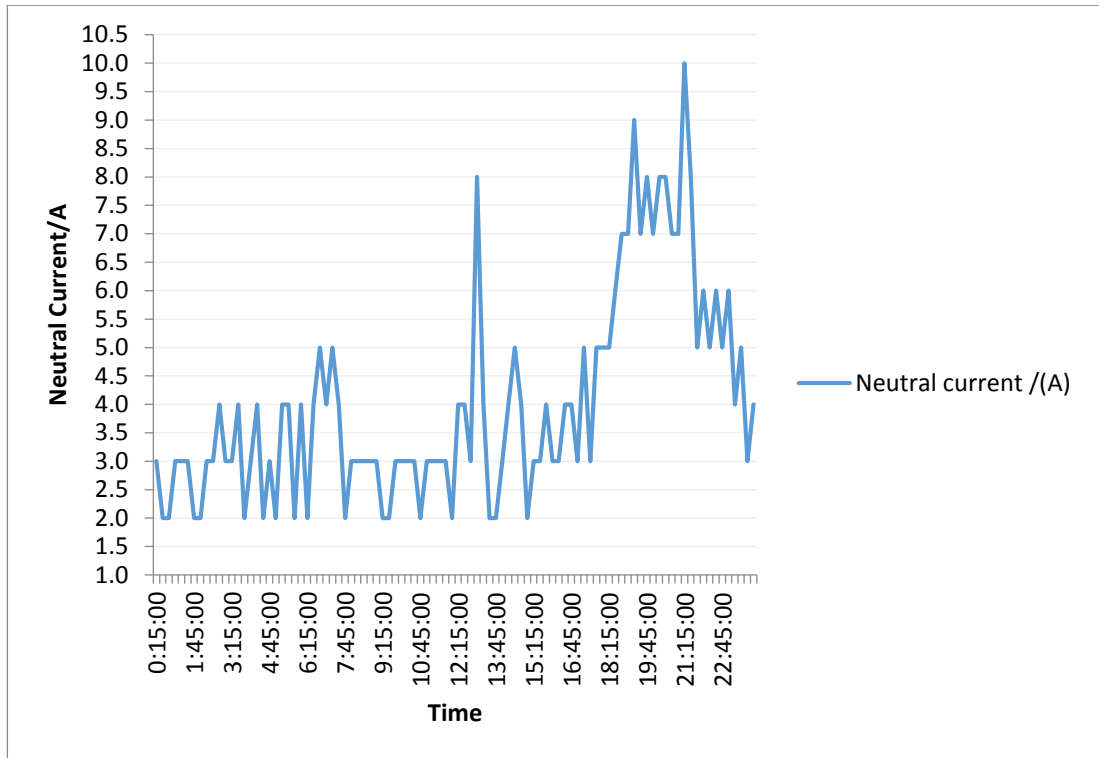


Figure 6.2: Neutral Current Variation of Feeder start taken on 2016.12.18

Considered feeder is newly constructed and consumers are attached only for phase “R” and phase “Y” as described at Chapter-4. Phase current profiles taken at 2016.12.18 are shown in Figure 6.1. Considerable amount of return current is existence relative to number consumer connected according to the Figure 6.2. Analyzing of energy loss occurred on such feeder is important area to study and correlated with current profiles of conductors. Consideration of voltage variation is another important factor for such network.

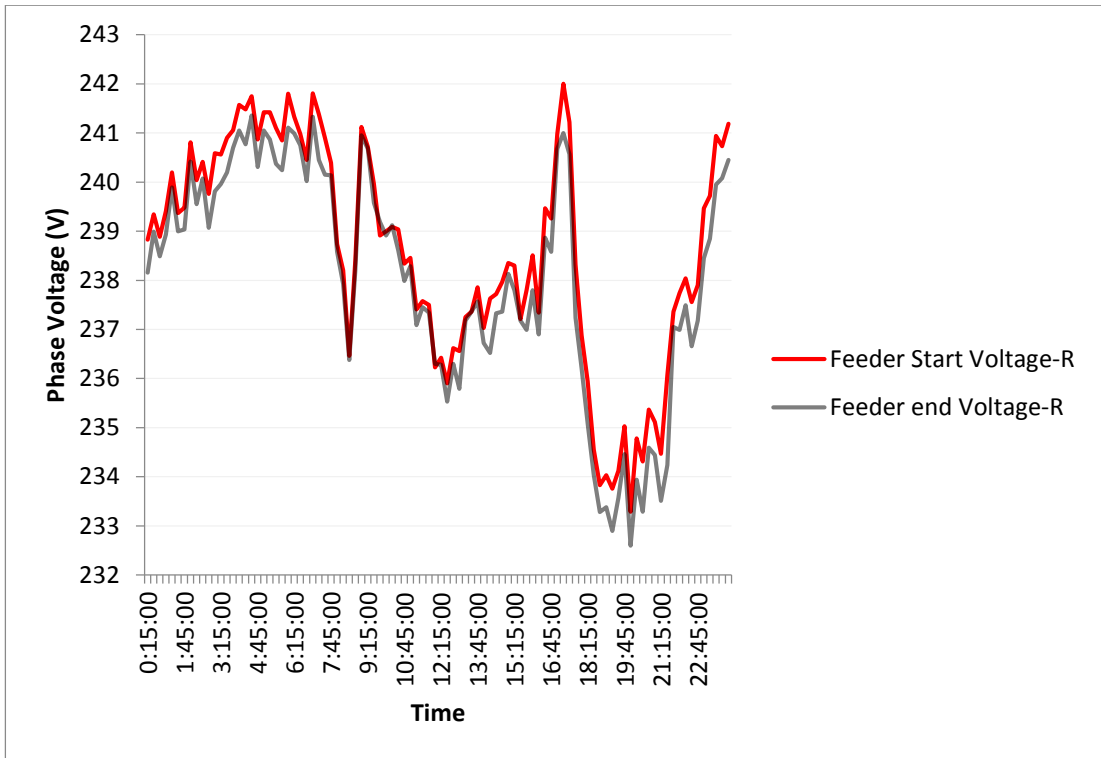


Figure 6.3: Voltage variation at feeder start and end of phase R taken on 2016.12.18

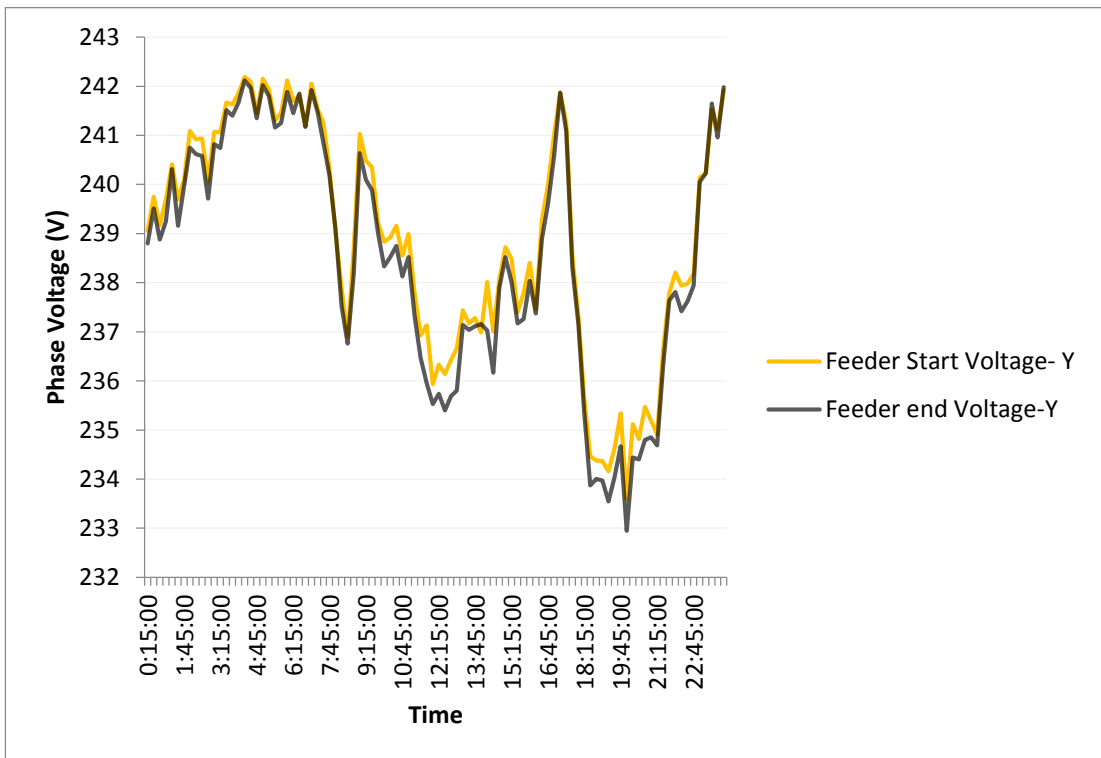


Figure 6.4: Voltage variation at feeder start and end of phase Y taken on 2016.12.18



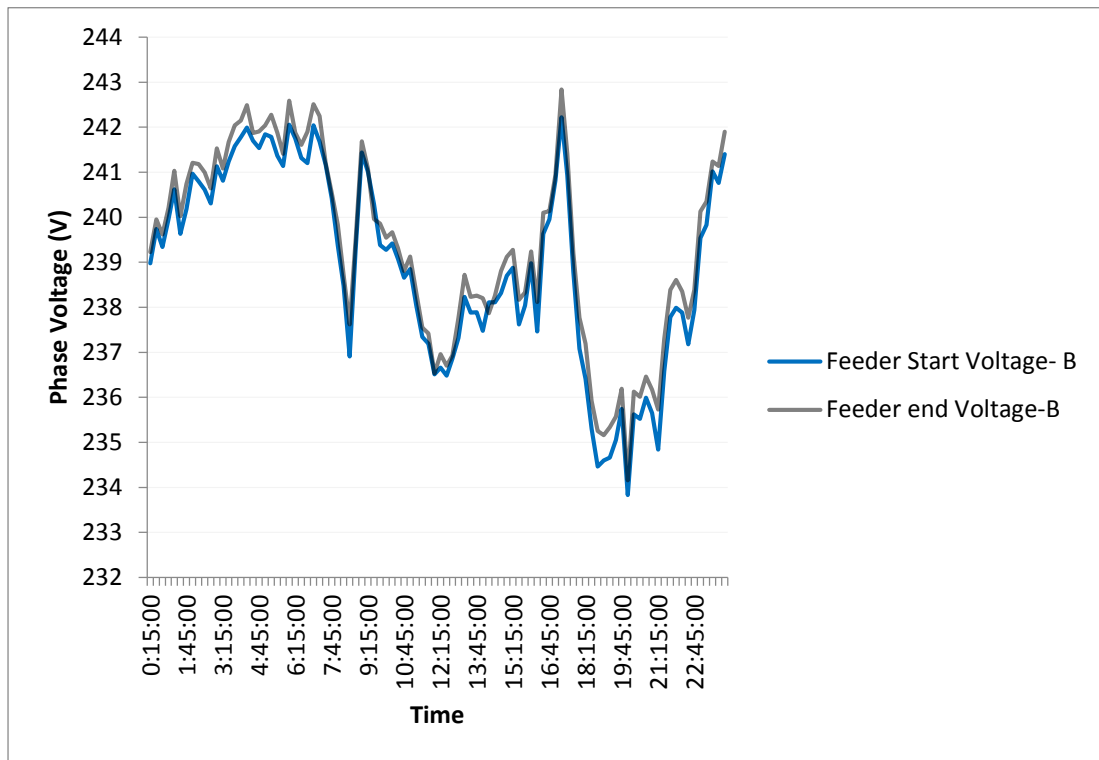


Figure 6.5: Voltage variation at feeder start and end of phase B taken on 2016.12.18

Phase “R” and Phase “Y” voltages of feeder end are following decreasing pattern comparing to feeder start according to the Figure 6.3 and Figure 6.4 But Phase “B” shows feeder end voltage rise comparing to feeder start when neutral current magnitude at considerable amount according to the Figure 6.5. These unbalance neutral current can be originated due to consumer connection pattern along the feeder, stochastic nature of power consumption of connected individual consumers and harmonic currents. But less probability available for harmonic currents generation from considered domestic loads.

So consumer connection pattern and stochastic nature of power consumption are majorly influence for unbalance situation creation for less harmonic polluted feeders. Figure 6.6 shows current profiles taken on 2016-12-18 for connected nine

consumers. Stochastic nature of power consumption can be clearly identified from these profiles and characterized load profile generation also challenge due to this nature. Objective of this research is to analyze the status of feeders for different consumer connection patterns using characterized electricity consumption profile of connected consumers. Arranging of these consumer connections among phases can be referred as load balancing within this context. Voltages and currents of the feeder are varying throughout the day. Frequency of deviation of voltages and currents from defined ranges and energy losses due to resistance of feeder is used for consumer connection pattern evaluation process.

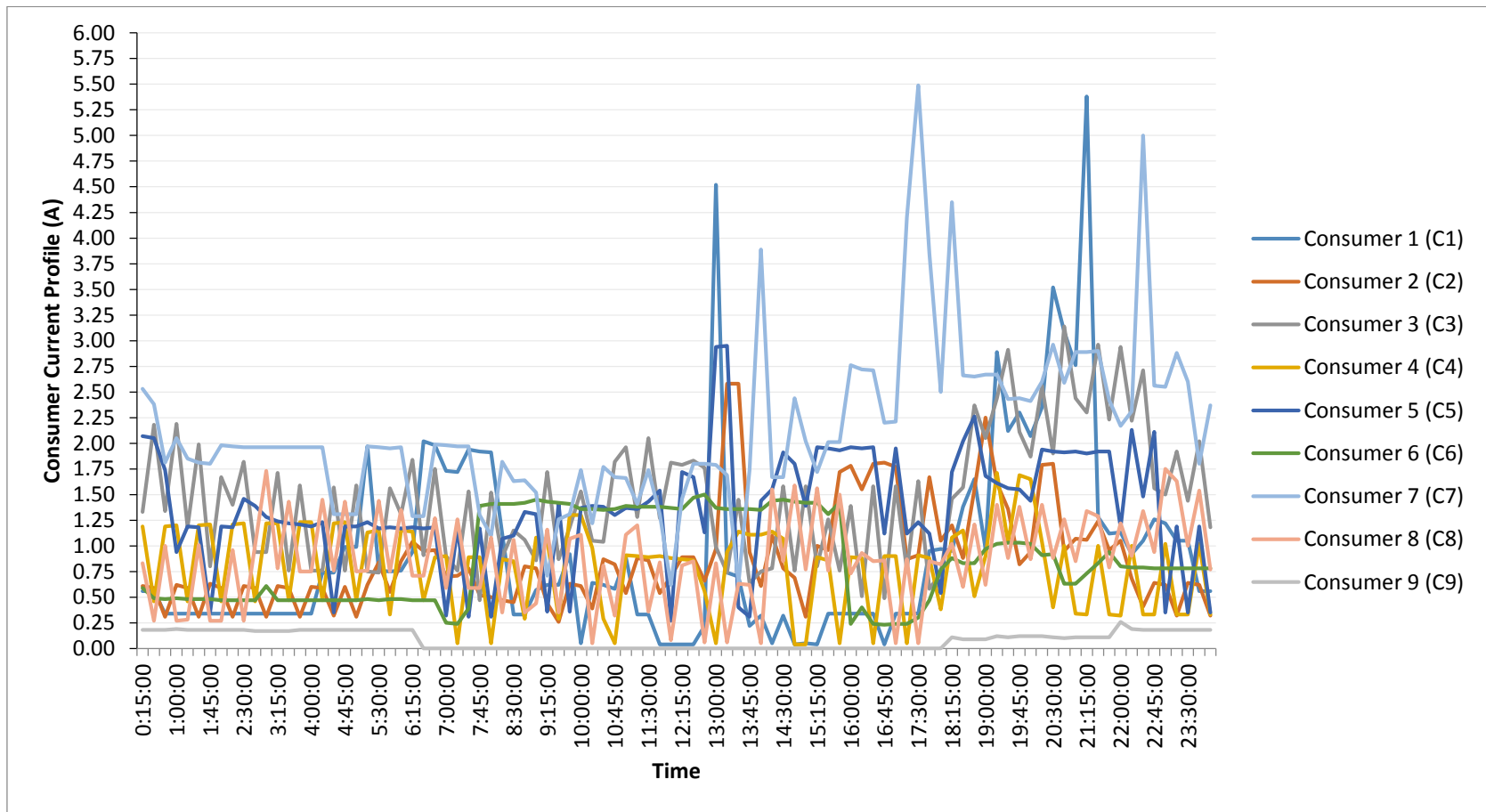


Figure 6.6: Consumer current profiles taken on 2016.12.18

## 6.2 Application of Proposed Algorithm

### 6.2.1 Consumer connection patterns

There are nine single phase consumers attached to considered feeder as per the Table 4.1 at chapter 4. Proposed pattern generation algorithm is implemented using MATLAB R2008a. Table 6.1 is summary of output of proposed pattern generation algorithm which consists of possible connection arrangements at each node and number of consumer connection patterns along the low voltage feeder.

Node number	Number of connections at node	Number of connection arrangements at each node after redefining of data set	Number of consumer connection patterns
Node-01			6X6X6X6X6=7776
Node-02	2	Factorial(3) = 6	
Node-03	2	Factorial(3) = 6	
Node-04	2	Factorial(3) = 6	
Node-05	2	Factorial(3) = 6	
Node-06			
Node-07	1	Factorial(3) = 6	
Node-08			

Table 6.1: Summarized output of pattern generation algorithm

Program used for generate consumer connection pattern is included in Appendix C.

### 6.2.1.1 Sample of consumer arrangements at nodes

Node -5		
R	Y	B
0	C8	C7
0	C7	C8
C8	0	C7
C8	C7	0
C7	C8	0
C7	0	C8

Table 6.2: Sample of consumer arrangements at node-5

Node -7		
R	Y	B
0	0	C9
0	C9	0
0	0	C9
0	C9	0
C9	0	0
C9	0	0

Table 6.3: Sample of consumer arrangements at node-7

Table 6.2 and Table 6.3 shows samples of consumer arrangements at node 05 and node 07. Zero elements are added according to the proposed algorithm for redefining consumer connection matrix. Some of the rows are appeared as duplicated because each added zero is considered as unique element during generation of consumer arrangement. Table 6.4 shows sample of consumer connection patterns generated by proposed algorithm implemented in the MATLAB R2008a.

### 6.2.1.2 Sample of consumer connection patterns

Node -2			Node -3			Node -4			Node -5			Node -7		
R	Y	B	R	Y	B	R	Y	B	R	Y	B	R	Y	B
C1	0	C2	C3	0	C4	C6	C5	0	C8	0	C7	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	0	C7	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	0	C7	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C8	C7	0	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	C8	0	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	0	C8	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C7	0	C8	0	C9	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	0	C8	0	0	C9
C1	0	C2	C3	0	C4	C6	C5	0	C7	0	C8	C9	0	0
C1	0	C2	C3	0	C4	C6	C5	0	C7	0	C8	C9	0	0
C1	0	C2	C3	0	C4	C5	C6	0	0	C8	C7	0	0	C9
C1	0	C2	C3	0	C4	C5	C6	0	0	C8	C7	0	C9	0
C1	0	C2	C3	0	C4	C5	C6	0	0	C8	C7	0	0	C9

Table 6.4: Sample of consumer connection pattern

### 6.3 Generation of Network Status for Each Consumer Connection Pattern Using Load Profiles of Connected Consumers

Accuracy of characterized load profile is important for generation of more realistic network status for evaluation. Load profiles of a certain consumer may vary due to their stochastic nature of electricity consumption. So most reasonable characteristic curves which used to represent certain consumer will be yielded for more realistic output after load flow analysis for each consumer assignment pattern. This is further study about load clustering and that is not the intention during the scope of this research. shows simple method proposed for generation of consumer characteristic curves to evaluate the performance of proposed algorithm.

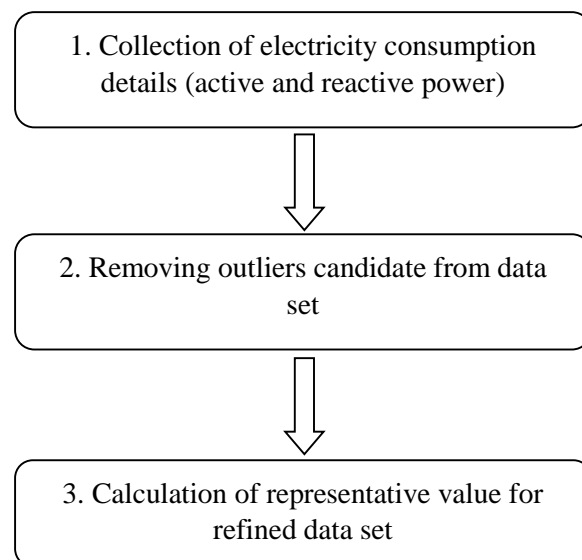


Figure 6.7: Characteristic Curve Generation for Consumers

#### *Collection of Electricity Consumption Details*

Active power and data for reactive power calculation recorded at consumer premises are used as input for characteristic curve generation process.

### ***Removing Outliers from data Set***

Difference between maximum and median value of sorted data is used for removing outliers from data set belong to particular time interval. Value of difference between maximum and median greater than 25 times of interquartile range (IQR) of sorted data set, and then maximum value is considered as outlier for that data set. Same procedure is followed for outliers removing belong to minimum values of measured data set. These values are removed from original data set until above conditions are satisfied. Defined range for outlier removing is selected to generate characteristic curves which provide monthly energy consumption approximately matches the measured energy consumption for that particular month.

### ***Calculation of Representative Value for Refined Data Set***

Centroid of the each data set is calculated to select as representative value for considered data set belong to particular time interval. Above procedure is needed to repeat for each time interval to generate characteristic curve for the period considered. Active power and reactive power data sets are considered separately and combined to develop apparent power characteristic curve. Characteristic curves are generated for each consumer for working day using this method. Figure 6.8 and Figure 6.9 are the sample of generated characteristic curves related to active power using above proposed method. Program used for generate characteristic curves are included in Appendix D.



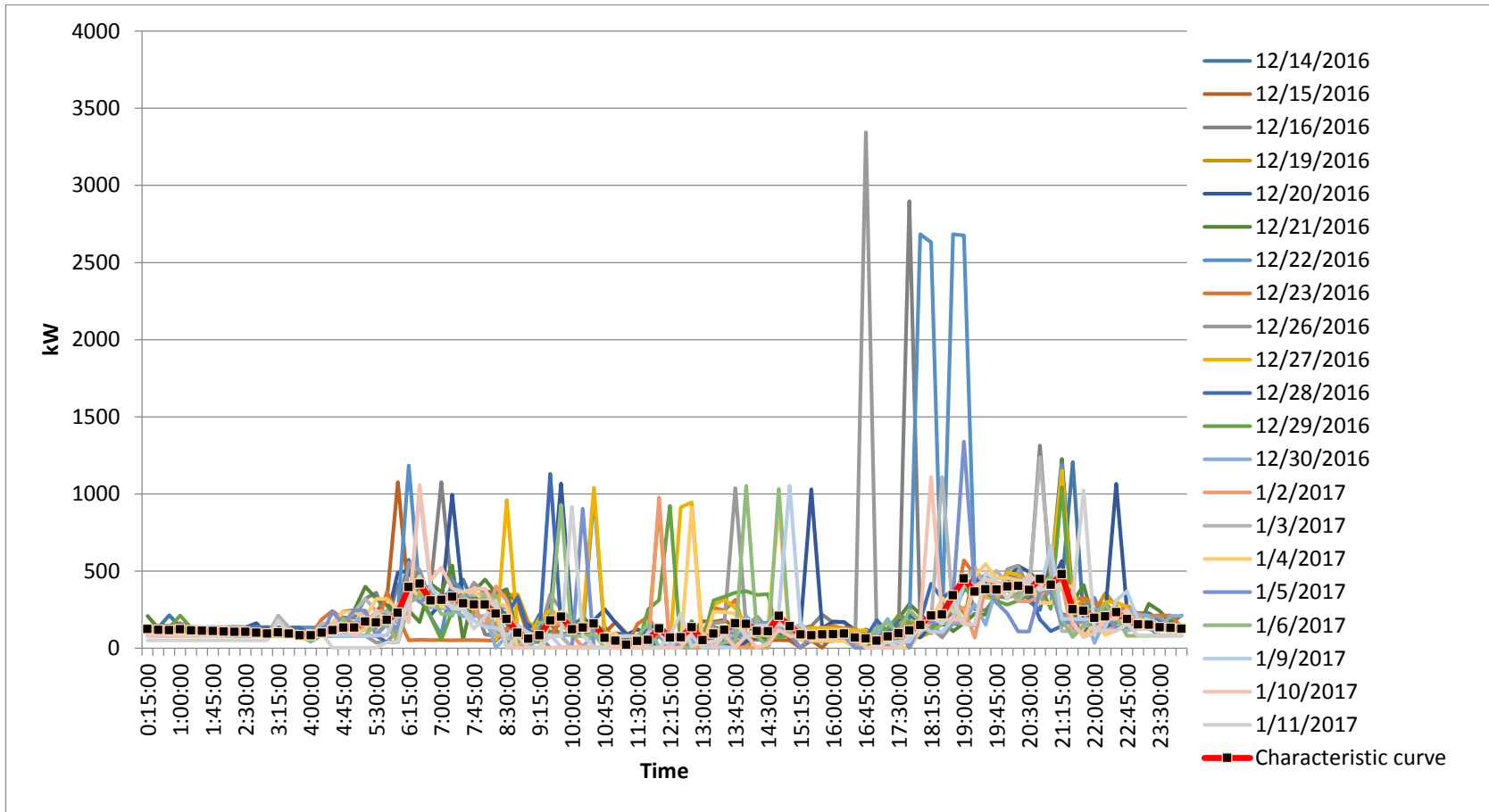


Figure 6.8: Measured and characteristic kW profile – consumer C1

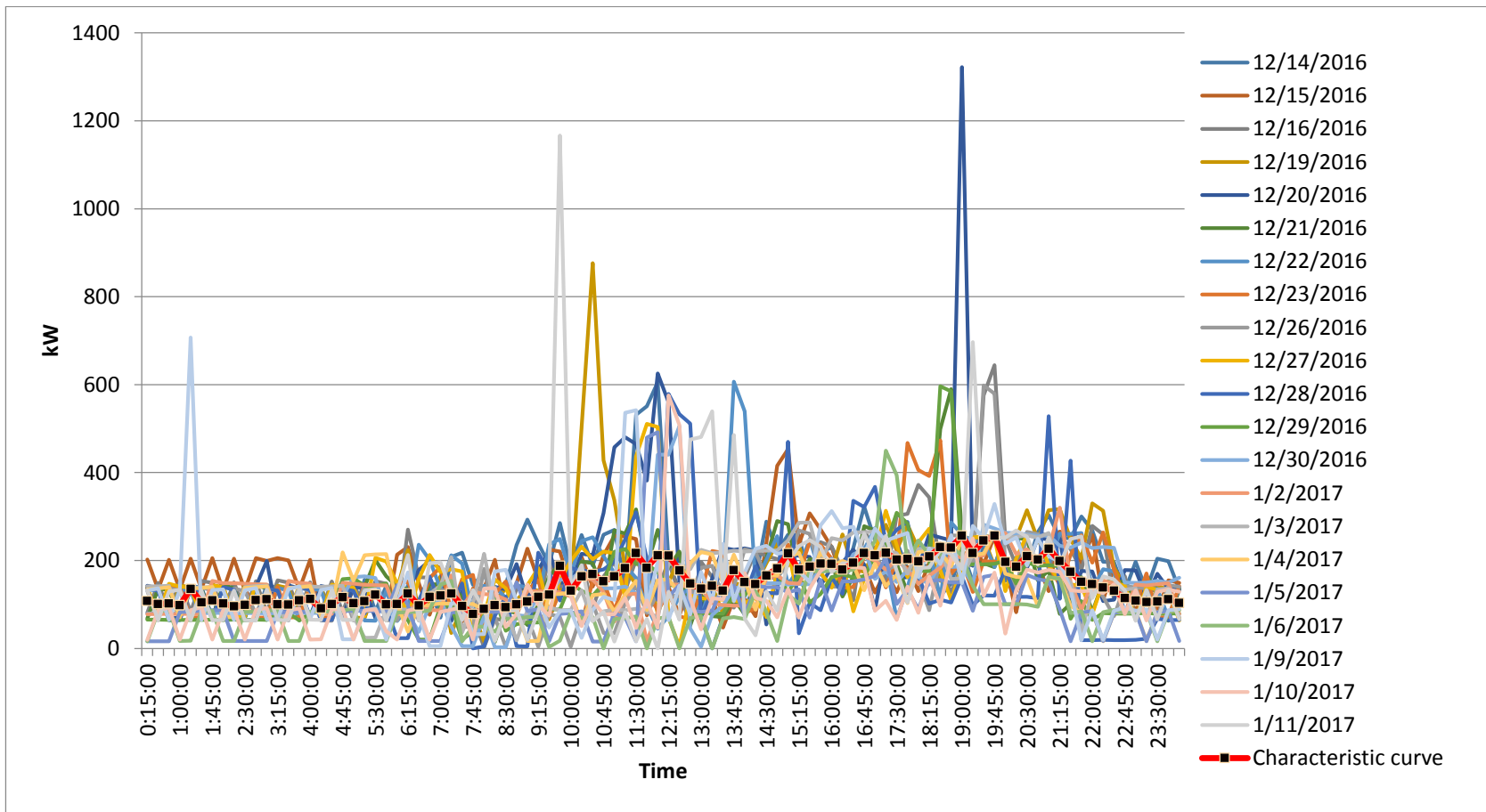


Figure 6.9: Measured and characteristic kW profile – consumer C2

Consideration of network status for existing consumer connection pattern using generated characterized load profiles is important for comparing with other possible consumer connection patterns. Nominal voltages are used as source voltages for each phase. Table 6.5 shows summary of evaluation about considered feeder using characteristic curves which represent the working days from each consumer. From the results, 0.097561kWh loss for day and monthly that value is 2.9268 kWh.

Figure 6.10 shows the corresponding current profiles. Normally considerable amount of consumers are connected to LV feeder and length also around 200m to 400m. Value of loss for such feeder will be considerable and total impact for entire distribution area will be significant.

Frequency of maximum Voltage Threshold violations	Frequency of minimum Voltage Threshold violations	Frequency of Phase Current Threshold violations	Frequency of Neutral Current Threshold violations	Network Loss for Corresponding Pattern(kWh) Per Day
0	0	0	0	0.097561

Table 6.5: Evaluation results for existing arrangement.

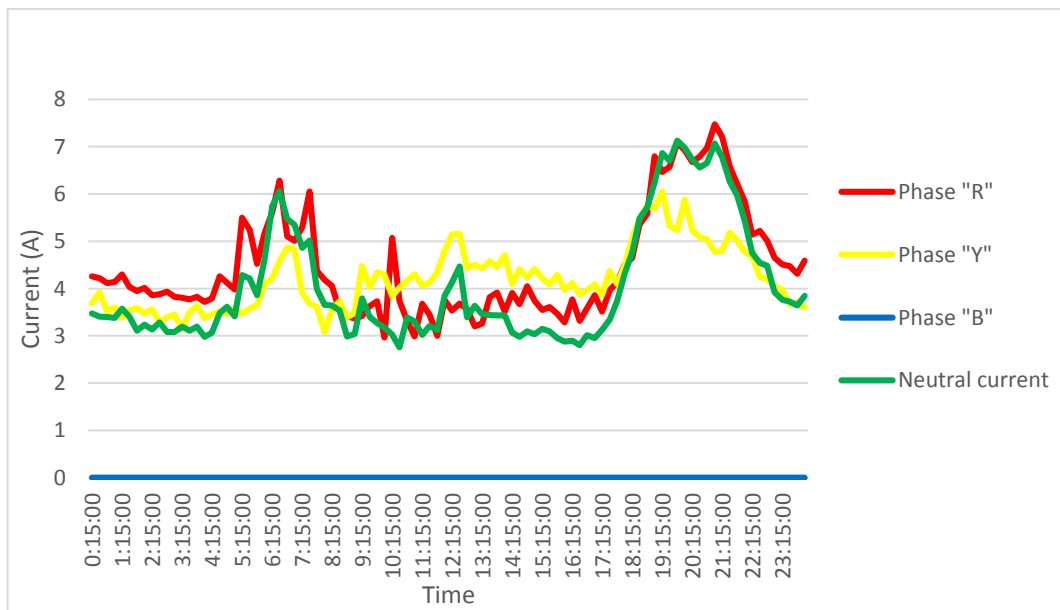


Figure 6.10: Current profile at feeder start for existing connection pattern

#### **6.4 Generation of Network Status for Each Consumer Connection Pattern Using Representative Load Profiles**

7776 consumer connection patterns can be generated for selected low voltage feeder which comprises of nine consumers. Network status for these patterns for certain time frame is needed to evaluate for comprehensive analysis of this feeder. Proposed algorithm was implemented using Matlab7.6.0 (R2008). Network statuses for sample of 1000 patterns are generated and stored for evaluation. Table 6.6 shows sample of results for patterns.

#### **6.5 Evaluation of Patterns**

Stored data set include feeder loss, frequency of violation maximum voltage threshold, frequency of violation of minimum voltage threshold, frequency of violation of conductor current capacity.

## 6.6 Sample of Results of Pattern Analysis

Pattern No.	Frequency of maximum Voltage Threshold violations	Frequency of minimum Voltage Threshold violations	Frequency of Phase Current Threshold violations	Frequency of Neutral Current Threshold violations	Network Loss for Corresponding Pattern(kWh) Per Day
1	0	0	0	0	0.099603
2	0	0	0	0	0.097118
3	0	0	0	0	0.099603
4	0	0	0	0	0.097118
5	0	0	0	0	0.095344
6	0	0	0	0	0.095344
7	0	0	0	0	0.089491
8	0	0	0	0	0.089172
9	0	0	0	0	0.089491
10	0	0	0	0	0.089172
11	0	0	0	0	0.085863
12	0	0	0	0	0.085863
13	0	0	0	0	0.087036
14	0	0	0	0	0.08347
15	0	0	0	0	0.087036
16	0	0	0	0	0.08347
17	0	0	0	0	0.084282
18	0	0	0	0	0.084282
19	0	0	0	0	0.061796
20	0	0	0	0	0.063001
21	0	0	0	0	0.061796
22	0	0	0	0	0.063001
23	0	0	0	0	0.060766
24	0	0	0	0	0.060766
25	0	0	0	0	0.044793
26	0	0	0	0	0.045377
27	0	0	0	0	0.044793
28	0	0	0	0	0.045377
29	0	0	0	0	0.045293
30	0	0	0	0	0.045293

Table 6.6: Sample results of pattern analysis

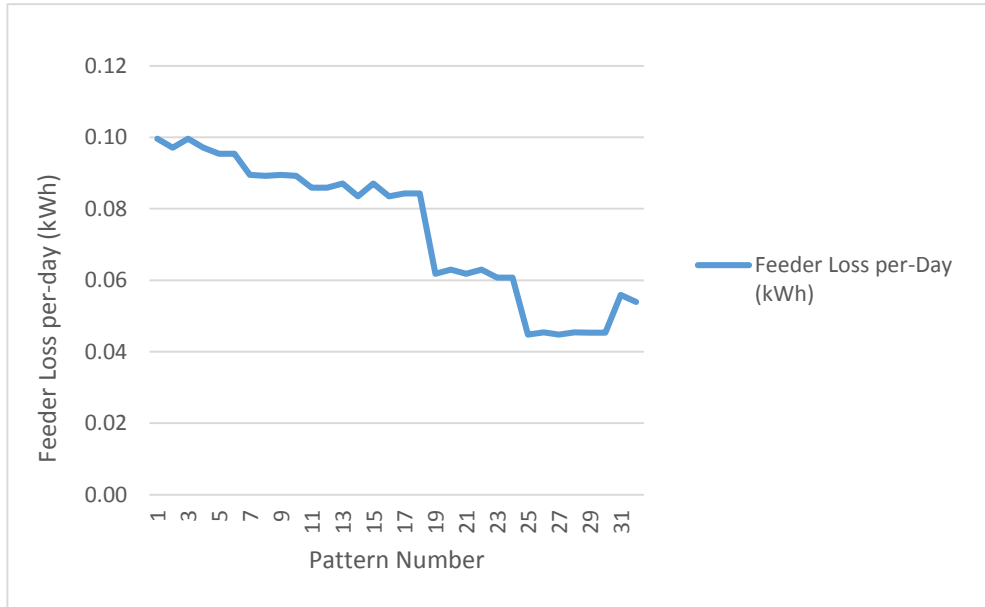


Figure 6.11: Feeder loss variation relevant to pattern for considered sample patterns

Table 6.6 Includes sample of results from 1000 consumer connection patterns evaluation. Network losses are relevant to a characteristic load profile of nine consumers for a period of one day for considered patterns which are generated by proposed algorithm. Minimum loss occurrence pattern selected as per the definition of objective function and constraints. Minimum loss occurred among evaluated 1000 pattern is 0.041564kWh per day. So evaluation of the entire possible pattern is important requirement for decision making about consumer arrangements of LV feeder to maintain network at optimum condition.

Node-02			Node-03			Node-04			Node-05			Node-07		
R	Y	B	R	Y	B	R	Y	B	R	Y	B	R	Y	B
0	C2	C1	C4	C3	0	0	C5	C6	C7	0	C8	0	C9	0

Table 6.7: Selected pattern among evaluated cases

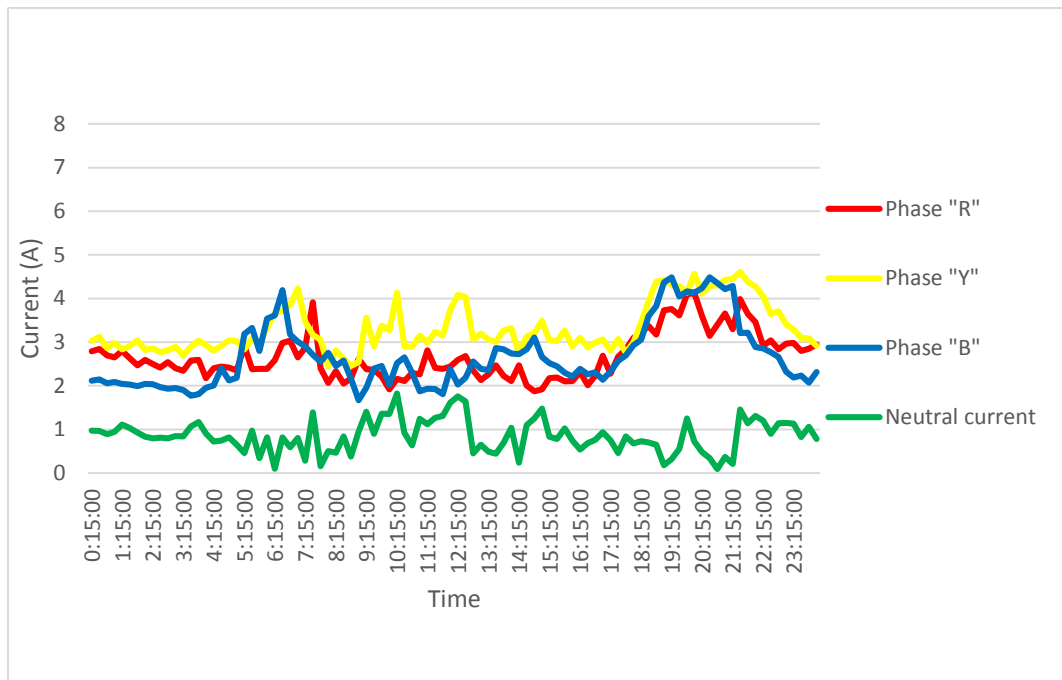


Figure 6.12: Current profile at feeder start for selected connection pattern

Figure 6.12 shows currents are shared between phases and neutral current also reduced comparing to existing arrangement. Feeder losses are related with conductor currents and these new current profiles are helped to improve network condition.

## 7 CONCLUSIONS & RECOMMENDATIONS

### 7.1 Conclusions on the Proposed Methodology

Electricity is empowering the world and established as fundamental requirement for day today life. Hundred percent electrification programs are conducting by governments which elaborate the importance of socio economic impact. Electrical energy is dissipated as loss through the distribution networks and required to maintain at optimum level due to limited nature of primary energy sources which are used for electricity generation. Consumers are using more sensitive electrical devices and consideration of quality of power is another important topic. So better network optimization methods are required for shaping the future of electricity distribution network.

Electricity distribution network modeling is one of most critical step in steady state analysis of distribution system. Chapter-2 includes discussion about the importance of incorporating inherent features of network during system modeling. Neutral grounded systems are more complex to model. Inclusion of ground path in to network model is challenge for designer. Accepted principles like Carson's method are based on assumptions. So validity of assumptions for each situation is needed to evaluate separately. Accurate representation of physical system in to model is yielding for better output during the simulation. System is modeled as five wires and ground path is limited to resistive component during this research scope as explained in the chapter-02 & chapter-03.

There are many options for load flow analysis. Some of the methods are complex and some are failed due to different reasons. So selection of appropriate load flow analysis method is another important requirement. Load flow method is needed to customize according to network model to obtain better result. Chapter-03 related with development of customized load flow analysis method for considered network



model. Current division between neutral conductor and ground path is calculated in the backward sweep at each iteration step. Self-impedance of ground path is required to know for this calculation. Different assumptions are used by researchers during their scope and validity is limited. Ground path is approximated to resistive component as explained in chapter-03.

Validation of proposed load flow program for considered network model is explained in chapter-04. Calculated and measured values are compared. Distribution of error values of voltages and currents are presented using graphical format and around 95% of deviations between calculated and measured voltages are fallen between +0.5V and -0.5V. 91% current errors are fallen between +0.2V and -0.2V. Accuracy of the impedance model and errors in the measurements are mainly contributed for deviations. Measurements are averaged values for fifteen minute time interval. Time synchronization of all the energy meters is required for better analysis of particular time interval during validation. However developed network model and load flow analysis method is sufficient for evaluation of proposed network optimization method.

Load balancing can be defined as consumer connection arrangement within the electricity distribution context. Different consumer connection patterns are creating different status in the low voltage feeder. Network status is varying throughout the day based on the electricity consumption of each consumer for a particular consumer attached pattern. Proposed algorithm is generating possible consumer connection patterns for particular set of consumers. Voltages and currents can be deviated from defined ranges for each pattern at different time intervals. Network statuses for each consumer connection pattern is generated using characteristic curves of each consumer and stored frequency of voltage and current deviations from defined thresholds. Total feeder loss also recorded for each consumer connection pattern. These values are used to select best consumer connection pattern for the network as detailed explanation of chapter-05.

Chapter-6 includes application of proposed method for sample feeder. Results from proposed algorithm are discussed under that section. Detailed analysis of

relationship between consumer connection patterns and network status is important area in electricity distribution sector for providing better service to their customer. Sample analysis was done for nine consumers connected small feeder and that shows considerable energy loss due to improper consumer connection arrangement. Phase and neutral currents at the feeder start vary between 7.5A and 3A for the existing consumer connection pattern and energy loss is 0.097561kWh per day for considered characteristic curves. Phase current at the feeder start vary between 4.5A and 2A and neutral current at the feeder start vary below 1.8A for the selected pattern out of 1000 pattern evaluation. Energy loss is reduced up to 0.041564 kWh per day. Also results are emphasized about availability of voltages and currents within the pre-defined limits. Proposed method is shown the possibilities for further improvement of feeder. When considering about entire distribution network, total energy loss will be at significant value and economic impact cannot be neglected. So proposed method can be utilized by electricity distribution network operators to maintain their network at optimum condition.

## **7.2 Recommendations for Future Work**

Accurate characteristic curves are required to obtain more realistic output from proposed load balancing technique. So development of new methods for more accurate characteristic curve generation is important especially for consumers who show stochastic behavior in electricity consumption. Impedance matrix of the network is another important factor influence to results. Approximations related to ground path is needed to further evaluate for better results.

Harmonic consideration is another important area for completeness of analysis of electricity distribution network. Passive consumers attached in the distribution network are converting to active consumer with their domestic electricity generation capability. Distributed generation entity additions such as solar systems are creating revaluation for status of low voltage distribution network. Proposed network optimization method will be required to further improve to suit for distributed generation entity addition. Further studies of these areas are recommended as future works.

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## Appendix A - Aerial Bundle Conductor Data and Impedance Calculations

### Cable data

Table A.01 shows the cable data of 50 ABC.

Conductor	Formation	A(mm <sup>2</sup> )	R(Ω/km)	D1 (mm)	D2(mm)	t (mm)
Phase	Hard drawn Aluminum	50	0.61	8.2	11.5	1.65
Neutral	Aluminum Alloy	35	0.98	7.2	11	1.9

Table A.01: Cable data

A-Nominal cross section area

R-DC conductor resistance measured at 30C

D1-Nominal diameter Without Insulation

D2- Nominal diameter With Insulation

t-Insulating sheath thickness

Insulation Material- XLPE - Cross Link Poly Ethylene

### Span Length between Nodes

Table A.02 shows the span length details of considered feeder..

	Node 1-2	Node 2-3	Node 3-4	Node 4-5	Node 5-6	Node6-7	Node7-8
Length(m)	29	32	20	57	38	45	34

Table A.02:- Span length

### Calculation of Primitive impedance matrix for considered feeder

Primitive impedance matrix can be calculated using following equations.

$$\hat{z}_{ii} = r_i + \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{ii} \sqrt{f/\rho}} \right)$$

$$\hat{z}_{ij} = \frac{\mu_0 \omega}{8} + j\omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{ij} \sqrt{f/\rho}} \right)$$

Self-impedance calculation for Phase conductors ( $Z_{aa}$ ) was done using Matlab 7.6 (R2008a) including ground effect. Following is the code used for calculation.

```
format short g
Ra=0.61;
f=50;
p=100;
R_Ground=9.869*10^-4*50*10^-3;
% constant k, assuming permeability of free space in H/m %
u=4*pi*10^-7;
k = 2*10^-7;
w=2*pi*f;
ZRa=(Ra/1000)+R_Ground;
Daa=0.758*4.1*10^-3;
ZXa=k*w*log((658.9)/(Daa*sqrt(f/p)));
Zaa=complex(ZRa,ZXa);
```

$Z_{bb}$  and  $Z_{cc}$  can be calculated similar manner.

Self-impedance calculation for Neutral conductors ( $Z_{nn}$ ) was done using Matlab 7.6 (R2008a) including ground effect. Following is the code used for calculation.

```
format short g
Rn=0.98;
f=50;
p=100;
R_Ground=9.869*10^-4*50*10^-3;
```

```

% constant k, assuming permeability of free space in H/m
k = 2*10^-7 ;
w=2*pi*f;
ZRn=(Rn/1000)+R_Ground;
Dnn=0.758*3.6*10^-3;
ZXn=k*w*log((658.9)/(Dnn*sqrt(f/p)));
Znn=complex(ZRn,ZXn);

```

Mutual-impedance calculation for Phase conductors ( $Z_{ab}$ ) was done using Matlab 7.6 (R2008a) including ground effect. Following is the code used for calculation.

```

Dab=0.019485572
f=50;
p=100;
R_Ground=9.869*10^-4*50*10^-3;
% constant k, assuming permeability of free space in H/m
k = 2*10^-7 ;
w=2*pi*f;
ZRab =R_Ground;
ZXab =k*w*log((658.9)/(Dab*sqrt(f/p)));
Zab=complex(ZRab,ZXab);

```

Other phase to phase mutual impedance components can be calculated similar manner.

Mutual-impedance calculation for Phase to neutral ( $Z_{an}$ ) was done using Matlab 7.6 (R2008a) including ground effect. Following is the code used for calculation.

```

GMDn=0.01125;
f=50;
p=100;
R_Ground=9.869*10^-4*50*10^-3;
% constant k, assuming permeability of free space in H/m
k = 2*10^-7 ;
w=2*pi*f;
ZRpn=R_Ground;
%Dij=((11.5+11)/2)*10^-3;
ZXpn=k*w*log((658.9)/(GMDn*sqrt(f/p)));
Zan=complex(ZRpn,ZXpn);

```

Other phase to neutral mutual impedance components can be calculated similar manner. Following is the calculated impedance matrix ( $\Omega/m$ ) for considered conductors.



$$\begin{bmatrix} 0.00065934 + 0.00079237i & 4.9345e - 005 + 0.00067703i & 4.9345e - 005 + 0.00067703i & 4.9345e - 005 + 0.00071154i \\ 4.9345e - 005 + 0.00067703i & 0.00065934 + 0.00079237i & 4.9345e - 005 + 0.00067703i & 4.9345e - 005 + 0.00071154i \\ 4.9345e - 005 + 0.00067703i & 4.9345e - 005 + 0.00067703i & 0.00065934 + 0.00079237i & 4.9345e - 005 + 0.00071154i \\ 4.9345e - 005 + 0.00071154i & 4.9345e - 005 + 0.00071154i & 4.9345e - 005 + 0.00071154i & 0.0010293 + 0.00080054i \end{bmatrix}$$

### Calculation of self-reactance of phase “a” for considered feeder

Self-reactance calculation for Phase conductors ( $Z_{aa}$ ) was done using Matlab 7.6 (R2008a). Following is the code used for calculation.

```
k = 2*10^-7;
w=2*pi*f;
Daa=0.758*4.1*10^-3;
Xaa=k*w*log(1/(Daa));           (Ω/m)
```

### Calculation of total reactance calculation for term $\bar{Z}_{aa} + \bar{Z}_{gg} - \bar{Z}_{ga} - \bar{Z}_{ag}$

$$(\bar{Z}_{aa} + \bar{Z}_{gg} - \bar{Z}_{ga} - \bar{Z}_{ag}) = \omega \frac{\mu_0}{2\pi} * \ln \left( \frac{658.9}{D_{aa} \sqrt{f/\rho}} \right)$$

Total-reactance calculation for above considered terms was done using Matlab 7.6 (R2008a). Following is the code used for calculation.

```
f=50;
p=100;
k = 2*10^-7;
w=2*pi*f;
Daa=0.758*4.1*10^-3;
Xa=k*w*log((658.9)/(Daa*sqrt(f/p)));
```

## **Appendix B - Load Flow Calculation**

Power flow analysis was implemented based on the customized forward-backward iterative technique using Matlab 7.6 (R2008a). Following is the code used for implementation. Measured data are stored in the excel tables and retrieve during program execution.

- Apparent power for each node relevant to corresponding phase for measured time intervals are stored in the 'Data input node power 2016.12.18.xls'.
- Voltage values for each node relevant to corresponding phase for measured time intervals are stored in the 'Actual voltage profile 2016.12.18.xls'.
- Measured current of starting span for corresponding phase for measured time intervals are stored in the 'Actual currents span 2016.12.18.xls'.
- Current for each node relevant to corresponding phase for measured time intervals are stored in the 'Actual node current 2016.12.18.xls'.

All above data are included in the Compact Disc provided with dissertation.

## Load Flow Program

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input parameters for radial feeder without spurs-Number of poles and span
lengths
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Node connected measured apparent power extraction-extraction from excel
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for Load_sheet=2;
exl = actxserver('excel.application');
exlWkbk = exl.Workbooks;
exlFile = exlWkbk.Open([docroot '/techdoc/matlab_external/examples/Data
input node power 2016.12.18.xls']);
exlSheet1 = exlFile.Sheets.Item(Load_sheet);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
dat_range = ['A2:H' num2str(numrows)]; % Read to the last row
rngObj = exlSheet1.Range(dat_range);
exlData = rngObj.Value;
L_V=str2double(exlData);

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Source & Node measured Voltage extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for Voltage_sheet=1;
exl = actxserver('excel.application');
exlWkbk = exl.Workbooks;
exlFile = exlWkbk.Open([docroot '/techdoc/matlab_external/examples/Actual
voltage profile 2016.12.18.xls']);
exlSheet1 = exlFile.Sheets.Item(Voltage_sheet);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
dat_range = ['A2:R' num2str(numrows)]; % Read to the last row
rngObj = exlSheet1.Range(dat_range);
exlData = rngObj.Value;
V_V=cell2mat(exlData);

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Measured span current extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for span_current_sheet=1;
exl = actxserver('excel.application');
exlWkbk = exl.Workbooks;
exlFile = exlWkbk.Open([docroot '/techdoc/matlab_external/examples/Actual
currents span 2016.12.18.xls']);
exlSheet1 = exlFile.Sheets.Item(span_current_sheet);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
dat_range = ['A2:D' num2str(numrows)]; % Read to the last row
rngObj = exlSheet1.Range(dat_range);
exlData = rngObj.Value;
SC_X=cell2mat(exlData);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Measured node current extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```

for node_current_sheet=1;
exl = actxserver('excel.application');
exlWkwbk = exl.Workbooks;
exlFile = exlWkwbk.Open([docroot '/techdoc/matlab_external/examples/Actual
node current 2016.12.18.xls']);
exlSheet1 = exlFile.Sheets.Item(node_current_sheet);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
dat_range = ['A2:N' num2str(numrows)]; % Read to the last row
rngObj = exlSheet1.Range(dat_range);
exlData = rngObj.Value;
NC_X=cell2mat(exlData);

end

for Loop=1:96;

x=8;
Spanmatrix=[29 32 20 57 38 45 34];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node connected measured apparent power extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Load_row_index=Loop;

Load_matrix(1,1)=0;
Load_matrix(2,1)=0;
Load_matrix(3,1)=0;

Load_matrix(1,2)=L_V(Load_row_index,2);
Load_matrix(2,2)=0;
Load_matrix(3,2)=0;

Load_matrix(1,3)=0;
Load_matrix(2,3)=L_V(Load_row_index,3);
Load_matrix(3,3)=0;

Load_matrix(1,4)=0;
Load_matrix(2,4)=L_V(Load_row_index,4);
Load_matrix(3,4)=0;

Load_matrix(1,5)=L_V(Load_row_index,5);
Load_matrix(2,5)=0;
Load_matrix(3,5)=0;

Load_matrix(1,6)=0;
Load_matrix(2,6)=0;
Load_matrix(3,6)=0;

Load_matrix(1,7)=L_V(Load_row_index,7);
Load_matrix(2,7)=0;
Load_matrix(3,7)=0;

Load_matrix(1,8)=0;
Load_matrix(2,8)=0;
Load_matrix(3,8)=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Source voltage definition
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Voltage_row_index=Loop;

```

```

Node_voltage_matrix=zeros(3,8);

[B,Y] =(pol2cart(0,V_V(Voltage_row_index,1)));
Node_voltage_matrix(1,1)=complex(B,Y);

[K,L] =(pol2cart(-2*pi/3,V_V(Voltage_row_index,2)));
Node_voltage_matrix(2,1)=complex(K,L);

[M,N] =(pol2cart(2*pi/3,V_V(Voltage_row_index,3)));
Node_voltage_matrix(3,1)=complex(M,N);
Node_voltage_matrix(4,1)=complex(0,0);

%%%%%%%%Actual voltage extraction for one minute instant

Voltage_row_index=Loop;

Act_Node_voltage_matrix=zeros(3,8);

Act_Node_voltage_matrix(1,1)=V_V(Voltage_row_index,1);
Act_Node_voltage_matrix(2,1)=V_V(Voltage_row_index,2);
Act_Node_voltage_matrix(3,1)=V_V(Voltage_row_index,3);

Act_Node_voltage_matrix(1,2)=V_V(Voltage_row_index,4);
Act_Node_voltage_matrix(2,2)=0;
Act_Node_voltage_matrix(3,2)=0;

Act_Node_voltage_matrix(1,3)=0;
Act_Node_voltage_matrix(2,3)=V_V(Voltage_row_index,6);
Act_Node_voltage_matrix(3,3)=0;

Act_Node_voltage_matrix(1,4)=0;
Act_Node_voltage_matrix(2,4)=V_V(Voltage_row_index,8);
Act_Node_voltage_matrix(3,4)=0;

Act_Node_voltage_matrix(1,5)=V_V(Voltage_row_index,10);
Act_Node_voltage_matrix(2,5)=0;
Act_Node_voltage_matrix(3,5)=0;

Act_Node_voltage_matrix(1,6)=V_V(Voltage_row_index,12);
Act_Node_voltage_matrix(2,6)=V_V(Voltage_row_index,13);
Act_Node_voltage_matrix(3,6)=V_V(Voltage_row_index,14);

Act_Node_voltage_matrix(1,7)=V_V(Voltage_row_index,15);
Act_Node_voltage_matrix(2,7)=0;
Act_Node_voltage_matrix(3,7)=0;

Act_Node_voltage_matrix(1,8)=V_V(Voltage_row_index,16);
Act_Node_voltage_matrix(2,8)=V_V(Voltage_row_index,17);
Act_Node_voltage_matrix(3,8)=V_V(Voltage_row_index,18);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Measured span current extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
sp_current_row_index=Loop;

Ac_span_current_matrix(1,1)=SC_X(sp_current_row_index,1);
Ac_span_current_matrix(2,1)=SC_X(sp_current_row_index,2);
Ac_span_current_matrix(3,1)=SC_X(sp_current_row_index,3);
Ac_span_current_matrix(4,1)=SC_X(sp_current_row_index,4);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Measured node current extraction
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

node_current_row_index=Loop;

Act_Node_current_matrix=zeros(3,8);

Act_Node_current_matrix(1,1)=0;
Act_Node_current_matrix(2,1)=0;
Act_Node_current_matrix(3,1)=0;

Act_Node_current_matrix(1,2)=NC_X(node_current_row_index,3);
Act_Node_current_matrix(2,2)=0;
Act_Node_current_matrix(3,2)=0;

Act_Node_current_matrix(1,3)=0;
Act_Node_current_matrix(2,3)=NC_X(node_current_row_index,6);
Act_Node_current_matrix(3,3)=0;

Act_Node_current_matrix(1,4)=0;
Act_Node_current_matrix(2,4)=NC_X(node_current_row_index,9);
Act_Node_current_matrix(3,4)=0;

Act_Node_current_matrix(1,5)=NC_X(node_current_row_index,12);
Act_Node_current_matrix(2,5)=0;
Act_Node_current_matrix(3,5)=0;

Act_Node_current_matrix(1,6)=0;
Act_Node_current_matrix(2,6)=0;
Act_Node_current_matrix(3,6)=0;

Act_Node_current_matrix(1,7)=NC_X(node_current_row_index,14);
Act_Node_current_matrix(2,7)=0;
Act_Node_current_matrix(3,7)=0;

Act_Node_current_matrix(1,8)=0;
Act_Node_current_matrix(2,8)=0;
Act_Node_current_matrix(3,8)=0;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Impedence
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%Grounding resistance at trnasfomer neutral bushing and feeder end.
Z_Grounding=63;

%earth resistance per m ,Rd = 9.869*10^-4*f*10^-3
Z_Ground=9.869*10^-4*50*10^-3;

% PER METER IMPEDECE AT MIDDLE SPAN
%MImpedence=[0.000641+0.000087i 0 0 0;0 0.000641+0.000087i 0 0;0 0
0.000641+0.000087i 0;0 0 0 0.000641+0.000087i];
MImpedence=[0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00067703i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00067703i
0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00071154i;4.9345e-005 + 0.00067703i 4.9345e-005 + 0.00067703i 0.00065934
+ 0.00079237i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00071154i 4.9345e-
005 + 0.00071154i 4.9345e-005 + 0.00071154i 0.0010293 + 0.00080054i];

% PER METER IMPEDECE AT END SPAN(GROUNDED NEUTRAL END)
%EImpedence=[0.000641+0.000087i 0 0 0;0 0.000641+0.000087i 0 0;0 0
0.000641+0.000087i 0;0 0 0 0.000641+0.000087i];
EImpedence=[0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00067703i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00067703i
0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00071154i;4.9345e-005 + 0.00067703i 4.9345e-005 + 0.00067703i 0.00065934

```

```

+ 0.00079237i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00071154i 4.9345e-
005 + 0.00071154i 4.9345e-005 + 0.00071154i 0.0010293 + 0.00080054i];
Espan=Spanmatrix(1,x-1)*EImpedence;

% PER METER IMPEDENCE AT START SPAN(GROUNDED NEUTRAL END)
%SImpedence=[0.000641+0.000087i 0 0 0;0 0.000641+0.000087i 0 0;0 0
0.000641+0.000087i 0;0 0 0 0.000641+0.000087i];
SImpedence=[0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00067703i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00067703i
0.00065934 + 0.00079237i 4.9345e-005 + 0.00067703i 4.9345e-005 +
0.00071154i;4.9345e-005 + 0.00067703i 4.9345e-005 + 0.00067703i 0.00065934
+ 0.00079237i 4.9345e-005 + 0.00071154i;4.9345e-005 + 0.00071154i 4.9345e-
005 + 0.00071154i 4.9345e-005 + 0.00071154i 0.0010293 + 0.00080054i];
Sspan=Spanmatrix(1,1)*SImpedence;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Source voltage based intial Current calculation for entire nodes
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=1:x

% Phase current calculation

Node_current_a=zeros(1,1);
Node_current_b=zeros(1,1);
Node_current_c=zeros(1,1);
Node_current_a=conj(Load_matrix(1,i)/Node_voltage_matrix(1,1));
Node_current_b=conj(Load_matrix(2,i)/Node_voltage_matrix(2,1));
Node_current_c=conj(Load_matrix(3,i)/Node_voltage_matrix(3,1));
Node_current_unbalance=(Node_current_a+Node_current_b+Node_current_c);

Node_current_matrix(1,i)=Node_current_a;
Node_current_matrix(2,i)=Node_current_b;
Node_current_matrix(3,i)=Node_current_c;
Node_current_matrix(4,i)=Node_current_unbalance;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node based Impedence calculation for unbalance current division
calculation-Node to source through ground path/neutral conductor
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%% Node to source through ground path %%%%%%%%%

if i==x
Z_back_i=zeros(1,1);
Z_back_i=0;
Z_back_i=(2*Z_Grounding) + Z_Ground;

elseif i==x-1

Z_back_i=zeros(1,1);
Z_back_i=0;
Z_back_i=Espan(4,4) + (2*Z_Grounding) + Z_Ground;

else

Z_back=zeros(1,1);
zT_back_i=zeros(1,1);
Z_back_i=zeros(1,1);
Z_back=0;
zT_back_i=0;
Z_back_i=0;
for j=i:x-2
zT_back_i=Spanmatrix(1,j)*MImpedence(4,4);
Z_back=Z_back+zT_back_i;

```

```

end

Z_back_i=Z_back+Espan(4,4) + (2*Z_Grounding) + Z_Ground;
end

%%% Node to source through neutral conductor %%%%%%%%%%%

if i==1
z_front_i=0;

elseif i==x
z_front=zeros(1,1);
zT_front_i=zeros(1,1);
z_front_i=zeros(1,1);
z_front=0;
zT_front_i=0;
z_front_i=0;
for k=1:i-2
zT_front_i=Spanmatrix(1,k)*MImpedence(4,4);
z_front=z_front+zT_front_i;
end
z_front_i=z_front+Espan(4,4);

else

z_front=zeros(1,1);
zT_front_i=zeros(1,1);
z_front_i=zeros(1,1);
z_front=0;
zT_front_i=0;
z_front_i=0;
for k=1:i-1
zT_front_i=Spanmatrix(1,k)*MImpedence(4,4);
z_front=z_front+zT_front_i;
end
z_front_i=z_front;
end

Return_path_impedence_matrix(1,i)=Z_back_i;
Return_path_impedence_matrix(2,i)=z_front_i;

%%% Impedence ratio calculation between two paths %%%%%%%%%%%

Node_current_n=Node_current_unbalance*(Z_back_i/(z_front_i+Z_back_i));
Node_current_g=Node_current_unbalance*(z_front_i/(z_front_i+Z_back_i));
Z_back_i=0;
z_front_i=0;

Node_current_matrix(5,i)=Node_current_n;
Node_current_matrix(6,i)=Node_current_g;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for Ground and Neutral seperatly considering
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=1:x
spani_jNCR_l=zeros(1,1);
spani_jGCR_l=zeros(1,1);
span_current_matrix(5,1)=0;    %%no ground current flow between first
node(source) ,only neutral current
span_current_matrix(5,2)=0;    %%no ground current flow between second node
node(source),only neutral current

```



```

for k=i:x
spani_jNCR_l=spani_jNCR_l+Node_current_matrix(5,k);
end
span_current_matrix(4,i)=spani_jNCR_l;

if (i>1)
for k=2:i
spani_jGCR_l=spani_jGCR_l+Node_current_matrix(6,k);
end

span_current_matrix(5,i+1)=spani_jGCR_l;
end

spani_jNCR_l=0;
spani_jGCR_l=0;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for phase currents
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:x

spani_jacT=zeros(1,1);
spani_jacT=0;
for k=i:x
spani_jacT=spani_jacT+Node_current_matrix(1,k);
end
span_current_matrix(1,i)=spani_jacT;

spani_jbcT=zeros(1,1);
spani_jbcT=0;
for k=i:x
spani_jbcT=spani_jbcT+Node_current_matrix(2,k);
end
span_current_matrix(2,i)=spani_jbcT;

spani_jccT=zeros(1,1);
spani_jccT=0;
for k=i:x
spani_jccT=spani_jccT+Node_current_matrix(3,k);
end
span_current_matrix(3,i)=spani_jccT;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for Resultant Neutral current
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for k=1:x
span_current_matrix(6,k)=span_current_matrix(4,k)-span_current_matrix(5,k);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node VOLTAGE MATRIX
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=2:x-1
SPAN_i_IMPEDENCE=zeros(4,4);
SPAN_i_IMPEDENCE=Spanmatrix(1,i-1)*MImpedence;
Direct_span_current_matrix=(-1)*span_current_matrix(6,i);
Span_drop_matrix(:,i)=SPAN_i_IMPEDENCE*[span_current_matrix(1,i);span_curren
t_matrix(2,i);span_current_matrix(3,i);Direct_span_current_matrix];

```

```

Phase_drop_matrix(:,i)=[Span_drop_matrix(1,i)-
Span_drop_matrix(4,i);Span_drop_matrix(2,i)-
Span_drop_matrix(4,i);Span_drop_matrix(3,i)-Span_drop_matrix(4,i)];

Node_voltage_matrix(4,i)=Node_voltage_matrix(4,i-1)-Span_drop_matrix(4,i);
Node_voltage_matrix(1,i)=Node_voltage_matrix(1,i-1)-Phase_drop_matrix(1,i);
Node_voltage_matrix(2,i)=Node_voltage_matrix(2,i-1)-Phase_drop_matrix(2,i);
Node_voltage_matrix(3,i)=Node_voltage_matrix(3,i-1)-Phase_drop_matrix(3,i);
end

SPAN_E_IMPEDENCE=Spanmatrix(1,x-1)*EImpedence;
Direct_span_current_matrix_x=(-1)*span_current_matrix(6,x);
Span_drop_matrix(:,x)=SPAN_E_IMPEDENCE*[span_current_matrix(1,x);span_curren
t_matrix(2,x);span_current_matrix(3,x);Direct_span_current_matrix_x];

Phase_drop_matrix(:,x)=[Span_drop_matrix(1,x)-
Span_drop_matrix(4,x);Span_drop_matrix(2,x)-
Span_drop_matrix(4,x);Span_drop_matrix(3,x)-Span_drop_matrix(4,x)];

Node_voltage_matrix(4,x)=Span_drop_matrix(4,x-1)-Span_drop_matrix(4,x);
Node_voltage_matrix(1,x)=Node_voltage_matrix(1,x-1)-Phase_drop_matrix(1,x);
Node_voltage_matrix(2,x)=Node_voltage_matrix(2,x-1)-Phase_drop_matrix(2,x);
Node_voltage_matrix(3,x)=Node_voltage_matrix(3,x-1)-Phase_drop_matrix(3,x);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculated_Node_Power_matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%P=VI*

A=conj([Node_current_matrix(1,:);Node_current_matrix(2,:);Node_current_matri
x(3,:)]);
B=[Node_voltage_matrix(1,:);Node_voltage_matrix(2,:);Node_voltage_matrix(3,:
)];

for i=1:3
for j=1:x
Calculated_Node_Power_matrix(i,j)=B(i,j)*A(i,j);
end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node_Power_mismatch_matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Node_Power_mismatch_matrix=Load_matrix-
[Calculated_Node_Power_matrix(1,:);Calculated_Node_Power_matrix(2,:);Calculated
_Node_Power_matrix(3,:)];

max(abs(Node_Power_mismatch_matrix(:)));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Iteration process
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

while(max(abs(Node_Power_mismatch_matrix(:)))>0.0001)

for i=1:x

% Phase current calculation

Node_current_a=zeros(1,1);
Node_current_b=zeros(1,1);

```

```

Node_current_c=zeros(1,1);
Node_current_a=conj(Load_matrix(1,i)/Node_voltage_matrix(1,i));
Node_current_b=conj(Load_matrix(2,i)/Node_voltage_matrix(2,i));
Node_current_c=conj(Load_matrix(3,i)/Node_voltage_matrix(3,i));
Node_current_unbalance=(Node_current_a+Node_current_b+Node_current_c);

Node_current_matrix(1,i)=Node_current_a;
Node_current_matrix(2,i)=Node_current_b;
Node_current_matrix(3,i)=Node_current_c;
Node_current_matrix(4,i)=Node_current_unbalance;

%%% Impedence ratio calculation %%%%%%%%%%%

if i==x
Z_back_i=zeros(1,1);
Z_back_i=0;
Z_back_i=(2*Z_Grounding) + Z_Ground;

elseif i==x-1

Z_back_i=zeros(1,1);
Z_back_i=0;
Z_back_i=Esplan(4,4) + (2*Z_Grounding) + Z_Ground;

else

Z_back=zeros(1,1);
zT_back_i=zeros(1,1);
Z_back_i=zeros(1,1);
Z_back=0;
zT_back_i=0;
Z_back_i=0;
for j=i:x-2
zT_back_i=Spanmatrix(1,j)*MImpedence(4,4);
Z_back=Z_back+zT_back_i;
end

Z_back_i=Z_back+Esplan(4,4) + (2*Z_Grounding) + Z_Ground;
end

if i==1
z_front_i=0;

elseif i==x
z_front=zeros(1,1);
zT_front_i=zeros(1,1);
z_front_i=zeros(1,1);
z_front=0;
zT_front_i=0;
z_front_i=0;
for k=1:i-2
zT_front_i=Spanmatrix(1,k)*MImpedence(4,4);
z_front=z_front+zT_front_i;
end
z_front_i=z_front+Esplan(4,4);

else

z_front=zeros(1,1);
zT_front_i=zeros(1,1);
z_front_i=zeros(1,1);
z_front=0;
zT_front_i=0;
z_front_i=0;

```

```

for k=1:i-1
zT_front_i=Spanmatrix(1,k)*MImpedence(4,4);
z_front=z_front+zT_front_i;
end
z_front_i=z_front;
end

Node_current_n=Node_current_unbalance*(Z_back_i/(z_front_i+Z_back_i));
Node_current_g=Node_current_unbalance*(z_front_i/(z_front_i+Z_back_i));
Z_back_i=0;
z_front_i=0;

Node_current_matrix(5,i)=Node_current_n;
Node_current_matrix(6,i)=Node_current_g;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for Ground and Neutral seperatly considering
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for i=1:x
spani_jNCR_l=zeros(1,1);
spani_jGCR_l=zeros(1,1);
span_current_matrix(5,1)=0; %%no ground current flow between source and
first node ,only neutral current
span_current_matrix(5,2)=0; %%no ground current flow between first node
and second node ,only neutral current
for k=i:x
spani_jNCR_l=spani_jNCR_l+Node_current_matrix(5,k);
end
span_current_matrix(4,i)=spani_jNCR_l;

if (i>1)
for k=2:i
spani_jGCR_l=spani_jGCR_l+Node_current_matrix(6,k);
end

span_current_matrix(5,i+1)=spani_jGCR_l;
end

spani_jNCR_l=0;
spani_jGCR_l=0;
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for phase currents
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=1:x

spani_jacT=zeros(1,1);
spani_jacT=0;
for k=i:x
spani_jacT=spani_jacT+Node_current_matrix(1,k);
end
span_current_matrix(1,i)=spani_jacT;

spani_jbcT=zeros(1,1);
spani_jbcT=0;
for k=i:x
spani_jbcT=spani_jbcT+Node_current_matrix(2,k);
end
span_current_matrix(2,i)=spani_jbcT;

```

```

spani_jccT=zeros(1,1);
spani_jccT=0;
for k=i:x
spani_jccT=spani_jccT+Node_current_matrix(3,k);
end
span_current_matrix(3,i)=spani_jccT;

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% span current matrix -for Resultant Neutral current
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for k=1:x
span_current_matrix(6,k)=span_current_matrix(4,k)-span_current_matrix(5,k);
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node VOLTAGE MATRIX
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

for i=2:x-1
SPAN_i_IMPEDENCE=zeros(4,4);
SPAN_i_IMPEDENCE=Spanmatrix(1,i-1)*MImpedence;
Direct_span_current_matrix=(-1)*span_current_matrix(6,i);
Span_drop_matrix(:,i)=SPAN_i_IMPEDENCE*[span_current_matrix(1,i);span_curren
t_matrix(2,i);span_current_matrix(3,i);Direct_span_current_matrix];

Phase_drop_matrix(:,i)=[Span_drop_matrix(1,i)-
Span_drop_matrix(4,i);Span_drop_matrix(2,i)-
Span_drop_matrix(4,i);Span_drop_matrix(3,i)-Span_drop_matrix(4,i)];

Node_voltage_matrix(4,i)=Node_voltage_matrix(4,i-1)-Span_drop_matrix(4,i);
Node_voltage_matrix(1,i)=Node_voltage_matrix(1,i-1)-Phase_drop_matrix(1,i);
Node_voltage_matrix(2,i)=Node_voltage_matrix(2,i-1)-Phase_drop_matrix(2,i);
Node_voltage_matrix(3,i)=Node_voltage_matrix(3,i-1)-Phase_drop_matrix(3,i);
end

SPAN_E_IMPEDENCE=Spanmatrix(1,x-1)*EImpedence;
Direct_span_current_matrix_x=(-1)*span_current_matrix(6,x);
Span_drop_matrix(:,x)=SPAN_E_IMPEDENCE*[span_current_matrix(1,x);span_curren
t_matrix(2,x);span_current_matrix(3,x);Direct_span_current_matrix_x];

Phase_drop_matrix(:,x)=[Span_drop_matrix(1,x)-
Span_drop_matrix(4,x);Span_drop_matrix(2,x)-
Span_drop_matrix(4,x);Span_drop_matrix(3,x)-Span_drop_matrix(4,x)];

Node_voltage_matrix(4,x)=Span_drop_matrix(4,x-1)-Span_drop_matrix(4,x);
Node_voltage_matrix(1,x)=Node_voltage_matrix(1,x-1)-Phase_drop_matrix(1,x);
Node_voltage_matrix(2,x)=Node_voltage_matrix(2,x-1)-Phase_drop_matrix(2,x);
Node_voltage_matrix(3,x)=Node_voltage_matrix(3,x-1)-Phase_drop_matrix(3,x);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculated_Node_Power_matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%P=VI*

A=conj([Node_current_matrix(1,:);Node_current_matrix(2,:);Node_current_matri
x(3,:)]);
B=[Node_voltage_matrix(1,:);Node_voltage_matrix(2,:);Node_voltage_matrix(3,:
)];

for i=1:3
for j=1:x
Calculated_Node_Power_matrix(i,j)=B(i,j)*A(i,j);

```

```

end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Node_Power_mismatch_matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Node_Power_mismatch_matrix=Load_matrix-
[Calculated_Node_Power_matrix(1,:);Calculated_Node_Power_matrix(2,:);Calculated
_Node_Power_matrix(3,:)];

max(abs(Node_Power_mismatch_matrix(:)));

end

%Load_matrix;
%Node_current_matrix;
%span_current_matrix;
%Node_voltage_matrix;
%Calculated_Node_Power_matrix;
%
%Ac_span_current_matrix;

Validation_Table(Loop,1)=abs(Node_voltage_matrix(1,2));
Validation_Table(Loop,2)=abs(Node_voltage_matrix(1,5));
Validation_Table(Loop,3)=abs(Node_voltage_matrix(1,7));
Validation_Table(Loop,4)=abs(Node_voltage_matrix(1,8));
Validation_Table(Loop,5)=abs(Node_voltage_matrix(2,3));
Validation_Table(Loop,6)=abs(Node_voltage_matrix(2,4));
Validation_Table(Loop,7)=abs(Node_voltage_matrix(2,8));
Validation_Table(Loop,8)=abs(Node_voltage_matrix(3,8));

Validation_Table(Loop,9)=abs(Node_current_matrix(1,2));
Validation_Table(Loop,10)=abs(Node_current_matrix(1,5));
Validation_Table(Loop,11)=abs(Node_current_matrix(1,7));
Validation_Table(Loop,12)=abs(Node_current_matrix(2,3));
Validation_Table(Loop,13)=abs(Node_current_matrix(2,4));

Validation_Table(Loop,14)=abs(Ac_span_current_matrix(1,1));
Validation_Table(Loop,15)=abs(Ac_span_current_matrix(2,1));
Validation_Table(Loop,16)=abs(Ac_span_current_matrix(3,1));
Validation_Table(Loop,17)=abs(Ac_span_current_matrix(4,1));

end

%%% node Voltage comparison

Node_2VRME=[V_V(:,4)      Validation_Table(:,1)  V_V(:,5)];
Node_3VYME=[V_V(:,6)      Validation_Table(:,5)  V_V(:,7)];
Node_4VYME=[V_V(:,8)      Validation_Table(:,6)  V_V(:,9)];
Node_5VRME=[V_V(:,10)     Validation_Table(:,2)  V_V(:,11)];
Node_7VRME=[V_V(:,15)     Validation_Table(:,3)];
Node_8VRME=[V_V(:,16)     Validation_Table(:,4)];
Node_8VYME=[V_V(:,17)     Validation_Table(:,7)];
Node_8VBME=[V_V(:,18)     Validation_Table(:,8)];

%%% node current comparison

Node_2CRME=[NC_X(:,3)      Validation_Table(:,9)];
Node_3CYME=[NC_X(:,6)      Validation_Table(:,12)];
Node_4CYME=[NC_X(:,9)      Validation_Table(:,13)];
Node_5CRME=[NC_X(:,12)     Validation_Table(:,10)];
Node_7CRME=[NC_X(:,14)     Validation_Table(:,11)];

```

```

Node_Power_mismatch_matrix;

Voltage_Errors=[(Node_2VRME(:,2)-Node_2VRME(:,1))      (Node_3VYME(:,2)-
Node_3VYME(:,1))      (Node_4VYME(:,2)-Node_4VYME(:,1))      (Node_5VRME(:,2)-
Node_5VRME(:,1))      (Node_7VRME(:,2)-Node_7VRME(:,1))      (Node_8VRME(:,2)-
Node_8VRME(:,1))      (Node_8VYME(:,2)-Node_8VYME(:,1))      (Node_8VBME(:,2)-
Node_8VBME(:,1))];
numel(Voltage_Errors)
flatA = Voltage_Errors(:);
count_v_errors=sum(flatA > -0.5 & flatA < 0.5);
Percentage_confidence_V=(count_v_errors/numel(Voltage_Errors))*100;

Voltage_Errors=[(Node_2VRME(:,2)-Node_2VRME(:,1))      (Node_3VYME(:,2)-
Node_3VYME(:,1))      (Node_4VYME(:,2)-Node_4VYME(:,1))      (Node_5VRME(:,2)-
Node_5VRME(:,1))      (Node_7VRME(:,2)-Node_7VRME(:,1))      (Node_8VRME(:,2)-
Node_8VRME(:,1))      (Node_8VYME(:,2)-Node_8VYME(:,1))      (Node_8VBME(:,2)-
Node_8VBME(:,1))];
numel(Voltage_Errors)
flatA = Voltage_Errors(:);
count_v_errors=sum(flatA < -0.5 );
Percentage_confidence_V=(count_v_errors/numel(Voltage_Errors))*100;

Voltage_Errors=[(Node_2VRME(:,2)-Node_2VRME(:,1))      (Node_3VYME(:,2)-
Node_3VYME(:,1))      (Node_4VYME(:,2)-Node_4VYME(:,1))      (Node_5VRME(:,2)-
Node_5VRME(:,1))      (Node_7VRME(:,2)-Node_7VRME(:,1))      (Node_8VRME(:,2)-
Node_8VRME(:,1))      (Node_8VYME(:,2)-Node_8VYME(:,1))      (Node_8VBME(:,2)-
Node_8VBME(:,1))];
numel(Voltage_Errors)
flatA = Voltage_Errors(:);
count_v_errors=sum(flatA > +0.5 );
Percentage_confidence_V=(count_v_errors/numel(Voltage_Errors))*100;

Current_Errors=[(Node_2CRME(:,2)-Node_2CRME(:,1))      (Node_3CYME(:,2)-
Node_3CYME(:,1))      (Node_4CYME(:,2)-Node_4CYME(:,1))      (Node_5CRME(:,2)-
Node_5CRME(:,1))      (Node_7CRME(:,2)-Node_7CRME(:,1))];
numel(Current_Errors);
flatB = Current_Errors(:);
count_c_errors=sum(flatB > -0.2 & flatB < 0.2);
Percentage_confidence_c=(count_c_errors/numel(Current_Errors))*100;

```

## Appendix C - Consumer Connection Pattern Generation

### Consumer connection pattern generation algorithm.

```
syms C1 C2 Ph_c_L Ph_b_L Ph_a_L Acum_Perm_2
data_2= [C1, C2];
if (0<(rem(numel(data_2),3)))
for i=numel(data_2)+1:(numel(data_2)+3-rem(numel(data_2),3));
data_2(1,i)=0;
end
end
%%%%% creating permutation matrix (All possible arrangements of load among
phases %%%%%%%%%
P_2=perms(data_2);
%%%%%%%% Number of load elements in permutation matrix %%%%%%%%%
numel(P_2);
%%%%%%%% size of permutation matrix %%%%%%%%%
size(P_2);
for z=1:size(P_2,1);
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%
Ph_a_L=zeros(1,1);
k=1;
while (k<(numel(data_2)))
Ph_a_L=Ph_a_L+P_2(z,k);
k=k+3;
end
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%
Ph_b_L=zeros(1,1);
j=2;
while (j<(numel(data_2)))
Ph_b_L=Ph_b_L+P_2(z,j);
j=j+3;
end
%%%%%%%%Accumilation of loads related to "phase c" in permutaion matrix at zth
permutation %%%
Ph_c_L=zeros(1,1);
l=3;
while (l<=(numel(data_2)))
Ph_c_L=Ph_c_L+P_2(z,l);
l=l+3;
end
Acum_Perm_2(z,1)=Ph_a_L;
Acum_Perm_2(z,2)=Ph_b_L;
Acum_Perm_2(z,3)=Ph_c_L;
end
syms C3 C4 Ph_c_L Ph_b_L Ph_a_L Acum_Perm_3
data_3=[C3,C4];
if (0<(rem(numel(data_3),3)))
for i=numel(data_3)+1:(numel(data_3)+3-rem(numel(data_3),3));
data_3(1,i)=0;
end
end
%%%%%%%%% creating permutation matrix (All possible arrangements of load among
phases %%%%%%%%%
P_3=perms(data_3);
%%%%%%%%% Number of load elements in permutation matrix %%%%%%%%%
```



```

numel(P_3);
%%%%%%%% size of permutation matrix %%%%%%%%%
size(P_3);
for z=1:size(P_3,1);
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%%
Ph_a_L=zeros(1,1);
k=1;
while (k<(numel(data_3)))
Ph_a_L=Ph_a_L+P_3(z,k);
k=k+3;
end
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%%
Ph_b_L=zeros(1,1);
j=2;
while (j<(numel(data_3)))
Ph_b_L=Ph_b_L+P_3(z,j);
j=j+3;
end
%%%%%%%%Accumilation of loads related to "phase c" in permutaion matrix at zth
permutation %%%%
Ph_c_L=zeros(1,1);
l=3;
while (l<=(numel(data_3)))
Ph_c_L=Ph_c_L+P_3(z,l);
l=l+3;
end
Acum_Perm_3(z,1)=Ph_a_L;
Acum_Perm_3(z,2)=Ph_b_L;
Acum_Perm_3(z,3)=Ph_c_L;
end
syms C5 C6 Ph_c_L Ph_b_L Ph_a_L Acum_Perm_4
data_4=[C5 C6];
if (0<(rem(numel(data_4),3)))
for i=numel(data_4)+1:(numel(data_4)+3-rem(numel(data_4),3));
data_4(1,i)=0;
end
end
%%%%%%%% creating permutation matrix (All possible arrangements of load among
phases %%%%%%%%%%
P_4=perms(data_4);
%%%%%%%%% NUmber of load elements in permutation matrix %%%%%%%%%%
numel(P_4);
%%%%%%%%% size of permutation matrix %%%%%%%%%%
size(P_4);
for z=1:size(P_4,1);
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%%
Ph_a_L=zeros(1,1);
k=1;
while (k<(numel(data_4)))
Ph_a_L=Ph_a_L+P_4(z,k);
k=k+3;
end
%%%%%%%%Accumilation of loads related to "phase B" in permutaion matrix at zth
permutation %%%%
Ph_b_L=zeros(1,1);
j=2;
while (j<(numel(data_4)))
Ph_b_L=Ph_b_L+P_4(z,j);
j=j+3;
end

```

```

%%%%Accumilation of loads related to "phase c" in permutaion matrix at zth
permutation %%%
Ph_c_L=zeros(1,1);
l=3;
while (l<=(numel(data_4)))
Ph_c_L=Ph_c_L+P_4(z,l);
l=l+3;
end
Acum_Perm_4(z,1)=Ph_a_L;
Acum_Perm_4(z,2)=Ph_b_L;
Acum_Perm_4(z,3)=Ph_c_L;
end
syms C7 C8 Ph_c_L Ph_b_L Ph_a_L Acum_Perm_5
data_5=[C7 C8];
if (0<(rem(numel(data_5),3)))
for i=numel(data_5)+1:(numel(data_5)+3-rem(numel(data_5),3));
data_5(1,i)=0;
end
end
%%%%% creating permutation matrix (All possible arrangements of load among
phases %%%%%%%%%
P_5=perms(data_5);
%%%%%%%% Number of load elements in permutation matrix %%%%%%%%%
numel(P_5);
%%%%%%%% size of permutation matrix %%%%%%%%%
size(P_5);
for z=1:size(P_5,1);
%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%
Ph_a_L=zeros(1,1);
k=1;
while (k<(numel(data_5)))
Ph_a_L=Ph_a_L+P_5(z,k);
k=k+3;
end
%%%%Accumilation of loads related to "phase B" in permutaion matrix at zth
permutation %%%
Ph_b_L=zeros(1,1);
j=2;
while (j<(numel(data_5)))
Ph_b_L=Ph_b_L+P_5(z,j);
j=j+3;
end
%%%%Accumilation of loads related to "phase c" in permutaion matrix at zth
permutation %%%
Ph_c_L=zeros(1,1);
l=3;
while (l<=(numel(data_5)))
Ph_c_L=Ph_c_L+P_5(z,l);
l=l+3;
end
Acum_Perm_5(z,1)=Ph_a_L;
Acum_Perm_5(z,2)=Ph_b_L;
Acum_Perm_5(z,3)=Ph_c_L;
end
syms C9 Ph_c_L Ph_b_L Ph_a_L Acum_Perm_7
data_7=[C9];
if (0<(rem(numel(data_7),3)))
for i=numel(data_7)+1:(numel(data_7)+3-rem(numel(data_7),3));
data_7(1,i)=0;
end
end
%%%%%%%% creating permutation matrix (All possible arrangements of load among
phases %%%%%%%%%

```

```

P_7=perms(data_7);
%%%%%%%% Number of load elements in permutation matrix %%%%%%%%%
numel(P_7);
%%%%%%%% size of permutation matrix %%%%%%%%%
size(P_7);
for z=1:size(P_7,1);
%%%%%%%%Accumilation of loads related to "phase a" in permutaion matrix at zth
permutation %%%%
Ph_a_L=zeros(1,1);
k=1;
while (k<(numel(data_7)))
Ph_a_L=Ph_a_L+P_7(z,k);
k=k+3;
end
%%%%%%%%Accumilation of loads related to "phase B" in permutaion matrix at zth
permutation %%%%
Ph_b_L=zeros(1,1);
j=2;
while (j<(numel(data_7)))
Ph_b_L=Ph_b_L+P_7(z,j);
j=j+3;
end
%%%%%%%%Accumilation of loads related to "phase c" in permutaion matrix at zth
permutation %%%%
Ph_c_L=zeros(1,1);
l=3;
while (l<=(numel(data_7)))
Ph_c_L=Ph_c_L+P_7(z,l);
l=l+3;
end
Acum_Perm_7(z,1)=Ph_a_L;
Acum_Perm_7(z,2)=Ph_b_L;
Acum_Perm_7(z,3)=Ph_c_L;
end
S2=Acum_Perm_2;
S3=Acum_Perm_3;
S4=Acum_Perm_4;
S5=Acum_Perm_5;
S7=Acum_Perm_7;
syms C Load_matrix
[p7,p5,p4,p3,p2] =
ndgrid(1:size(S7,1),1:size(S5,1),1:size(S4,1),1:size(S3,1),1:size(S2,1));
Combination= [S2(p2,:),S3(p3,:),S4(p4,:),S5(p5,:),S7(p7,:)];"

```

## Appendix D - Characteristic Curve Generation

Following code used to generate characteristic curves for nine consumers in the considered node. Input data stored in the excel workbooks and retrieve during program execution.

- Total individual consumptions of consumers for the period of characteristic curve generation are stored in the 'Individual consumption CC generation period.xlsx'.
- Active and reactive power consumptions of consumers for the period of characteristic curve generation are stored in the 'Consumers data.xlsx'.

### Program for Characteristic Curve Generation

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%Individual actual monthly consumption extraction %%%%%%%%%%%%%%
format short g
exl = actxserver('excel.application');
exlWkbk = exl.Workbooks;
exlFile = exlWkbk.Open([docroot
'/techdoc/matlab_external/examples/Individual consumption CC generation
period.xlsx']);
exlSheet1 = exlFile.Sheets.Item(1);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
rngObj = exlSheet1.Range('B2:B11');
exlData_C = rngObj.Value;
Individual_consumption=cell2mat(exlData_C);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%curve generation %%%%%%%%%%%%%%

for f=1:9;
exl = actxserver('excel.application');
exlWkbk = exl.Workbooks;
exlFile = exlWkbk.Open([docroot '/techdoc/matlab_external/examples/Consumers
data.xlsx']);
exlSheet1 = exlFile.Sheets.Item(f);
robj = exlSheet1.Columns.End(4); % Find the end of the column
numrows = robj.row; % And determine what row it is
rngObj = exlSheet1.Range('A2885:U2980');
exlData = rngObj.Value;
W_Active=cell2mat(exlData);

rngObj = exlSheet1.Range('A2987:I3082');
exlData = rngObj.Value;
H_Active=cell2mat(exlData);

rngObj = exlSheet1.Range('A3088:U3183');
exlData = rngObj.Value;
W_RActive=cell2mat(exlData);

rngObj = exlSheet1.Range('A3190:I3285');
exlData = rngObj.Value;
H_RActive=cell2mat(exlData);
```

```

size(W_Active);
size(H_Active);
size(W_RActive);
size(H_RActive);

%%% characteristic curve generation for working day active power
x=0;
Number_working_days=0;
sort_Raw_Data =0;

x=size(W_Active);
Number_working_days=x (1,2);
for T_i=1:96
sort_Raw_Data = sortrows(transpose(W_Active(T_i,:)));

for h=1:Number_working_days
while (abs((max(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == max(sort_Raw_Data)) = [];
end
while (abs((min(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == min(sort_Raw_Data)) = [];
end
h=h+1;
end
[idx,C] = kmeans(sort_Raw_Data,1);
Characteristic_point_active(T_i,1)=C;

T_i=T_i+1;

end

%%% characteristic curve generation for working day reactive power
y=0;
Number_working_days=0;
sort_Raw_Data =0;

y=size(W_RActive);
Number_working_days=y (1,2);
for T_i=1:96
sort_Raw_Data = sortrows(transpose(W_RActive(T_i,:)));

for h=1:Number_working_days

while (abs((max(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == max(sort_Raw_Data)) = [];
end
while (abs((min(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == min(sort_Raw_Data)) = [];
end

h=h+1;
end
[idx,C] = kmeans(sort_Raw_Data,1);

```

```

Characteristic_point_Ractive(T_i,1)=C;

T_i=T_i+1;

end

%%%complex characteristic curve for working day

complex_characteristic_w=complex(Characteristic_point_active,Characteristic_
point_Ractive);

%%% characteristic curve generation for Holiday day active power
x=0;
Number_working_days=0;
sort_Raw_Data =0;

x=size(H_Active);
Number_working_days=x (1,2);
for T_i=1:96
sort_Raw_Data = sortrows(transpose(H_Active(T_i,:)));

for h=1:Number_working_days

while (abs((max(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == max(sort_Raw_Data)) = [];
end
while (abs((min(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == min(sort_Raw_Data)) = [];
end
h=h+1;
end
[idx,C] = kmeans(sort_Raw_Data,1);
Characteristic_point_H_active(T_i,1)=C;

T_i=T_i+1;

end

%%% characteristic curve generation for working day reactive power
y=0;
Number_working_days=0;
sort_Raw_Data = 0;

y=size(H_RActive);
Number_working_days=y (1,2);
for T_i=1:96
sort_Raw_Data = sortrows(transpose(H_RActive(T_i,:)));

for h=1:Number_working_days

while (abs((max(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == max(sort_Raw_Data)) = [];
end
while (abs((min(sort_Raw_Data)-
median(sort_Raw_Data))>25*iqr(sort_Raw_Data))
sort_Raw_Data(sort_Raw_Data == min(sort_Raw_Data)) = [];
end

```

```

h=h+1;
end
[idx,C] = kmeans(sort_Raw_Data,1);
Characteristic_point_H_Ractive(T_i,1)=C;

T_i=T_i+1;

end
complex_characteristic_H=complex(Characteristic_point_H_active,Characteristic_point_H_Ractive);

%%%complex characteristic curve

Total_Characteristic_curve_Wmatrix(:,f)=[complex_characteristic_w];
Total_Characteristic_curve_Hmatrix(:,f)=[complex_characteristic_H];
end

%%%%%%%%%End of charactristic curve generation %%%%%%%%%%

%%%%%%%%%kWh calcaultion for 21- working day for nine consumers using
characteristic curves%%%%%%%%%

Total_Characteristic_curve_Wmatrix_active=real(Total_Characteristic_curve_Wmatrix);
Calculated_units_W=((sum(Total_Characteristic_curve_Wmatrix_active)*0.25)/1000)*21;

Total_Characteristic_curve_Wmatrix_Ractive=imag(Total_Characteristic_curve_Wmatrix);

%%%%%%%%%kWh calcaultion for Holiday day for nine consumers using
characteristic curves%%%%%%%%%

Total_Characteristic_curve_Hmatrix_active=real(Total_Characteristic_curve_Hmatrix);
Calculated_units_H=((sum(Total_Characteristic_curve_Hmatrix_active)*0.25)/1000)*9;

Total_Characteristic_curve_Hmatrix_Ractive=imag(Total_Characteristic_curve_Hmatrix);

%%%%%%%%%Total kWh calcaultion for Holiday day for nine consumers using
characteristic curves%%%%%%%%%

Calculated_units_consumer=Calculated_units_W+Calculated_units_H;

Calculated_units_consumer(1,10)=sum(Calculated_units_consumer(:));

Unit_difference=Individual_consumption-transpose(Calculated_units_consumer);

```