Real European Low Voltage Test Network for Smart Grid Applications

by
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Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems
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Abstract

With the rise in smart grid implementation in Europe, the requirement of a real test system where different smart grid application can be tested is inevitable. Most of the existing test feeders or networks are based on North American style distribution system. There are very few test systems representing the European style but they are not complete and do not represent actual European style network and feeder. In this thesis, changes are proposed in the existing model for IEEE European LV test feeder to make it represent an actual European style feeder. The proposed modified IEEE European LV test feeder will have four-wires model instead of three. The European distribution networks have TT grounding neutral, which is isolated from the ground of consumers. So the return path of all neutral current is through the neutral conductor, which gives rise in neutral voltage. The concept of neutral voltage is neglected in the original test bus system which we have included in modified test feeder.

In the second part, a methodology is discussed to convert GIS data obtained from EDP Spain to OpenDSS model using the set of codes. Further, a comprehensive European test network with 30 LV substations, 10290 buses and 8087 load point with smart meter data of 20 days has been proposed to represent the European style LV distribution system. This test system provides the possibility to reconfigure LV network as well as provides an important base for economic and technical studies in large scale Network.

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Glossary

Acronyms

ADR Automated Demand Response.

COM Component Objective Model.

CTF Comprehensive Test Feeder.

DERs Distribution Energy Resources.

DG Distributed Generation.

DSAS Distribution System Analysis Subcommittee.

EPRI Electric Power Research Institute.

LV Low Voltage.

LVNTS Low Voltage Network Test System.

MV Medium Voltage.

NEV Neutral-to-Earth voltage.

NILM Non-Intrusive Load Monitoring.

PLC Powerline communication.

PNNL Pacific Northwest National Laboratory.

PV Photo-Voltaic.

TFWG Test Feeder Working Group.

Matrices

$\mathbf{Y}_{prim}$ Primitive Admittance Matrix.

$\mathbf{Y}_{sys}$ System Admittance Matrix.

$\mathbf{Z}_{012}$ Sequence Impedence Matrix.

$\mathbf{Z}_{abc}$ Reduced Impedence Matrix.

$\mathbf{Z}_{prim}$ Primitive Impedence Matrix.

Variables

Ipc Compensation Current from Power Conversion(PC) Element.

V Voltage.

Chapter 1

Introduction

1.1 Background

Distribution network is going through major transformation in modern time. With the introduction of distributed energy resources (DERs) modern distribution networks are forced to be converted into smart from the conventional one. This change has promoted the introduction of various software and tools intended to develop advanced control and distribution automation. The rise of smart meter penetration will increase the need of the big data analytics and other computing resources to utilize the data from smart meter for the benefit of utilities and consumer. The data from smart meter will be a valuable resource in the study of load pattern, non-intrusive load monitoring (NILM) and automated demand response (ADR).

With the transformation in the paradigm of the distribution system where the consumers are no longer a consumer but 'prosumers'[1] utilities should be equipped with tools to monitor their prosumers in a more interactive way. Utilities in Europe are spending their resources to convert all metering systems into smart metering infrastructure. Still more has to be done in the field of utilizing the data from smart meters for greater use apart from simple billing purpose. The basic hurdle in this process is the shortage of test systems that are realistic enough and freely available

[1] As distributed resources are increasing, many author prefer to say 'prosumers' to the consumers who produce energy at some time and consume some other time

for testing various algorithms [1]. In recent years many test feeders for US-based system have been released but very few feeders are available that represent the true European LV test feeder. This restricts utilities from testing new algorithms and control strategies which can have positive role in reducing cost for consumer and utilities, increasing reliability of the supply, reduce the conflict of interest between network providers, system operators and market platform, improve the regulations for utility, better utilization of electrical assets and better integration of DERs and ESDs [2].

Distribution networks are vital infrastructure and detailed load and customer data raise the issue of privacy and security. Therefore only very few actual networks are available for the public use as a test network. This has compelled us to use only the available test feeders that have been published for some other reasons and sometimes the purposes are far beyond the original intention of the creation of test feeder [1]. The other challenge with feeder models is that there are regional differences between structure and operations of the circuit across the world. The electrical network is a modern infrastructure built in the twentieth century. Although they were developed parallel, there are some fundamental difference in North American and European distribution network. A typical residential consumer in North America receives three-phase power at 120/240 V at 60 Hz whereas in Europe the typical supply for a consumer is 240/420 V at 50 Hz. Similarly, in terms of terminal network, the North American system has a secondary transformer with a rating of between 10 kVA and 50 kVA serving 1 to 10 consumers while in Europe the secondary transformers are between 100 kVA to 1,000 kVA serving between 50 to 250 consumers through secondary LV Networks. Variety of differences can be obtained in distribution feeders within same country or in the same utility [3].

1.2 Motivation

The first set of openly available distribution test feeders was released in 1991 by IEEE Test Feeder Working Group(TFWG) [4]. It had set of four radial feeders to provide researchers with models to work in unbalanced load with untransposed distribution network. All these models were based on North American distribution network. In 2015, for the first time, European style test case was created by TFWG. The feeder was a simple representation of LV feeder in the United Kingdom but does not represent the exact model of European style feeders.

EDP HC Energia in Asturias, Spain is a distribution utility responsible for more than 650,000 customers in Spain [2]. The company has selected the city Pola de Siero in Asturias as InoVCity to implement their smart grid project [3]. One of the objectives of the project is to equip the whole city with smart metering infrastructure for the active study of the load and make it test LV grid for research and development of new technical solutions. With the availability of smart meter data, a suitable test feeder is required to study the various aspects of smart grid features. The existing LV test systems are not suitable due to various limitations. The communication network for the smart grid implementation in Spain is power line communication (PLC). The advantage of PLC is that it is integrated with grid infrastructure, low cost of investment, no intervention from the third party and good performance [5]. But with the bandwidth limitation imposed by this technology, it is hard to get per minute load data from the smart meter using the PLC network [6] unlike the IEEE LV test feeder load profile. This test feeder considers multiple grounded neutral in LV network but in practice, the LV feeder in Spain has isolated neutral with neutral grounding only at transformer end. This assumption limits the observation of neutral to ground voltage parameter which is one of the important parameters for distribution networks in Europe. Also, the loads assumed in European LV test feeder are all single-phase load. But in real case, the loads are the mixture of single phase and three phase. All these factors motivates to work towards the creation of new LV test network for Spanish system.

[2]http://www.edphcenergia.es/es/mercado-y-zonas-de-distribucion/
[3]http://www.edphcenergia.es/es/inovgrid/inovcity-pola-de-siero/

1.3 Research Objectives

The principal objective of this thesis is to analyze the existing IEEE European LV test system and to propose a new one for the Spanish utility for their smart grid applications. The ultimate aim is to produce a test network for EDP Spain in which they can test various innovative ideas with the smart meter data. The first stage of the research will be to convert the existing European Test feeder to four wires model to see the change in the different system parameters. The second part will be to create an OpenDSS model of two small feeders representing the typical urban and rural feeders. The final aim will be to create a tool to convert GIS and smart meter raw data to OpenDSS format using MATLAB so that the utility will easily be able to convert any of their distribution feeders and networks to OpenDSS format.

1.4 Organization of Thesis

Chapter 1 presents the motivation behind the study and its possible applications in EDP Spain.

Chapter 2 is the literature review on different available test feeders and networks and smart grid applications researches that have been done by using them.

Chapter 3 deals about the simulation software used for simulation and its specific features.

Chapter 4 is the description of the modification proposed in IEEE European LV Test feeder to study the 4 wires distribution systems with TT grounded neutral model and modification of load data to per-second time series data.

Chapter 5 has the analysis of raw GIS data of LV network and strategies used to convert it into into OpenDSS script.

Chapter 6 describes the proposed real European LV test network of a complete city for the study of various smart grid applications.

Chapter 7 is the conclusion of the master thesis and the future work that can be done.

Chapter 2

State of Art

This chapter contains the description of existing test feeders that have been developed by TFWG with analysis of their purposes and limitation. There is also a review of the existing power flow solutions and motivation towards the selection of right one. Finally, it also has a discussion regarding different software for power flow analysis in distribution systems.

2.1 Distribution Test Feeder Models

A distribution network consists of the infrastructure required for delivery of electricity from transmission/sub-transmission level to the final consumer. Test Feeders in Distribution Networks are simplified models designed for specific purpose. The straightforward way of creating the test system is by taking data of an actual feeder from a real distribution network and removing the private data. The other method is clustering several actual networks to build synthetic representative test systems. The third method is building the test system through manual design. The fourth method of building a test system is by using planner tools based on economic and technical criteria to create a realistic distribution network [1].

2.1.1 IEEE feeders

In 1991, the first set of four test feeders was published by IEEE TFWG [4]. In 2001, a new feeder was added in test feeder list [7]. These test feeders were meant for providing a solution benchmark for distribution system analysis tool. With time the distribution system analysis tools have acquired sophisticated capabilities, road-map to different test cases were proposed by the Distribution System Analysis Subcommittee(DSAS) in 2009[8]. The paper explained the requirement of new test-feeders for different seven topics: neutral-to-earth voltage(NEV), short circuit benchmark model, DG protection, large distribution system model, inverter based DG models, comprehensive test feeder and asymmetrical contingencies test feeder. In 2008 line models for NEV analysis was presented in [9] based on the 4-wires multi-grounded neutral distribution system proposed by Kersting [10]. In 2010, TFWG proposed IEEE 8500-node test feeder in [11] to help benchmark the ability of the software under test to handle larger circuits similar to those commonly used in distribution system analysis and a Comprehensive Distribution Test Feeder in [12] to test all standard components of a distribution system. In 2014, the 342-node Low Voltage Networked Test System in [13] was designed to test the ability to study heavily meshed and networked systems in urban areas with numerous parallel transformers and parallel LV cables. The original intention and usage of these feeders are discussed in section following:

13 Node Test Feeder

This is small and highly loaded test feeder designed in 1991 which includes common features of North American distribution system like voltage regulators, shunt capacitor bank, three phase and single phase overhead and underground lines, and unbalanced loads [4]. This feeder provides a starting point to test convergence problem for power-flow in a highly unbalanced system. This system provides a simple system to check different algorithm for the unbalanced system, few of the highly cited works are in optimal capacitor placement using genetic algorithm [14], control of photo-voltaic with storage in micro-grid [15] and islanding detection in micro-grid [16] which shows that the usage of this test bus is diverse and not limited to the initial purpose to check convergence of the power flow solution.

123 Node Test Feeder

This test feeder presented in [4] operates at a nominal voltage of 4.16 kV. But it is a good test feeder to study the problem of voltage drop that must be solved with the application of voltage regulators and shunt capacitor [4]. This feeder is well-behaved and has no convergence problem. The presence of four voltage regulators makes it a good test case to assure coordinated regulation of voltage. It also includes numbers of switches to enable simple testing of intra-feeder reconfiguration strategy[1]. The most cited usage of the 123 node test system is optimal power flow in unbalanced situation[17], comprehensive operational planning framework for self-healing action[18] and stochastic reactive power management in smart grid[19] which shows the wide range of its usage apart from the purpose it was defined for.

34 Node Test Feeder

This feeder described in [4] is a part of actual feeder in Arizona. The feeder is very long and lightly loaded. Unbalanced load with both spot and distributed loads with Shunt capacitors, two in-line voltage regulators, and one in-line transformer makes it a typical feeder. Because of the long length and unbalanced loading, it can present a convergence problem [1]. The most cited paper using this test bus was on optimal DG placement [20] and the optimal allocation of energy storage system [21] apart from the original purpose of the test feeder.

37 Node Test Feeder

This feeder was obtained from the actual feeder in California with all underground network [4]. This test feeder was meant for testing the capability of software to handle the three-wire delta system which is a less common system in use [7]. Very few works has been done using this feeder, some of the representatives are on optimal power flow with DERs [22], DG as a provider of reactive power [23] and small signal analysis of micro-grid system [24].

4 Node Test Feeder

This feeder was published in [7] after ten years of original IEEE feeders. The primary purpose of this feeder was to provide a simple system for testing simulations of all possible three-phase transformer connections including open delta for both balanced and unbalanced load. There were total 6 types of transformer connections for step-down and step-up operations. This test feeder is widely used in testing different algorithms for state estimation [25] or for testing of step-voltage regulators [26] apart from the original purposes.

The NEV Test Feeder

The NEV Test Feeder presented in [9] is a medium size radial feeder with a base voltage of 12.47 kV. In all previous methods, the assumption was made that there is no impedance between the neutral conductor and the earth ground. This assumption is the base for Kron's reduction which reduces the primitive 4x4 impedance matrix to 3x3 phase impedance matrix by assuming neutral voltage at point of grounding is 0.0 V. [27] This assumption is valid in many cases except the cases where the neutral voltage rises above 0.0 V. Study of neutral voltage is an important issue when there are problems with broken ground connection and harmonic studies. This test case is widely used in load modeling [28] and harmonic analysis [29].

8500 Node test Feeder

This test feeder presented in [11] was designed to check the working of distribution analysis tools for the larger network. It has incorporated the various features of North American distribution system like multiple feeder regulators, center-tapped transformers, per-phase capacitor bank and LV secondary distribution. The test case has loads for both balanced and unbalanced condition. It is a 12.47 kV large radial feeder with 170 km of overhead lines and underground cable. This test bus has been used for different purposes like load modeling with time series load [30] and smart grid and DERs integration studies [31].

Comprehensive Distribution Test Feeder(CTF)

This feeder presented in [12] was developed to test the models of all distribution components and to test the convergence qualities of a verity of switching schemes. To make it a complex test feeder, it includes three, two and single phase overhead and underground lines with and without neutral, three phases, single phase and center tapped transformers, step voltage regulators, induction machines, spot loads, switched capacitor banks and single-phase 120 and 240 volt loads on center tapped transformers. It also has modeling of the parallel underground and overhead lines. Despite being complete with all type of available distribution elements, this test feeder might give unrealistic result for studies of distribution system except the main purpose of testing the distribution network simulation software [1]. This test feeder has been used for some DG applications [32] apart from its original intention to test software.

342 node Test system(LVNTS)

This test system defined in [13] was designed to present distribution system analysis software with a heavily meshed and networked systems, systems with numerous parallel transformers and modeling of low voltage parallel cables. This is called a test system instead of test feeder as it has multiple 13.2 kV feeders supplying 120 V highly meshed network and 480 V spot networks [3]. The system is in use in many parts of US where numerous parallel lines are serving the consumer and fault in one line isolates that line without affecting the consumers. This system has been used to study optimal dispatch with DERs [33] and communication applications [34].

European(UK) Low Voltage Test Feeder

The European Low-Voltage Test Feeder is a 400 V radial system representing a type of feeder in United Kingdom [35]. The voltage at the transformer end is kept at 416

V to comply with the typical operational values in the United Kingdom. It consists of a single transformer and a single LV feeder with 55 single phase loads connected in different phases. The load has time series data with 1440 values for each minute of a day. This is the first IEEE test feeder operating at 50 Hz. The purpose of this feeder was to accommodate the capability of software to operate in different distribution systems around the globe [3]. This model is widely used in DERs and smart grid applications [36, 37] and topology mapping [38] due to its time series data and coordinates. The model still uses Carson's equation with Kron's reduction [27] for converting the line into 3 wires model. Most of the European feeder is TT earthed, i.e., the neutral is earthed at transformer end and the neutral provided to consumer provides the return path to all neutral current. The application of Kron's reduction which assumes multiple neutral grounding performs well in the shorter LV network but gives different result in a longer network with unbalanced load [39, 40]. This master thesis proposes a modification in the IEEE LV test feeder to accommodate the calculation of actual neutral voltage and is further discussed in Chapter 4.

Apart from these radial test feeders IEEE TFWG is now working on to create new test cases on quasi-static time series, Chinese circuit, large-scale urban-core network and microgrid[35]. It shows that TFWG is putting effort to prepare test feeder of global systems but still it has to do a lot in the design of test feeders which are not North American Type.

2.1.2 Other North American Test Circuits

There are different open source feeder models designed as a part of EPRI's Green Circuit project database and PNNL taxonomy feeder study. Unlike IEEE test feeders, these feeders are not designed to check the power flow solving algorithm, but as a representative feeder which can be used by researchers to use in case studies. EPRI feeder set has six large feeders obtained from the real networks. All of them have data of bus coordinate and time series data of load to provide a more realistic case. The feeder J1, K1, and M1 are deeply focused on accessing the impact of distributed PV and other DERs penetration. Remaining three feeders are for testing power flows and other applications in smart grid environment. In 2009, PNNL also published a set of 24 taxonomy radial distribution test feeders designed to represent US continental area.

Feeder J1

This is a real feeder located in the North-eastern US available online at [41]. The feeder has 1.7 MW of consumer-owned PV, 1300 residential, commercial and light industrial customers and 58 miles of line. The complaint of the consumer regarding high voltage was one of the reasons to choose it as a case feeder. The target of the feeder was to verify if the PV and slow load tap changer is the cause of the over-voltage. This feeder is used for voltage regulator applications in feeders with PV [42].

Feeder K1

This is a real feeder located in the south eastern US [43]. The feeder has 1 MW customer-owned PV along with 500 commercial and residential loads and 28 miles of primary line. It has a substation load tap changer(LTC) and a single capacitor bank at mid-feeder. The objective of this feeder is to study the power flow solution in high PV penetration without voltage regulators.

Feeder M1

This is relatively shorter and compact circuit with 1500 consumers and 13 miles of underground feeder [44]. This feeder has a unique radio-controlled capacitor bank of rating 1200 kvar 3 phase. This test feeder aims at studying the various capacitor bank management strategies.

Feeder Ckt5, Ckt7, and Ckt24

These are large-scale test networks presented in [45] available for testing power flow in smart grids environment. Ckt5 has 1379 customers, Ckt7 has 5694 customers and

Ckt24 has 3885 customers. Ckt5 and Ckt7 are primarily residential with longer feeder length while Ckt7 is shorter, compact and heavily loaded with commercial loads.

PNNL Taxonomy Feeders

The 24 radial distribution feeder models presented in [46] are the representative synthetic feeders constructed based on the statistical analysis of distribution feeder models supplied by 17 utilities of USA. The data of 575 distribution feeders from 151 separate substations were collected and a clustering algorithm was used to generate synthetic test feeders. The original IEEE test feeders were meant for checking the ability of software while they provide insufficient data relevant to the actual distribution system. These feeders were designed to provide researchers with the variety of feeder models in which smart grid ideas can be tested and implemented. These test models were constructed assuming that distribution analysis solution methods are valid. The US was divided into 5 climatic regions to carry out the classification and 23 prototype feeders were generated based on the clustering algorithm, to represent the respective subgroups. The 24$^{\text{th}}$ feeder was included to represent a general feeder type that was found in all five of the climatic zone. These feeders are used to study the various DERs and smart grid applications [47, 48].

2.1.3 Non-American Test and Representative Feeders

Several works have been done to create representative feeders in Europe, Australia, and England where the feeders are different from the North American one.

Representative Western Australia Feeders

The Australian Representative feeder consists of nine prototypical MV feeders and eight LV feeders as presented in [49]. The model uses the clustering algorithm as in PNNL feeder[46] but with fewer numbers of variables. The prototype feeders were selected from the analysis of 204 members of MV feeder database and 8858 members of LV feeder database.

Table 2.1: Description of MV feeder subsets for Western Australian Prototype feeder [49]

Cluster number	Description of feeder
1	light urban residential 1
2	heavy urban residential
3	heavy mixed metropolitan
4	moderate suburban residential
5	light urban residential 2
6	commercial/industrial
7	light suburban residential
8	rural short
9	rural long

Table 2.2: Description of LV feeder subsets for Western Australian Prototype feeder [49]

Cluster number	Description of feeder
1	small commercial/residential with low transformer utilization and short lines
2	residential mainly using overhead lines
3	residential with high transformer utilization, mainly using underground lines
4	residential with low transformer utilization, only using underground lines
5	median mixed commercial/residential with mainly using overhead lines
6	medium commercial/industrial with short LV lines
7	small residential with high transformer utilization, using short total LV lines
8	residential with high transformer utilization mainly using overhead lines

Table 2.1 and table 2.2 show the description of the type of the MV and LV feeders selected as prototype feeders. Out of 9 MV feeders, 5 are residential feeders,2 are rural feeders, 1 is commercial and 1 is a mixed metropolitan feeder. In LV feeders, out of 8 feeders, 5 are residential and 3 are mixed feeders. These feeders are used in mainly clustering applications as it provides easier way to cluster the distribution feeders.

Representative Residential LV Feeder for North England

The representative feeder for England was presented in [50] based on the clustering algorithm. The feeders were characterized using 19 features which included time-series data, presence of DERs, network parameters and consumer classification. A set of 383 feeders were taken initially which was reduced to 232 after cleansing and validation.

In the paper, 11 representative feeders were chosen to represent the Distribution system of North England, of which 8 were without PV and 3 had PV. These feeders are basically used to study the impact of PV penetration [50, 51].

European Representative Electricity Distribution Network

This is the first complete European style reference network model that can automate the layout of large-scale distribution network based on the street map and consumer information[52]. Three large-scale networks and six feeder type networks were built based on the data from 79 large European System Operators(DSOs). The indicators as submitted by DSOs in an online survey was used to create the proposed network. The constructed representative networks are categorized into two groups: Large-scale Networks and Feeder type Networks. Large scale networks are the networks including high voltage(HV), medium voltage(MV) and LV including both LV and MV consumers, MV-LV feeders and MV/LV substations. Feeder type networks are divided into MV feeder networks and LV feeder networks. Even though they represent the large scale networks, all networks are considered as three phase and balanced which is not the real scenario. The Reference Network Model(RNM) used by the authors is a very good model for Distribution planning and network growth strategies as discussed in [2].

2.2 Analysis of Existing Models

This thesis proposes the creation of the first large scale real European test network covering LV network of a whole city considering the three-phase unbalanced system. On reviewing the previous works no such system is previously available for research and study. In IEEE Distribution test feeders, there is a large scale network (8500 node system) [11], but it represents the North American type distribution system. The IEEE European Low Voltage Test Feeder presented in [35] is first European type feeder, but it lacks proper representation as it has only one LV feeder originating from transformer and 55 connected loads which are not the usual case. Further, it neglects the TT type of earthing in which the neutral is grounded at the transformer only and consumer earth and neutral are isolated. The time series load is a good feature of this test feeder but in practice getting 1-minute load pattern is very hard if PLC is used for communication. Also, the LV networks in Europe has multiple LV feeders used for back-feeding the consumers during transformer outages which can be represented through large scale network only. The synthetic network presented in [52] represents the large scale European feeder but it fails to address the issue of unbalanced three-phase network. Further, the network model created is a synthetic one and is based on the street map. The development of the actual distribution network is a long-term process and has many redundancies in the network path due to various restrictions. The actual network is never optimal as the network changes with load-growth and the feeder does not follow the shortest path always. These representative feeders are good tools to study the distribution resources optimization and distribution planning in a new city but not a complete one to interpret the actual European LV network.

This thesis thus aims to start the creation of a complete real European test network based on real network data of a whole city. It is done in different steps. At first, the IEEE European LV Test feeder is modified to represent the TT neutral ground system to compare the differences. Second, small feeders are simulated using the 4 wires LV system. The third will be the development of the script to create an OpenDSS file directly from the GIS raw file and fourth will be the creation of complete LV network model using the script.

Chapter 3

Simulation Software

This chapter discusses the basics of OpenDSS software and MATLAB®tools used for simulation of the distribution system. OpenDSS is the software used for the power flow simulation while MATLAB is used for pre- and post-processing the data.

3.1 OpenDSS

OpenDSS is an open source software developed by EPRI for simulating utility power distribution systems[1]. The OpenDSS tool has been used since 1997 and supports all frequency domain analysis commonly performed in the distribution systems. It also supports the other new type of analysis designed to meet the future needs related to smart grid, grid modernization, storage system and renewable energy integration [53].

One important feature of OpenDSS is that it uses a text interface unlike its counterpart software which uses graphical interfaces like CYME[2] and Synergi[3]. Each piece of equipment should be represented on an individual line in the text editor. It might be a huge task to model a large distribution system but advantageous in the case where the real data is obtained from GIS where we can automate the process to

[1] http://smartgrid.epri.com/SimulationTool.aspx
[2] http://www.cyme.com/software/#cap
[3] https://www.dnvgl.com/services/power-distribution-system-and-electrical-simulation-software-synergi-electric-5005

create the OpenDSS model from GIS raw data which is one of the scopes of this thesis and will be discussed in Chapter 5. This chapter discusses the different components used in distribution system simulation using OpenDSS.

3.1.1 Power Flow Algorithm OpenDSS

The program has different built-in power flow solution mode of which we are interested in following power flow mode:

- Snapshot mode
- Daily Power Flow mode
- Yearly Power Flow mode

Snapshot mode solves the power flow for a single instant while daily and yearly power flow mode can be used for the time sequence data where you have load data in a certain interval of time of a day or whole year. Apart from these, there are other modes of power flow like harmonics, dynamics, fault study, etc. which are important applications in distribution system studies.

The power solvers of distribution systems are generally formulated with radial circuits in mind [27] which works very well in radial and weakly meshed circuits. But in the case of OpenDSS, power solver was evolved from the program designed for harmonic analysis making it quite different from the other distribution power flow solvers [53]. OpenDSS uses primitive admittance matrix approach in building the system model. A primitive admittance matrix $\mathbf{Y}_{prim}$ is computed for each circuit element in the model. These small matrices are then used to construct the system admittance matrix $\mathbf{Y}_{sys}$. The procedure of generating $\mathbf{Y}_{prim}$ is shown in fig 3-1and equation 3.1.

Z is the 2x2 matrix describing the impedance characteristics of the coupled impedance. As shown in fig 3-1, the two impedance system has 4 nodes or terminals and equations to represent the current and voltage with respect to the zero-voltage reference in each node can be written in the form of nodal admittance matrix. This matrix relating the voltage and current is shown in equation 3.1. The primitive $\mathbf{Y}_{prim}$ is accumulated to make a system Y matrix($\mathbf{Y}_{sys}$) and the new relationship is shown in equation 3.2 where Ipc(V) represents the compensation current from all power conversion elements in the circuit.

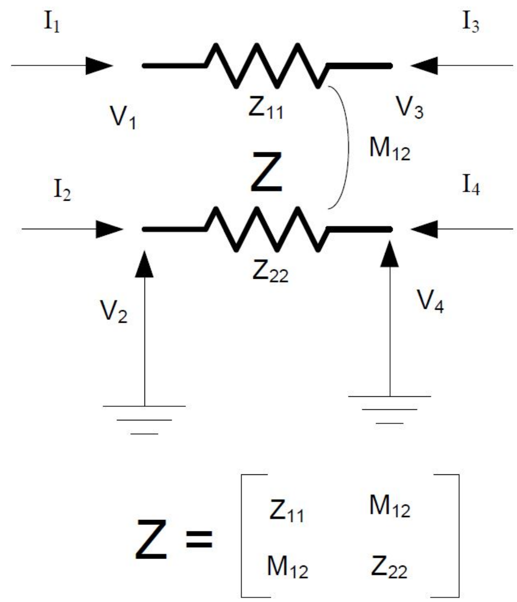

Figure 3-1: Building of $\mathbf{Y}_{prim}$ for simple two phase Coupled Impedance [53]

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Z^{-1} & -Z^{-1} \\ -Z^{-1} & Z^{-1} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \end{bmatrix} \tag{3.1}$$

$$I_{PC}(V) = \mathbf{Y}_{sys} * V \tag{3.2}$$

The currents injected from the PC elements in the circuit are the function of voltage and represents the non-linear portion of currents from loads, generators, storage and PV elements of the circuit. OpenDSS uses "fixed-point iteration" method to solve the non-linear equation as shown in equation 3.3.

$$V_{n+1} = [\mathbf{Y}_{sys}]^{-1} * Ipc(V_n) \quad n = 0, 1, 2, ...until \quad converged \tag{3.3}$$

The iteration achieves a good convergence for distribution system when:

1. The initial guess of voltage is close to the final solution,

2. The series impedance of power delivery elements is less than equivalent shunt impedance of the power conversion element. [53]

In the distribution systems, the first condition is easily achieved. During the sequential time power flow solution, the voltage from the previous solution is taken as start point which decreases the convergence time. To satisfy the second condition, a limit of voltage is kept below which the power conversion models revert to the linear model. Alternatively, OpenDSS also provides Newton power flow algorithm. It is more robust than the fixed-point iteration for difficult circuits [54]. It takes twice the calculations as compared to fixed point algorithm and is seldom required in solving distribution systems. This algorithm is faster when performing long time series simulation as $\mathbf{Y}_{sys}$ remains constant during the simulation.

3.1.2 OpenDSS Architecture

The OpenDSS program is a script-driven simulation engine whose architecture is represented in fig 3-2.

The engine has a main executive which can obtain the script from user written dynamic link libraries(DLL) or through the Microsoft Component Object Model(COM) interface. The OpenDSS Executive is written in the Delphi programming language. One of the reasons for using Delphi was to accommodate the COM interface with the program easily [53].

The various components of the distribution system are divided into five object class in OpenDSS:

- **Power Delivery Elements**: Line, Transformer, Capacitor, and Reactor

- **Power Conversion Elements**: Load, Generator, Voltage source, Current source, Storage

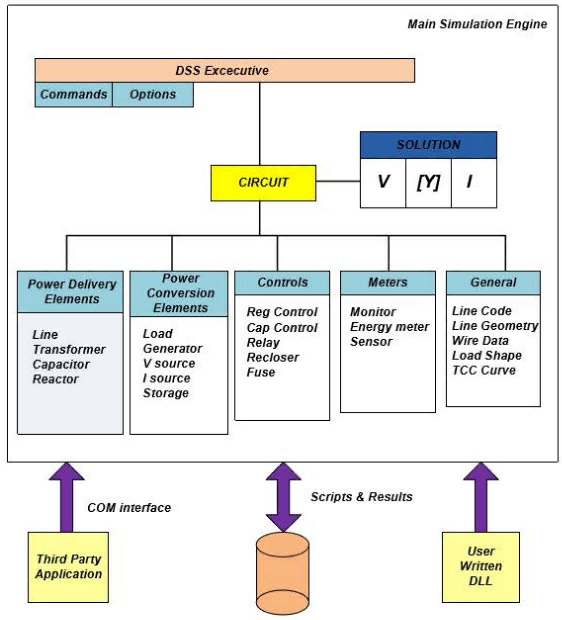

Figure 3-2: OpenDSS Architecture [53]

- **Controls**: RegControl, CapControl, Relay, Reclose, Fuse
- **Meters**: Monitor, EnergyMeter, Sensor
- **General**: LineCode, LineGeometry, WireData, LoadShape, GrowthShape, Spectrum, TCCcurve, XfmrCode

Each component has to be defined through the script. The typical script used in our simulation are shown in Listing 3.1.

Listing 3.1: Script to define Various Distribution Components

```
New Line.feeder1 Bus1=31.1.2.3.4 Bus2=31_1.1.2.3.4 phases=4 Linecode=205
   Length=1 Units=m !Script to define Line element
New Transformer.TD401346 windings=2 Buses=[65045 3865289.1.2.3.4]
   Conns=[Delta Wye] kVs=[22 0.420] kVAs=[630 630] XHL=4.0 !Script to
   define Transformer
New energymeter.m1 LINE.65043 1 !Script to define Energymeter
New Load.LOAD1 Phases=1 Bus1=1233.2.4 kV=0.23 kW=1 PF=0.95 daily=Shape_1
   !Script to define Load
```

```
New Loadshape.Shape_1 npts=24 minterval=60
    mult=(file=day_20_profile\shape_1.csv) useactual=true !Script to
    define Loadshape
New Reactor.grnd1 phases=1 bus1=31.4 bus2=31.0 R=5 X=0.01 !Script for new
    Reactor for Neutral Grounding
```

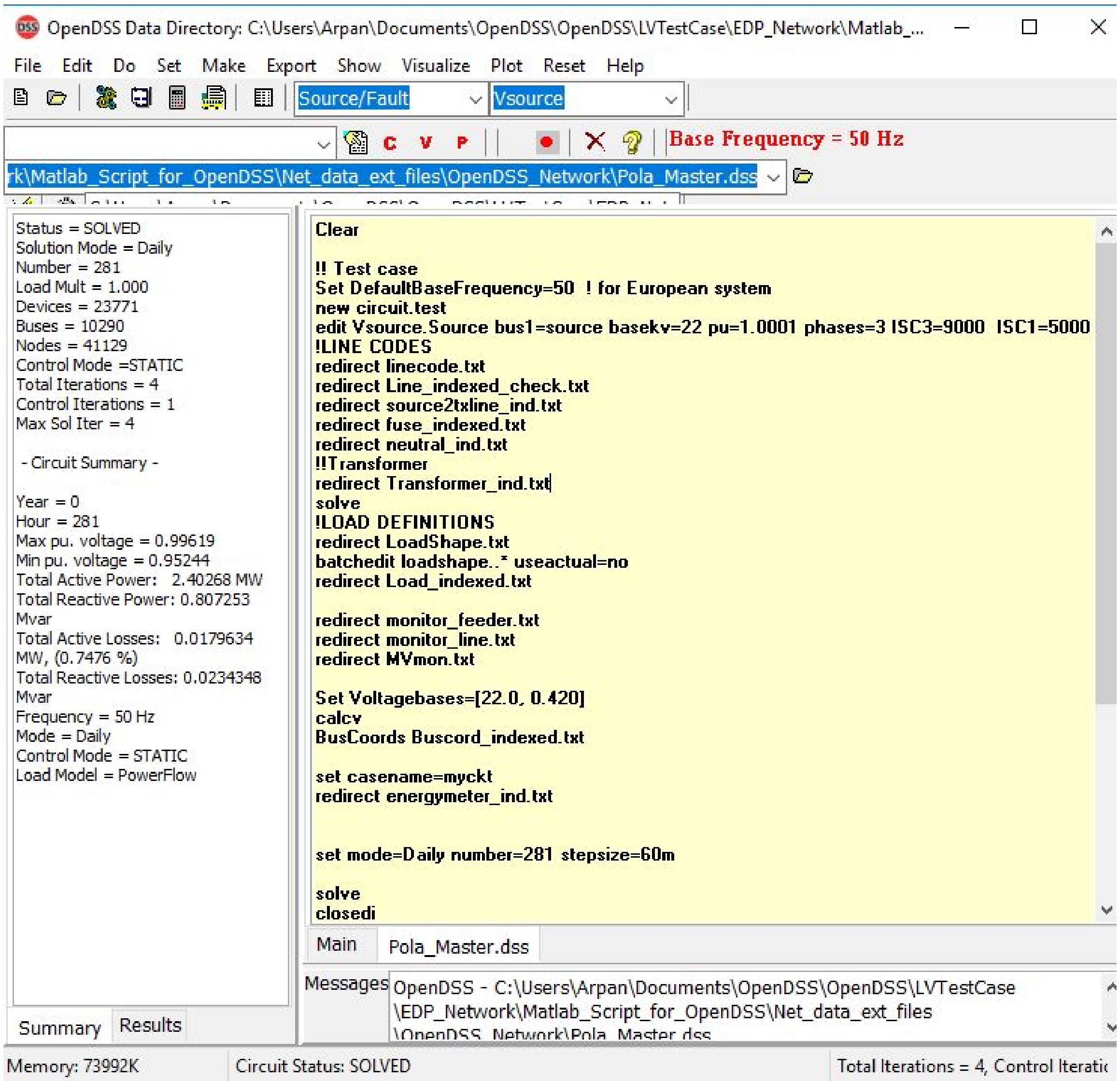

Figure 3-3: OpenDSS Interface with the master file

The main circuit model is made through sparse nodal admittance set of equations. The $\mathbf{Y}_{sys}$ is constructed from the nodal matrix of each circuit element. Circuit object tracks the connection in the circuit with the data from individual circuit element.

The circuit elements on other hand are just aware of their connected bus.

The OpenDSS Interface needs a master file to link with the various circuit elements file. Interface as shown in fig 3-3 represents a master file which links all circuit elements. The OpenDSS Graphics Interface is suitable for basic operations and Power Flow results but provides a very limited option for pre-processing of the data and post-processing of the output results.

3.1.3 OpenDSS using COM Interface

The script-based interface of OpenDSS provides many applications regarding power flow but has many limitations in applying new algorithms as well as post-processing the output in the desired way. The OpenDSS engine is used for power flow solving while other operations to change the network configuration and optimization of a different variable can be performed in third party software by taking the output from the OpenDSS as feedback. The code presented below allows MATLAB to run the OpenDSS program through COM interface.

```
clear all;
clc;
DSSObj = actxserver('OpenDSSEngine.DSS');
if ~DSSObj.Start(0),
disp('Unable to start the OpenDSS Engine');
return
end
DSSText = DSSObj.Text; % Used for text interfacing from matlab to opendss
DSSCircuit = DSSObj.ActiveCircuit; % active circuit
DSSSolution=DSSCircuit.Solution;
% Write Path for master and associated file
DSSText.Command='Compile (C:\User\Master.dss)';
DSSText.Command='batchedit load..* Vmin=0.8'; % Set Vmin lower so that
    load model property will remain same
DSSTransformers=DSSCircuit.Transformers;
```

The COM interface can be launched through other popular programs like VBA and Python. The DSS COM Interface has three basic children class:

- The **Text** provides user to launch DSS script command directly from the MATLAB or another program.
- The **Circuit** provides access to the circuit elements that make up the circuit.
- The **Solution** gives access to the solution; making able to define solution parameter, solve the circuit and view properties of the solution.

3.2 MATLAB®

MATLAB software by Mathwork Inc. is one of the commonly used software in scientific computing. Though MATLAB was designed for numerical computing its scope is very wide and increasing allowing a great range of scope to the researchers[4]. It is suited to the applications which deal with big matrices and vectors. MATLAB has a wide range of embedded functions that can be used in numerical techniques. In our application we used MATLAB for three purposes:

1. To read the GIS data and smart meter data in csv format and convert them into the OpenDSS script,
2. To run the OpenDSS script using COM interface and extract the data from monitors, and
3. To post-process the results obtained from the OpenDSS solver to display it in a more presentable form.

MATLAB functions can be used to search for optimal solutions by use of their embedded functions which is not available in OpenDSS. The other advantage of programming through MATLAB is to observe the change in the circuit output with the change in the circuit configuration in GIS. The MATLAB can also be used for interactive programming to see the effect of different events in the network.

[4]https://www.mathworks.com/products/matlab.html

Chapter 4

IEEE European Low Voltage Test Feeder

In Europe, the distribution grids are quite different from the North American grid. Most of the IEEE test system discussed in chapter 2 are designed keeping in mind the North American system except the European LV test feeder. In the current chapter, the basic feature of the IEEE European LV test feeder feeder is discussed. The feeder is critically analyzed and some modifications are suggested to represent the real European system.

4.1 Description of the test feeder

The test feeder is unique in nature compared to other test feeders as it has the following main features:

- The test feeder is at voltage level 416 V which is a typical feature of European distribution system.
- Load shapes are given in time series form for 24 hours every 1 minute giving 1440 load data points.

This feeder was introduced to include the diversity in the distribution feeders around the world. The time series data is an important feature of this case as it plays vital role in distribution research and planning. With the evolving demand side with storage and PV in consumer premises, the static load flow for peak load is no more sufficient for the distribution planning. The quasi-static data helps to study the influence of various DERs in the distribution system. The time series data also provides the test case to study the distribution system control using capacitor, regulators, and various load balancing mechanism. The other important aspect of this test feeder is operating frequency, which is 50 Hz unlike 60 Hz in other test cases.

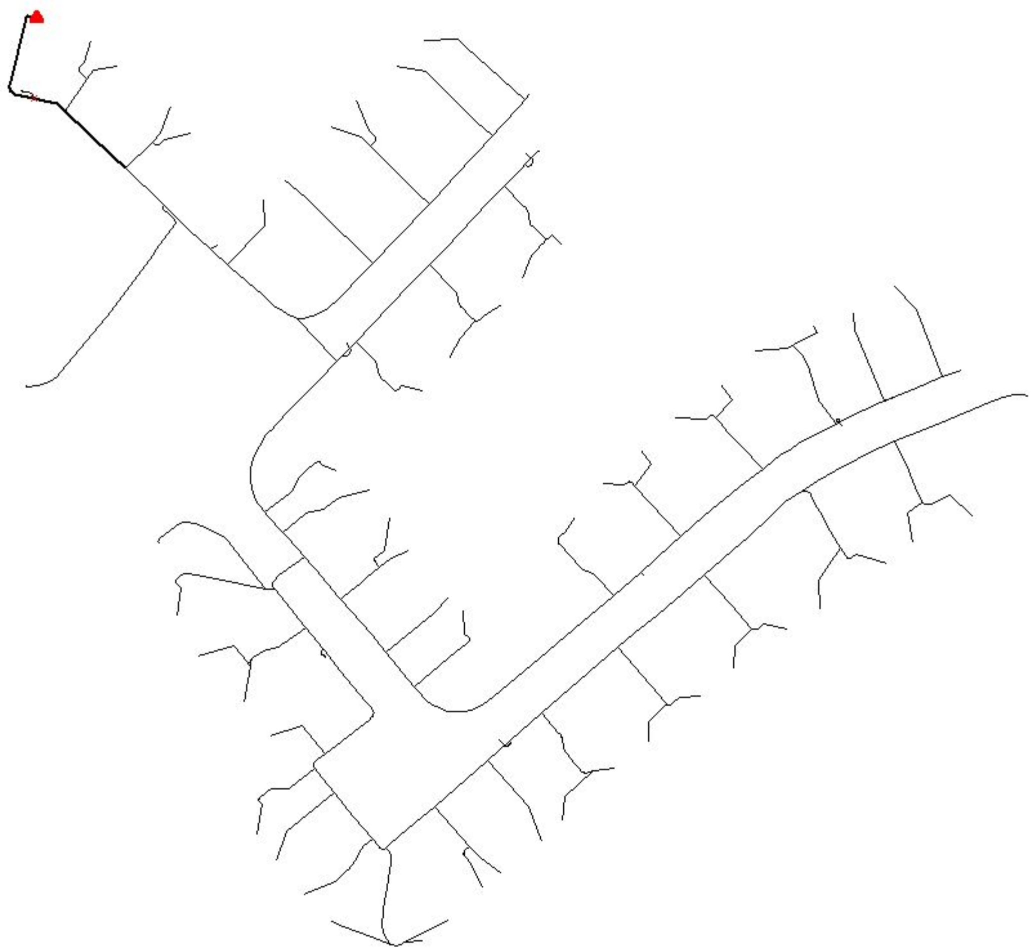

Figure 4-1: One-line Diagram of European Low Voltage test feeder obtained from the OpenDSS test case

Voltage Source

The test feeder is connected to the medium voltage (MV) system through a distribution transformer at the substation. The step-down transformer steps down the voltage from 11 kV to 416 kV which is the operating voltage of the lateral feeders. The one-line diagram of the LV-Test feeder is represented in fig 4-1. The MV system of the feeder is 11 kV Voltage source whose impedance is specified by the short circuit current, ISC3=3000 A and ISC1=5 A as shown in Master file 4.1.

Listing 4.1: OpenDSS Master File for IEEE LV test feeder

```
clear
Set DefaultBaseFrequency=50 ! for European system
New circuit.LVTest
Edit Vsource.Source BasekV=11 pu=1.05 ISC3=3000 ISC1=5 !Source Defination
Redirect LineCode.txt
Redirect LoadShapes.txt
batchedit loadshape..* useactual=no
Redirect Lines.txt
Redirect Transformers.txt
Redirect Loads.txt
Redirect Monitors_all.txt
New energymeter.m1 LINE.LINE1 1
Set voltagebases=[11 .416]
Calcvoltagebases
buscoords buscoords.txt !Linking Buscoordinate file
solve
```

Circuit Elements

The **transformer** at the substation is rated 0.8 MVA, rated voltage 11/0.416 kV with delta/grounded-wye connection. The winding resistance and reactance are 0.4% and 4% respectively.

The **distribution lines** are defined by the line code and length. Line code is represented in form of sequence impedance and admittance. All lines are defined as a three-phase line with multiple grounded neutral connection. The definition uses the sequence component modeling where the effect of neutral resistance is considered through reduced Carson's equation [27]. Table 4.1 shows the sample line and line code parameter required for simulation.

Table 4.1: Definition of Line and Line code in IEEE European LV test feeder

Line Definition								
Name	Bus1	Bus2	phases	Linecode	Length	Units		
LINE15	15	16	3	2c_.007	0.09654	m		
Line Code Definition								
Name	nphases	R1	X1	R0	X0	C1	C0	Units
2c_.007	3	3.97	0.099	3.97	0.099	0	0	Ω/km

The **loads** are constant PQ. The feeder has 55 single-phase loads. The load is defined by kW and power factor. The **load shape** element defines the multiplying factor for the load in every minute of a day. Each shape file has 1440 multipliers to represent each minute of the day. Table 4.2 shows the definition of load where Model 1 refers to the constant PQ load. The phase in which load is connected is referred by 1, 2, or 3. The load-shape file links the load file with a .csv file which has 1440 values for each minute of the day.

Table 4.2: Definition of Load and Load-shape in IEEE European LV test feeder

Load Definition									
Name	Nphases	Bus	phases	kV	Model	Connection	kW	PF	Yearly
LOAD20	1	349	1	0.23	1	wye	1	0.95	Shape_20
Load shape Definition									
Name		npts		minterval		File		useactual	
Shape_20		1440		1		Load_profile_20.csv		TRUE	

4.2 Limitation of the test feeder

The inclusion of long low voltage feeder with a large transformer and operating frequency of 50 Hz makes the test feeder quite near to the European style grid. The use of per minute time series data to represent data make it suitable for other studies related to control and demand management. Despite the inclusion of maximum characteristics of European style feeder few important points can still be modified to make it similar to European style feeder.

Neutral Grounding

The test feeder assumes the line to be three-phase by reducing the neutral conductor through Kron's Reduction in Carson's equation [40]. This might give a good result for balanced load case and MV distribution system where neutral is grounded in the span of few poles. But in the case of European Distribution System, LV lines are longer, unbalanced and with isolated neutral. The neutral supplied to the consumer is grounded only at the substation. The assumption in Kron's reduction where the neutral is earthed multiple times gives a wrong interpretation of consumer end voltage [40]. The consumer earth ground and neutral are not mixed causing all neutral current to return back to the substation through neutral wire. In this case, the neutral voltage is above the assumed 0 V ground voltage. The neutral current flowing through the neutral conductor causes the rise in the neutral voltage in the ratio of neutral impedance. Further, the voltage received by the consumer will be phase to neutral voltage instead of ground to earth voltage as assumed in the model. In the real scenario, this voltage may rise up to the value which can sufficiently diminish the voltage quality reaching to the consumer.

Per minute time series Load

The load presented in time series form is a very important feature of the test feeder. But in the case of smart meter connected with PLC, it represents the unrealistic case. Due to the bandwidth restriction in PLC [6] achieving 1-minute load from a smart meter is almost impossible. In a trial with EDP HC Energia by the team, closest reach was 20 minutes sample. The more efficient and error free data was obtained when the sampling time for energy collection was kept for one hour. In another study done by the team, it was observed that even in the sampling period of 10 second conventional weighted least square (WLS) technique cannot be used for the state estimation accurately. The load pattern can be changed to the one-hour basis for making it similar to the real system or can be converted to per second time series to check the possibility of real-time control and state estimation in the distribution system.

Feeder type

The normal European network has transformers of 100 to 1000 kVA in size. Each LV substation has multiple LV feeders originating from them. The LV network has certain normal open (NO) and normal closed (NC) circuit breakers which allow the possibility to change the network configuration. The IEEE European LV test feeder misrepresent the actual European system as it has only one single feeder originating from the LV substation with 0.8 MVA transformer. Further, there is no provision for changing network configuration as it represents a single feeder in a single distribution transformer.

Load Type

The European LV feeder consists of both single-phase and three-phase load. The three-phase load can be balanced or unbalanced one. But the test feeder consists of 55 loads which are all single-phase. Further, the number of loads connected with 0.8 MVA transformer is quite unrealistic. Seeing the load pattern at the peak load, the distribution transformer is loaded at 10% of its capacity which is very low compared to the general norm of loading the distribution transformer around 70% during peak load.

To address these limitations in European style test feeder, few changes are proposed in section 4.3 and a new European style test system is proposed in chapter 6.

4.3 Modified IEEE European LV Test Feeder

In this section, two changes are proposed in the European LV test feeder. First, the feeder is changed from three line model to four line model with TT neutral grounding. In the second case, a new time series data for each second of one day is proposed.

4.3.1 Inclusion of Neutral Conductor TT Grounding

The IEEE LV test feeder uses the sequence impedance matrix instead of the primitive matrix to reduce 4-wires model to 3-wires model.

Sequence Impedance Matrix Calculation

Figure 4-2 represents the model assumed in the European LV test feeder where the primitive impedance matrix of a node is matrix $\mathbf{Z}_{prim}$ given as:

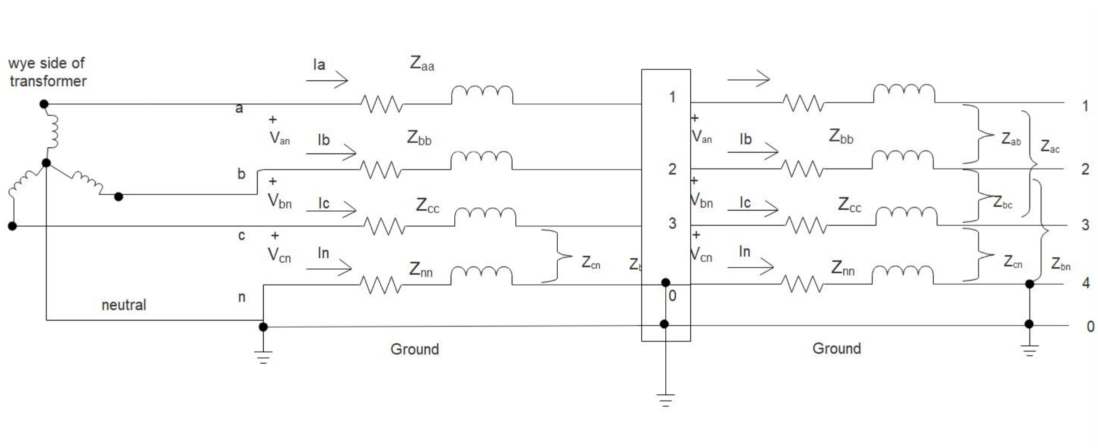

Figure 4-2: Impedance modeling in IEEE European LV test feeder

$$\left[\mathbf{Z}_{prim}\right] = \begin{bmatrix} z_{aa} & z_{ab} & z_{ac} & z_{an} \\ z_{ba} & z_{bb} & z_{bc} & z_{bn} \\ z_{ca} & z_{cb} & z_{cc} & z_{cn} \\ z_{na} & z_{nb} & z_{nc} & z_{nn} \end{bmatrix} \tag{4.1}$$

The $\mathbf{Z}_{prim}$ matrix is then reduced by Kron's equation [40] assuming that the line has multiple grounded neutral as shown in fig 4-2. The impedance matrix is converted now to a 3x3 matrix where each element is given as equation 4.2 where z_{ii} represents self-impedance and z_{ij} represents mutual impedance. The self and mutual impedance used are obtained from modified Carson's equation as shown in equations 4.3 and 4.4.

$$Z_{ij} = z_{ij} - z_{in} z_{nj} / z_{nn} \tag{4.2}$$

$$z_{ii} = r_i + 0.0953 + j0.12134 * [ln(1/GMR_i) + 7.934] \quad \Omega/mi \tag{4.3}$$

$$z_{ij} = 0.0953 + j0.12134 * [ln(1/D_{ij}) + 7.934] \quad \Omega/mi \tag{4.4}$$

The 3x3 matrix obtained after Kron's reduction is the reduced impedance matrix $\mathbf{Z}_{abc}$ given as equation 4.5 after partition between the row and column of phase c and row and column of neutral.

$$\begin{bmatrix}\mathbf{Z}_{abc}\end{bmatrix} = \begin{bmatrix}z_{abc}\end{bmatrix} - \begin{bmatrix}z_{an}\end{bmatrix}\begin{bmatrix}z_{nn}\end{bmatrix}^{-1}\begin{bmatrix}z_{na}\end{bmatrix} \tag{4.5}$$

The sequence impedance in European LV test feeder is represented by zero (Z_0) and positive (Z_1) sequence impedance as shown in table 4.1. The diagonal terms of the sequence impedance matrix are zero (Z_0), positive (Z_1), and negative (Z_2) sequence impedance. Z_1 and Z_2 are considered equal in the case of the radial distribution network. Further, to model the system in the base of sequence impedance the following assumptions are made:

- All self-impedance should be equal.
- All phase to phase mutual impedance should be equal.
- All phase to neutral mutual-impedance should be equal [40].

So, the simplified $\mathbf{Z}_{abc}$ can be written as 4.6 where Z_s is reduced self-impedance and Z_m reduced mutual impedance.

$$\begin{bmatrix}\mathbf{Z}_{abc}\end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \tag{4.6}$$

The sequence impedance matrix $\mathbf{Z}_{012}$ can be represented in form of reduced phase impedance matrix $\mathbf{Z}_{abc}$ as equation 4.7.

$$\begin{bmatrix}\mathbf{Z}_{012}\end{bmatrix} = \begin{bmatrix}A\end{bmatrix}^{-1}\begin{bmatrix}\mathbf{Z}_{abc}\end{bmatrix}\begin{bmatrix}A\end{bmatrix} \quad where, \begin{bmatrix}A\end{bmatrix} = \begin{bmatrix}1 & 1 & 1\\ 1 & a^2 & a\\ 1 & a & a^2\end{bmatrix} \tag{4.7}$$

On further calculations of equation 4.7 sequence impedance matrix is obtained as

$$\begin{bmatrix}\mathbf{Z}_{012}\end{bmatrix} = \begin{bmatrix}Z_s + 2 * Z_m & 0 & 0\\ 0 & Z_s - Z_m & 0\\ 0 & 0 & Z_s - Z_m\end{bmatrix} \tag{4.8}$$

The sequence impedance will now become:

$$Z_0 = Z_s + 2 * Z_m \tag{4.9}$$

$$Z_1 = Z_2 = Z_s - Z_m \tag{4.10}$$

Primitive Impedance Matrix Calculation from $\mathbf{Z}_{012}$

For making the modified IEEE LV test feeder have the same impedance as the base case, reverse equations were formed to derive the primitive matrix without ground return path since all neutral current is assumed to return from the neutral conductor.

$$Z_1 = z_{ii} - z_{ij} = r_i + jx_i \tag{4.11}$$

In equation 4.11, it is observed that Z1 represents the primitive self-impedance when the return path of ground, i.e., earth resistance is not considered. This neutral impedance can be calculated based on the neutral sizing. But there is no documentation about conductor sizes, so it is assumed that neutral impedance is equal to the phase impedance. Further, any mutual impedance is neglected because in simplified Carson formula earth impedance forms the mutual impedance.

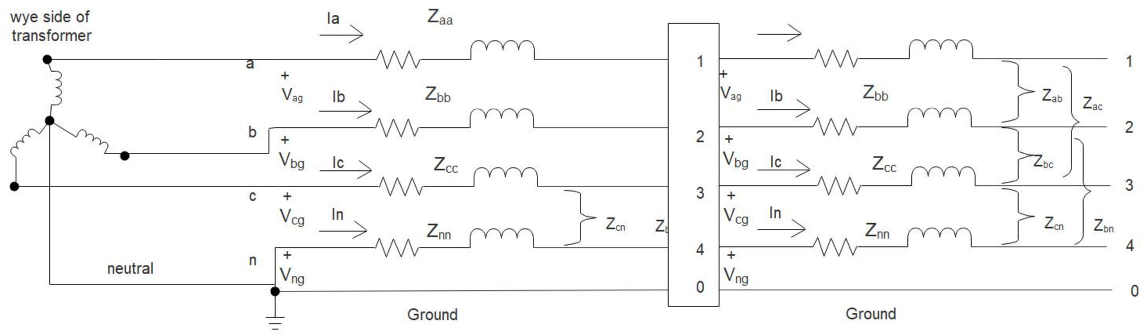

Figure 4-3: Modified Impedance modeling as per real European style TT grounding

Modification in OpenDSS code

The figure 4-3 represents the actual European style LV feeder where neutral is grounded at the substation and it is isolated from any other ground. The return path of consumer neutral current is provided by a neutral conductor. OpenDSS has a special feature which allows simulating this system as a four-phase system with few modifications in codes.

The **line code** in OpenDSS is now converted for 4-phase with the primitive matrix excluding any mutual impedance and dirt resistance.

```
New LineCode.2c_.007 nphases=4 baseFreq=50 units=km
~ rmatrix = [3.97 | 0  3.97 | 0 0  3.97 | 0 0 0 3.97]
~ xmatrix = [ 0.099| 0  0.099 | 0 0  0.099| 0 0 0 0.099]
```

The **line** is converted from default three-phase system to four-phase considering the neutral. OpenDSS takes Bus1=10.1.2.3.0 when we write Bus1=10 and assumes that the neutral is at the same potential as the ground at 0 V. But to simulate isolated neutral Bus1=10.1.2.3.4 expression should be used where .1.2.3.4 represent three phases and neutral.

```
New Line.LINE1 Bus1=1.1.2.3.4 Bus2=2.1.2.3.4 phases=4 Linecode=4c_70
   Length=1.098 Units=m
New Line.LINE2 Bus1=2.1.2.3.4 Bus2=3.1.2.3.4 phases=4 Linecode=4c_70
   Length=0.11511 Units=m
```

The **transformer** is modified to represent the delta-wye connection with star point available for connection in wye side (Low Voltage side). Delta side is connected with three phase MV line without neutral.

```
New Transformer.TR1 Buses=[SourceBus 1.1.2.3.4] Conns=[Delta Wye] kVs=[11
    0.416] kVAs=[800 800] XHL=4 sub=y
```

To represent the transformer neutral grounding, a **reactor** element is defined connected to the fourth phase (star point as shown in figure 4-3) with the ground. It is assumed that the ground resistor in the distribution system remains around 5Ω based on the feedback of distribution utility in Spain.

```
New Reactor.ground phase=1 bus1=1.4 bus2=1.0 R=5 X=0.01
```

The **load** element is defined as 1 phase connected with respective phase and neutral (.4) instead of the ground as seen below

```
New Load.LOAD1 Phases=1 Bus1=34.1.4 kV=0.23 kW=1 PF=0.95 Yearly=Shape_1
New Load.LOAD2 Phases=1 Bus1=47.2.4 kV=0.23 kW=1 PF=0.95 Yearly=Shape_2
```

Observations after Modification

The voltage pattern was observed after the modification of the European LV test feeder to accommodate the neutral wire.

It can be seen from fig 4-4 that when the neutral conductor is considered, the voltage obtained by the consumer is lower than the original model where the return path is considered as ground. The voltage difference is high at the point where the neutral voltage is increasing. The neutral voltage is produced due to the voltage drop in the neutral conductor, which in the original case was neglected assuming the return path to be earth and earth has less impedance than the neutral wire being used in the distribution system. In another observation represented in fig 4-5, the neutral voltage is observed to rise up to 10 Volts. The cases might deteriorate if the load increases and the unbalances become extreme. In the load data provided in the

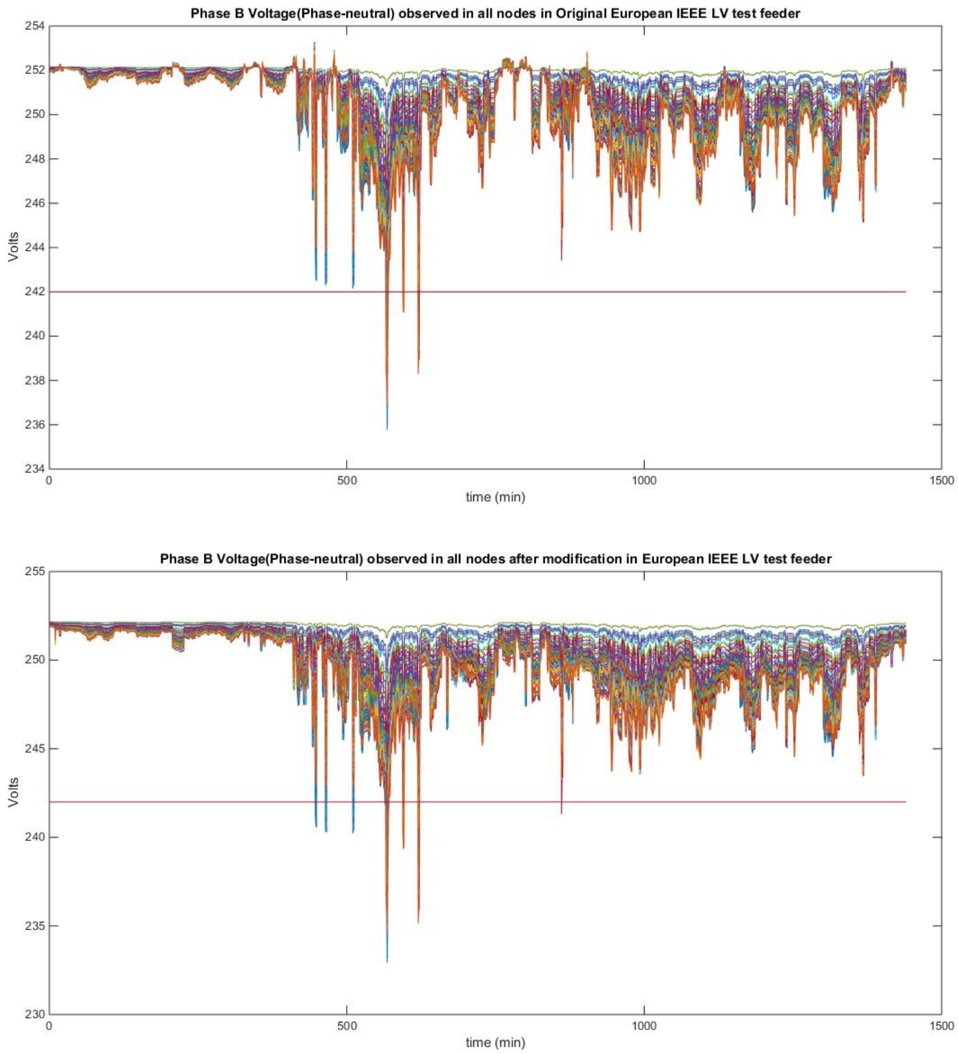

Figure 4-4: Phase B Voltage(Ph-ground) in all nodes in (a) Original and (b) Modified European LV test Feeder

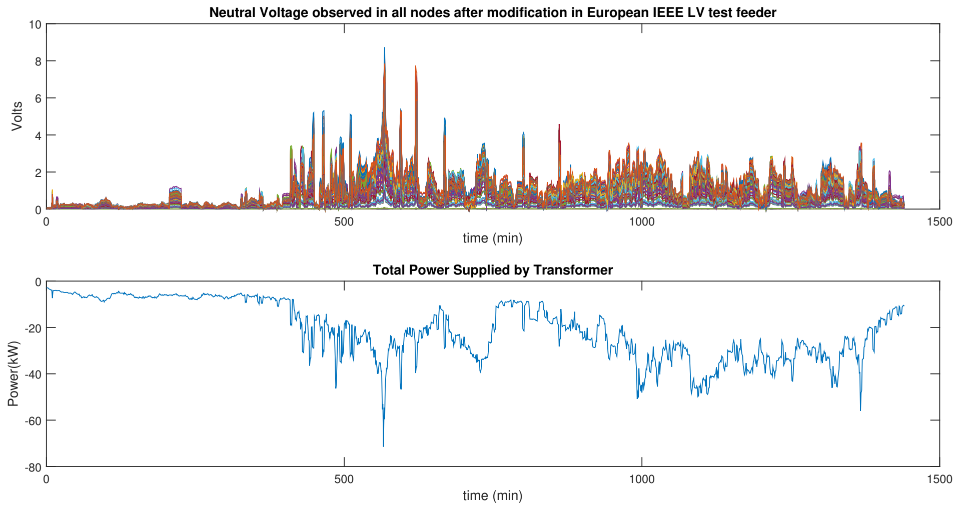

Figure 4-5: (a) Neutral Voltage in all nodes for a day with European style TT grounding in modified IEEE European LV test Feeder (b) Total Power Supplied by the Distribution Transformer

test case, the transformer is very sparsely loaded, i.e., the peak load is less than 70 KW that too for very less time (10% Peak Loading). It is also seen that the peak in neutral voltage is observed when the load is at the peak. The problem of neutral voltage will increase in the feeder and cannot be neglected as done in IEEE European LV Test Feeder.

Figure 4-6 shows the difference between modified and original test feeder in terms of the node current in a line. As observed in the top figure representing the four-wires model, the fourth wire represents the neutral wire and the current is the vector sum of all phase currents. The current returned from the ground is 0 A. In bottom figure, representing the 3-wires model, the same return current is seen but passing through the ground. It shows that the top figure represents the European style feeder in a more realistic way than the original test feeder. The assumption that the potential of neutral to be equal to ground potential i.e., 0 V at every node in the original European test feeder can be avoided if the modified model is adopted. This will help to understand the real unbalanced simulations in the European style LV distribution networks. The neutral voltage profile in figure 4-7 along the node shows that towards the end of very long feeder the neutral voltage is more prominent. The test feeder

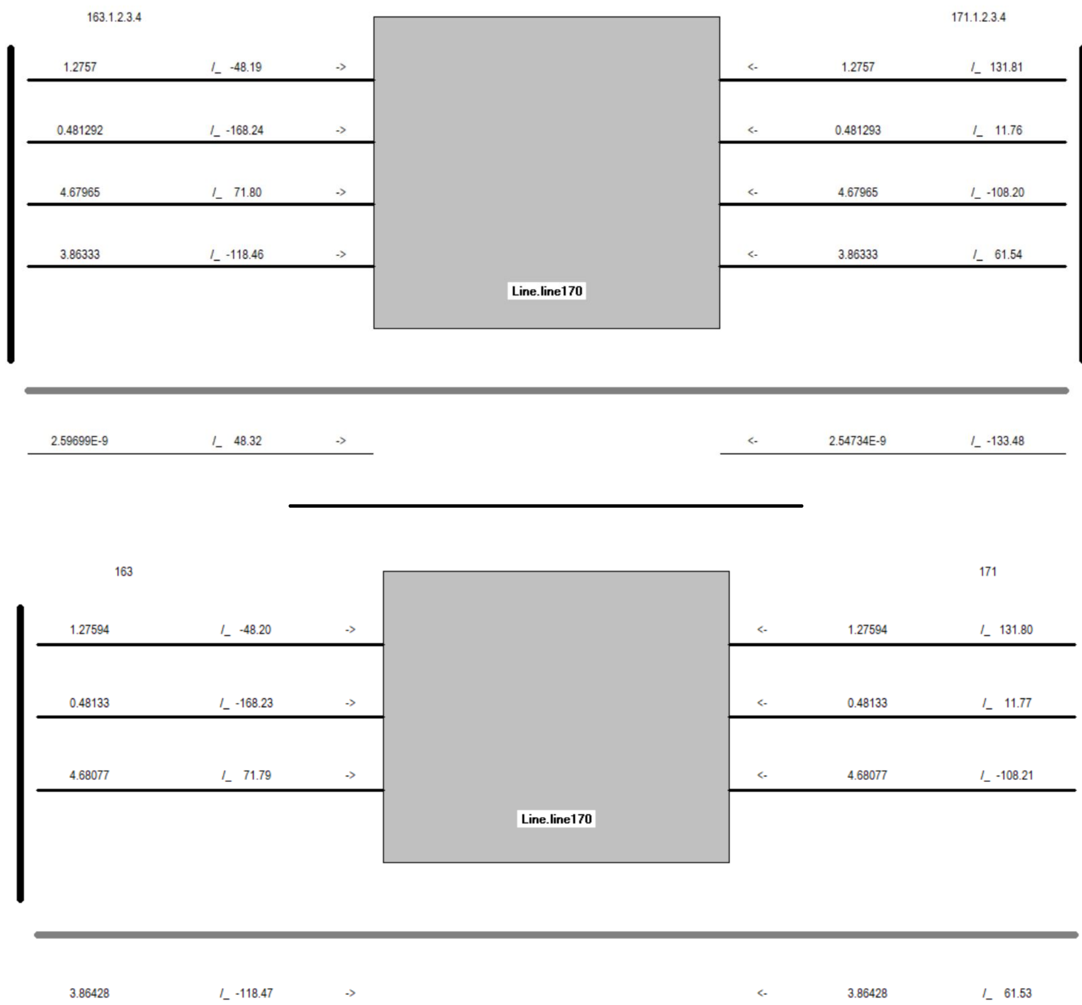

Figure 4-6: Comparison of Current in different node for Line 170 between Modified and Original European LV Test feeder

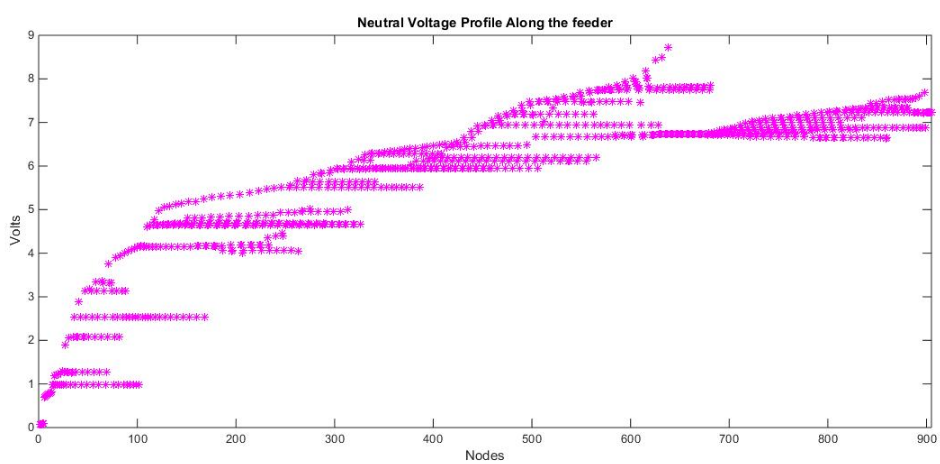

Figure 4-7: Neutral Voltage profile along the feeder

presented is just 500 m long. But in many cases, feeder length is longer than that creating a greater neutral voltage. Neutral voltage study thus provides an important tool for distribution system planner and must be included in the test feeder.

4.3.2 Per Second Time-series Load Data

As part of a research project at Vienna University of Technology a data set of per-second resolution of electric power profile of 30 households in Austria was recorded. The Data was generated in the research project "ADRES-CONCEPT" (EZ-IF: Development of concepts for ADRES – Autonomous Decentralized Regenerative Energy Systems, project no. 815 674) [55]. Using least mean square error in per day consumption, per-second profile with the lowest error was assigned to each IEEE load profile with energy factored by the total energy of the IEEE load. The new load profile thus will have the same energy consumption at the end of the day but will have per second resolutions with 86400 data points. Change in the OpenDSS code was done to accommodate the per second load data by changing the **loadshape** element.

```
New Loadshape.Shape_1 npts=86400 sinterval=1
    mult=(file=IEEE_modified_100profiles\New_Match_IEEE_P_1.txt)
    useactual=true
New Loadshape.Shape_2 npts=86400 sinterval=1
    mult=(file=IEEE_modified_100profiles\New_Match_IEEE_P_2.txt)
    useactual=true
```

The aim was to provide researchers with load data of lower sampling period and also to see the impact in overall balancing while considering the per-second resolution of the load.

Results of Modification

The neutral voltage profile observed in the modified case was less than the original case because the load becomes more balanced in taking a lower resolution.

The figure 4-8 represents the high-resolution phase current and the neutral voltage

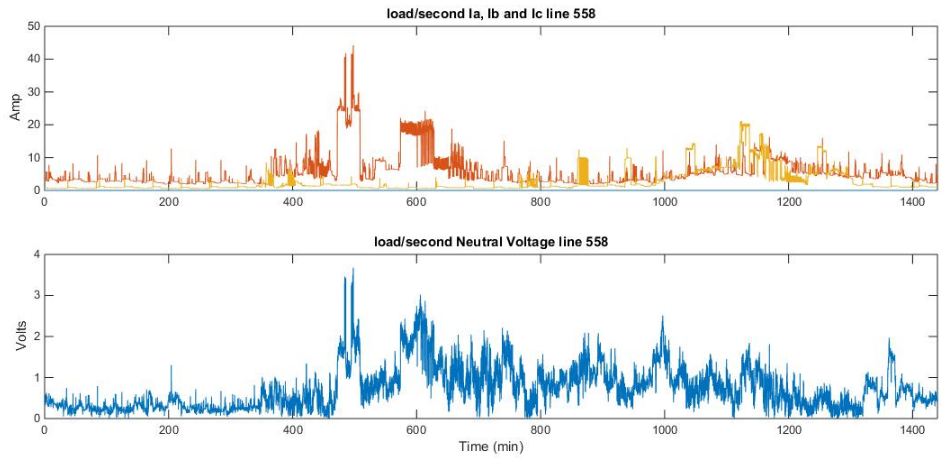

Figure 4-8: Phase Current and Neutral Voltage at Bus 558 after Load modification to Per-second load

at node 558. The lower neutral voltage shows that the load is more balanced on lowering the resolution but further researches are required to verify it. The modified load pattern can be used to study the distribution state estimation.

Still, after the modification, many limitations of the IEEE European test feeder as discussed in section 4.2 could not be addressed. In the next chapter, a method is proposed to convert the real LV network of a city in Spain to the real European test network to address all the limitations.

Chapter 5

Integration of Raw data to OpenDSS Code

One of the purposes of this master thesis is to deliver EDP HC Energia an OpenDSS model of distribution network taking in account the network data, load position and smart-meter readings. The model should be able to accommodate any changes and configuration of the network structure. It should also provide the good visual representation of the network status for the distribution planning as well as possibility to add storage and renewable elements in future. Based on the experience of converting the IEEE European LV test feeder to 4-wires model as discussed in chapter 4, the new model is directly simulated in 4-wires format. Further, the way to convert the GIS data directly into indexed form was also explored, so that the data will be available to researchers without the breach of any privacy. In the following sections, the network data obtained from the GIS application explained along with the strategy for their conversion in an OpenDSS format with proper re-annotations.

5.1 Description of Raw Data

The raw file for the network was in *xlsx* format with name *Red_NAME_DATE.xlsx*[1]. The description of the load was extracted with name *Inventario_Contadores_NAME.xlsx*[2]. The smart meter energy readings were extracted in *Curva_Carga_Contadores_NAME.csv*[3]. Due to the limitation of the excel file, the files for smart meter energy reading were in multiple files to accommodate all meters and their consumption record. The phase of the loads was determined by PLC communication and field verification and included in *phase meters.xlsx*. The first three files were extracted from Bentley GIS tool[4] being used by EDP HC Energia using Oracle database handling tool.

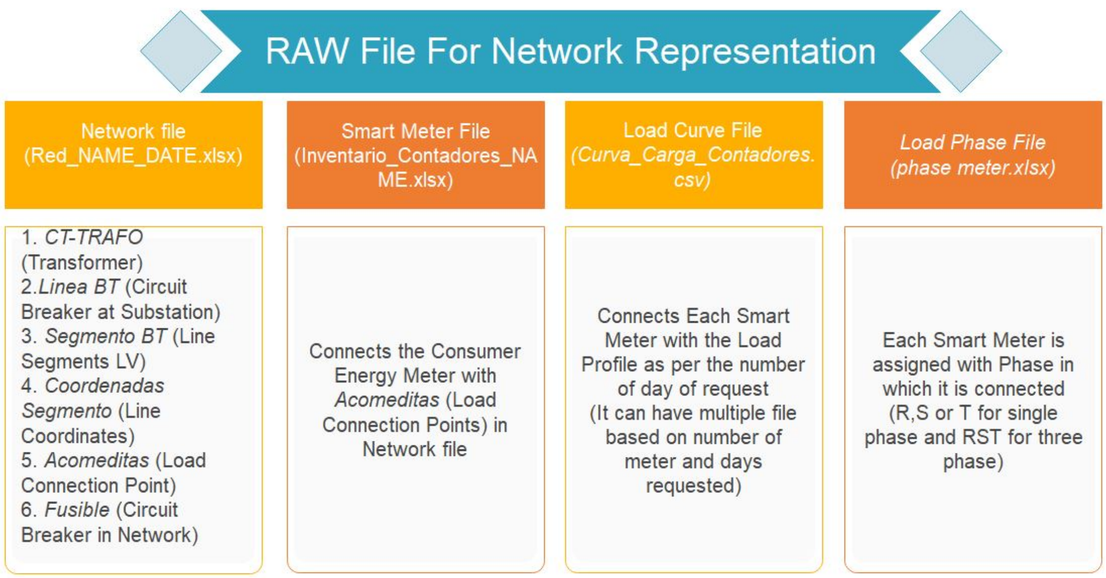

Figure 5-1: Description of Raw file used to Create OpenDSS model of large Distribution Network

5.1.1 Network Data (*red*)

The Network data consist of the details of all distribution elements component in LV side. The Spanish distribution system generally have manual tap-changers in

[1] *Red* is the Spanish word for 'network'
[2] *Inventario Contadores* is Spanish words for 'Inventory Counter'
[3] *Curva Carga Contadores* is Spanish words for 'Load Curve from Smart Meter'
[4] https://www.bentley.com/en/products/brands/openutilities

11/0.416 kV substations but they are operated very seldom and is neglected in this model. The line component and fuses used to change the network configurations are the important components of the a distribution system which defines the topology. Figure 5-1 shows the various sub-file included in Network file. There are six sub-files in Network file which have been analyzed and converted to OpenDSS Model.

Transformer (*CT-Trafo*)

Transformer data consist of the details of distribution transformer. As shown in figure 5-2 transformer file consists of 11 columns. Of them, column G represents the unique code to the transformer. In the simulation, it is considered as the name of the transformer. Column F (*Mslink Celda*) represents the bus 1 of the transformer, i.e.,

	A	B	C	D	E	F	G	H	I	J	K
1	MSLINK	CLAVE_BDI	DES	X	Y	MSLINK CELDA	CLAVE CELDA	CLAVE TRAFO	DES TRAFO	POTENCIA TRAFO	NUDO CELDA TRAFO
2	65043	C000601	CT MARQUESA DE	284345.89	4807588.1	65045	PO006217	TD401346	TRAFO CT MARQUESA	630	3865289
3	65079	C000606	CT PLAZA CUBIER	284452.71	4807732.3	65081	PO006365	TD400291	TRAFO CT PLAZA CUB	1000	3864018

Figure 5-2: File from GIS representing Transformer in Network

MV side and column K (*Nudo Celda Trafo*) represents the bus 2 of the transformer i.e., LV side. The column J represents the capacity of the transformer (*Potencia Trafo*) in kVA. The connection for all transformer is taken as delta-wye and the % impedance is 4%. The column D and E represent the X and Y coordinates of the substation. The MV and LV side of the transformer are assumed to be in the same coordinates.

LV Circuit Breaker at Substation (*Linea BT*)

The circuit breaker data at substation consists of the details of the feeder originating from each substation and their status as shown in figure 5-3. The entry in column E (NO) represents the origin bus which links with bus 2 of the transformer. It signifies the transformer in which the breaker is connected. The column B (*Clave Linea*) represents the feeder number for feeders in each transformer. The column A (*Mslink*) is the unique ID for each feeder. The column I (*EST Normal*) and column J (*Est*

	A	B	C	D	E	F	G	H	I	J
1	Mslink	Clave Línea	Mslink CT	Clave CT	NO	NE	X	Y	EST_NORMAL	EST_OPERAC
2	775431	1	65043	C000601	3865289	108023	284346.61	4807583.8	C	C
3	775433	2	65043	C000601	3865289	108024	284346.69	4807584.49	C	C
4	775435	3	65043	C000601	3865289	108025	284346.79	4807585.18	C	C
5	775437	4	65043	C000601	3865289	108026	284346.89	4807585.88	C	C
6	775439	5	65043	C000601	3865289	108027	284346.99	4807586.56	C	C
7	775441	6	65043	C000601	3865289	108028	284347.08	4807587.25	A	A

Figure 5-3: File Representing the LV circuit Breaker at the origin of feeder

Operac) represent the normal condition and present condition of the breaker. The value **C** refers the breaker is closed[5] and **A** refers the breaker is open[6]. The column G and H represent the X and Y coordinates of the bus2 of the breaker. The length of the line connecting the LV side of terminal and breaker by distance formula in the coordinates from bus 2 of transformer represented bt Trafo_x and Trafo_y (Column D and E of *CT Trafo*) and Bus 2 of the Feeder Breaker represented by Lin_x and Lin_y (Column G and H of *Linea BT*), the length of feeder is given by:

$$Distance(d) = \sqrt{(Trafo\_x - Lin\_x)^2 + (Trafo\_y - Lin\_y)^2} \tag{5.1}$$

Line Segments (*Segmento BT*)

The line segments file has details of segments of each feeder defined in LV circuit breaker(*Linea BT*) as shown in figure 5-4. The column A (*Mslink*) is the unique Id

	A	B	C	D	E	F	G	H
1	Mslink	Longitu	Tipo	Mslink Lín	Clave Línea	Nudo Origen	Nudo Des	Tipo Cable
2	74437	41	Subterráneo	73796	5	41291	3225463	BT - RZ 0,6/1 KV 3*150 AL/95 ALM
3	1374735	31	Subterráneo	73796	5	1169197	2528898	BT - RV 0,6/1 KV 3(1*150 KAL) + 1*95 KAL
4	1374736	1	Subterráneo	73796	5	1169202	1169197	BT - RV 0,6/1 KV 4*25 KAL
5	1374737	24	Subterráneo	73796	5	1169207	1169197	BT - RV 0,6/1 KV 3(1*150 KAL) + 1*95 KAL
6	2375075	1.05	Subterráneo	73796	5	2528544	2523889	BT - RZ 0,6/1 KV 3*150 AL/95 ALM
7	2375085	127.84	Subterráneo	73796	5	2528565	2528544	BT - RZ 0,6/1 KV 3*150 AL/95 ALM

Figure 5-4: File Representing the Line segments of each feeder

for each segment. Column B represents the length of the segment in meter. Column D (*Mslink Linea*) is the unique code for each feeder. Column F (*Nudo Origen)* is the Bus 1 of the segment while Column G (*Nudo Destino*) is the Bus 2 of the segment. Column H represents the type of the cable (*Tipo Cable*) of that segment.

[5] C refers *cerrado* which means Closed

[6] A stands for *abierto* in Spanish which means Open

Line Segment Coordinates (*Coordenadas Segemntos*)

The line segment is the line between two points where there are same cable type and no branching. The line segment parameter is enough to calculate the nodal power flow. But if we want to represent the line segment in the map, it requires the coordinates. The 'line segment coordinates' is the file which has data of all the line segments as shown in figure 5-5. Each line segment can have two or more coordinates

	A	B	C	D	E	F	G	H
1	Mslink	Longitud	Tipo	Mslink Línea	Clave Línea	Orden Vértice	X	Y
2	74242	34	Aéreo	74239	1	0	284321.44	4807668.4
3	74242	34	Aéreo	74239	1	1	284321.15	4807667.9
4	74242	34	Aéreo	74239	1	2	284321.27	4807667.8
5	74242	34	Aéreo	74239	1	3	284321.18	4807667.7
6	74242	34	Aéreo	74239	1	4	284321.12	4807667.5

Figure 5-5: File Representing the Coordinates of each Line segments of each feeder

based on the type of line. If it is a straight line then two coordinates will be enough to represent the line segment but if it has curves or change in direction, it needs more coordinates to represent it in the map. The column A (*Mslink*) is the unique code assigned for each segment. The part of the segment is represented by column F (*Orden Vertice*) whose value starts from 0 and ends with the number of coordinates required to represent the line segment. The column G and H represent X and Y coordinates of the part of the segments that form the line segment. This file can be neglected if we do not want the visual representation of the network but is an important file in our case as we want a visual representation of data.

Load Connection Point (*Acometidas*)

The load connection file as shown in figure 5-6 provides the link between the loads and the network. Column B (*Clave BDI*) of this file is the unique load connection point Id which connects the load in smart meter record file. The bus in the network in which this load connection point is connected is given in column C (*Nudo Origen*).

	A	B	C	D	E	F
1	Mslink	Clave BDI	Nudo Origen	Nudo Destino	X	Y
2	1220006	15152501	954350	3790730	284846.86	4807846.4
3	80007	15173201	2573500	3774374	284351.97	4808061.26
4	80016	15171001	44255	3858408	284454.47	4808006.08

Figure 5-6: File Representing the Load connection points in the network

Circuit Breaker in Network (*Fusible*)

This file plays an important role to model the change in network connectivity. The LT network of a city consists of many breakers which are normally open or closed and can be used to change the network configurations. As shown in figure 5-7, column

	A	B	C	D	E	F	G
1	Mslink Fusible	X	Y	Nudo Origen	Nudo Extremo	Est. Normal	Est. Operac
2	80034	284481.72	4808081.4	44257	1402524	A	A
3	2360167	284165.18	4807961.4	2509198	2509208	C	C
4	80316	284750.28	4807605.7	44402	2450688	A	A
5	2190519	284386.87	4808042.5	2247084	3385738	C	C
6	2190522	284387.64	4808041.7	2247104	3385739	C	C

Figure 5-7: File Representing the position and status of Circuit Breaker in network

D (*Nudo origen*) and F (*Nudo Extremo*) represent the bus 1 and bus 2 of the circuit breaker. The column F (*Est normal*) is the normal operating condition of the circuit breaker while column G (*Est operation*) represents the current satus of the circuit breaker. As in circuit breaker at the substation, **A** refers open condition (*abierto*) and **C** refers to the closed condition (*cerrado*) of the circuit breaker.

5.1.2 Smart Meter Record File (*Inventario Contadores*)

The smart meter record file consists of all the smart meter in the network of interest. The file has all the information of the load ranging from the transformer connected to, full address of the consumer and many more. But for the load flow simulation and visual representation, the only point of interest is the connection point of the smart meter in the network. As shown in figure 5-8, column A of the data has the unique ID of each smart meter (*referencia*) and column R has the unique Id of load

	A	R	S	T	U	V	W
1	Referencia	Acometid	Linea	Clave Ct	Hueco	Nombre N	Mat Teleg
2	SAG0145432047	36767901	2	C000601	1	TRAFO CT M	1
3	SAG0145443412	4285302	4	C000601	1	TRAFO CT M	1
4	SAG0155188330	4281701	5	C000601	1	TRAFO CT M	1
5	SAG0155194846	39365571	3	C000601	1	TRAFO CT M	1

Figure 5-8: File Representing the Smart meter in the network

connection point (*acometidas*) defined already in network file.

5.1.3 Load Curve File (*Curva Carga Contadores*)

Load curve file is required to define the time series load data for each load as shown in figure 5-9. It is the data obtained from the smart meter every hour. In our model

	C	D	E	F	G	H	I
1	Referencia	Fecha	Dia	Estacion	Activa E	Activa S	Reactiva1
2	ZIVS004318347	2/26/2018 0:00	2/25/2018 0:00	W	64.505	0	7.39
3	ZIVS004318347	2/26/2018 1:00	2/26/2018 0:00	W	54.767	0	6.69
4	ZIVS004318347	2/26/2018 2:00	2/26/2018 0:00	W	52.836	0	5.974
5	ZIVS004318347	2/26/2018 3:00	2/26/2018 0:00	W	49.369	0	6.348
6	ZIVS004318347	2/26/2018 4:00	2/26/2018 0:00	W	48.223	0	5.915
7	ZIVS004318347	2/26/2018 5:00	2/26/2018 0:00	W	50.291	0	5.914
8	ZIVS004318347	2/26/2018 6:00	2/26/2018 0:00	W	47.789	0	5.916

Figure 5-9: File Representing the Load Curve

we are interested in the active power for the load which is represented in column G (*Active E*). Column D (*fecha*) represents the time to which the active power belongs to while the column C (*referencia*) is the unique Id for the load. Each load will have 24 entries for a day and can be more if the days of interest are more. In few cases, due to missed communication, some of the loads have less than 24 entries for a day.

5.1.4 Phase Data

This is the file with phases of the all connected load in the network. The phase data was obtained by the field verification of the results obtained from PLC communication. As shown in figure 5-10, the file consists of unique Id for load

	A	B	C	D	E	F
1	ID	Fase	Linea	Medida	Ultimo Estado	CT
3	ZIV0034678234	R	TF1CB1LBT5	OK	ACTIVE	ct002051
4	ZIV0034678476	T	TF1CB1LBT4	OK	ACTIVE	ct002051
5	SAG0145411816	S	TF1CB1LBT7	OK	ACTIVE	ct002051
6	ZIV0034678236	S	TF1CB1LBT5	OK	ACTIVE	ct002051
7	ZIV0034678231	T	TF1CB1LBT5	OK	ACTIVE	ct002051
8	ZIV0034678473	T	TF1CB1LBT4	OK	ACTIVE	ct002051

Figure 5-10: File Representing the Phase in which Load is connected

(*referencia*) in column A and phase in column B. The R, S and T indicate phase A, B, and C respectively for single-phase load, while RST represents 3 phase loads.

5.2 Indexing of Circuit Element Data

The aim of this thesis is to generate the test network through the real network data. But as mentioned in [1] this requires conversion of data to remove private data. Also, the network elements should be re-annotated to make data analysis and representation easier. This section deals about the re-annotation process of all the data.

Load Indexing

The smart meter file is first sorted by CT number and then alphabetically and the load is renamed with integers starting from 1. Since all load names are unique it does not have any issue. The bus connected is linked with the load during indexing.

Line Indexing

The overall line is divided into three types: MV line, LV busbar and LV line. The MV lines are the lines connecting the source with the transformer. The LV busbars are the lines representing the segment from the LV side of the transformer to the circuit breaker.

Further, the circuit breaker in substations and between the LV network are also assumed as lines and are indexed differently. All lines are indexed in the format [xxxxx00], where xxxx represents the type of line and [00_00] represents the unique number for each line of the same type.

Table 5.1: Description of Codes used in line Indexing

Type of line	String[xxxx]	number[00_00]
Medium Voltage	mv	1,2,3...
LV Feeder from Transformer	feeder	1,2,3...
LV breaker in substation	cktbk	1,2,3..(for closed ckt only)
LV line	[blank]	1_0,1_1,1, 2_0,2_1,2_2,2_3,...
LV Breaker in mid-network	fuse	1,2,3,.. (both for closed and open)

As shown in table 5.1, [mv00] is used to signify the MV lines, [feeder00] is used to represent the feeder line from Transformer to LV Breaker in the substation, [cktbk00] to represent the circuit breaker in the substation and [fuse00] to represent circuit breaker in the middle of LV network. Remaining lines are simply represented by an integer [00] if they represent the monitored segment of line and by [00_00] if they are non-monitored segment, where the first integer represents the line segment and second the sub-segment of that line segment.

The indexing of the line was done to prevent the coordinates of the line segment from generating more monitored buses. As discussed in the network data, each line segment may require more than two coordinates to represent correctly in the map. But as discussed in [38], it is not necessary to monitor all those small segments. There is a need to define a separate line to visually represent the feeder as it is but different naming method is adopted to make the monitoring easy.

Figure 5-11 shows a simple example for LV line indexing scheme so that there is no need of further reduction of the circuit as researchers did for IEEE LV test feeder in [38]. It is observed that the line segment between point a and b is a line segment which is straight and do not need any segment, so the line code is 3. At point b, two line segments originate 4 and 5. For line 4 it is seen that representing it needs more coordinates (0,1,2,...,8) which means that it needs 8 lines to define as it is in the map but since there is no branching or any load in between, the current will be same for all of these segments. So instead of defining them all with an integer, only the last sub-segment is named as line 4 while the sub-segments are indexed as 4_0, 4_1, etc.

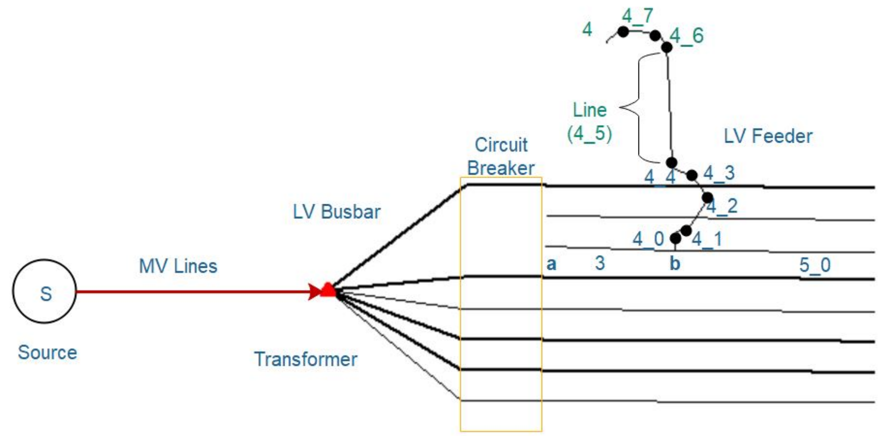

Figure 5-11: Simple Line Topology for Line Indexing

The advantage of this system is that while monitoring, one measuring tool (monitor in OpenDSS) would be enough to represent all these lines sub-segments.

Bus Indexing

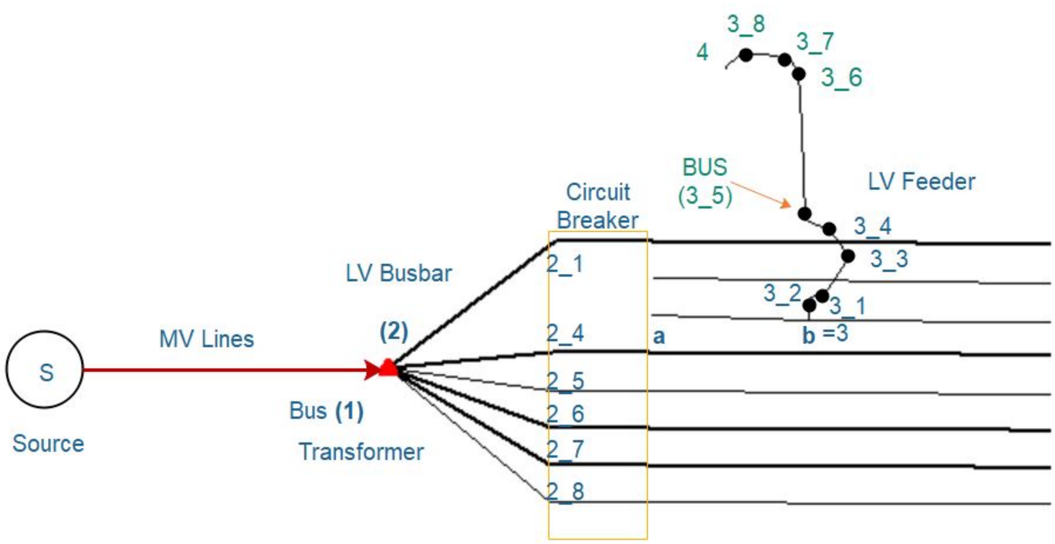

Figure 5-12: Simple Line Topology for Bus Indexing

The strategy used in bus indexing was to name the bus 2 of each line same as the line. The advantage of doing so is that it makes monitoring of the line easier and less confusing. Further in OpenDSS when you monitor the line the observed parameters are of Bus 2. So, making them with same name makes possible, monitoring the line and bus with less complexity.

As shown in figure 5-12, the line code for the segment 'ab' is 3. So, the bus 2 of the segment, i.e., point b is indexed as 3. The segment arising upward from point b has multiple segments to define coordinate and are indexed as 3_1,3_2,...,3_8. The end of the segment is the point of our interest so will be indexed by integer 4, which is also the name of the line joining Bus 3_8 and 4. The bus number is first assigned to the all HV side of the transformer, then to the LV side. The busbar of LV side is then assigned the name in the format [00_00]. As seen in the figure 5-12, if the system has only one transformer, HV side bus will be named 1, LV side as 2 and Bus 1 of circuit breaker as 2_1,2_2,....,2_8. The point to note here is we have omitted the LV busbar where the circuit breaker is open but retained their name to maintain uniformity. So, in the above case, bus 2_2 and 2_3 does not exist but will come in the role if the respective breaker is closed. Table 5.2 shows the number reserved for the different type of bus if the system has 'nt' numbers of transformers and 'ns' numbers of line segments.

Table 5.2: Description of Codes used in Bus Indexing

Type of Bus	Number Assigned
Medium Voltage Side of Transformer	1,2,3..,nt (nt=transformer number)
Low Voltage Side of Transformer	nt+1,nt+2,...,2*nt)
Bus 2 of Line segment	(2*nt+1),(2*nt+2)...,(2*nt+ns)
Starting Bus after Breaker	(2*nt+ns)+1,(2*nt+ns)+2,....
Substation Breaker Transformer side(Busbar)	(nt+1)_1,(nt+1)_2,...
Sub-segments of the line except first and last bus	(2*nt+1)_1, (2*nt+1)_2,...

5.3 Complexities in Data

The indexing method explained in section 5.2 solves the problem of hiding the private data as well as avoiding the monitoring of the small segments which were taken just for the visual representation of line segment. It also makes the model cleaner with shorter and easier name than the original data. But the data has a certain problem which makes it difficult to model directly.

Bus Indexing Complexities

The major problem was the improper definition of bus 1 and bus 2 in line segments and circuit breaker at mid-circuit. It was observed that in line segment (*Segmento BT*) file, the column F and G representing origin and destination did not have the proper orientation, i.e., either of them could be origin or destination. During indexing, the segments are named on the basis of the destination bus (Bus 2). So, knowing the right destination bus is very important for building a correct network.

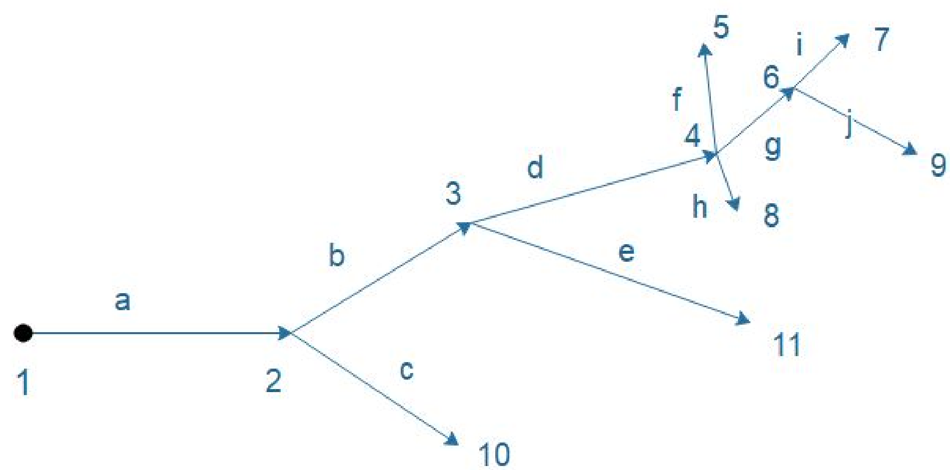

Figure 5-13: Simple Line model to Explain the Data Complexity

To explain this problem, an imaginary case is considered in figure 5-13 which is a network with 10 lines and 11 bus. The data in table 5.3 represents the raw data of the line segment. If they are used for indexing without any modification, there will be duplication in the line name as the all three lines a, b and c has now name 'line 2'. Further, the monitor element of the line b and c will give the value in opposite sign compared to line a as the direction of line b and c is opposite to the direction of current flow.

Table 5.3: Example of Line Segment Data in Raw form

line segment	Bus 1	Bus 2
b	3	2
a	1	2
c	10	2
d	4	3
e	3	11

A simple solution of this problem can be adding some alphabet after 2 in line b and c if they already appear in other lines but it will not solve the actual problem for which indexing was considered in the first hand. The other solution can be naming the line by Bus 1 name in case Bus 2 name is already taken by other lines. This solution solved a problem for only if the starting lines orientation is correct. But in raw data, the line segments were not ordered as in the example above. In such case, the orientation of the whole feeder becomes opposite. Further, in the radial network in the distribution system, a bus can be origin point of many line segment but can be destination point to only one line segment. So, if the sub-segments of line and line segments are designated by destination bus it is always unique. But in this solution, there are chances we have to rename using alphabets, which once again will not solve the problem. The same problem existed in the case of the circuit breaker (fusible) definition. Due to the wrong origin and destination bus position, in a few cases, the segments after the circuit breaker were isolated.

Further, there were a few lines which were not connected to the source and a few loads which did not have any connection points. These are the floating points in the GIS network due to mistakes in GIS indexing. These cases should be filtered out and checked with the utility regarding the physical existence of those feeders and update the same in GIS. In the next section, the solutions to these problems have been discussed.

5.4 Algorithm to re-annotate the Bus, Line, and Load

As discussed in the previous section arranging the origin and destination bus is important to model the network correctly. To achieve this in the first stage, the Bus 2 of the circuit breaker in the substation is used to find the origin point of every feeder using the algorithm shown in figure 5-14. In the second part, the origin and destination bus for following line segment is checked and rearranged if required along with the coordinates data in file *Coordenadas Segmentos*.

Both algorithms are based on the radial nature of the LV network that every bus can be destination bus to only one line but can be the origin point for many lines. In the first part, the destination buses of all circuit breakers in the substation which are closed are taken as a starting point to find the starting point of the line segment. If the destination bus of the breaker is found in origin bus of the segment then its destination bus is stored in a [segcon] vector with the segment code (It is the position of a line segment in *Segmento BT* file). But if it is found in destination bus column, then the exchange of bus is done for that segment and then destination bus is updated in [segcon] vector. At the end of the loop, a vector [segcon] with destination bus of all first feeders in the substation is created.

Algorithm for Line Segment Segment and Circuit Breaker in the Network

Once the first segment of the feeder with their origin and destination feeder is known, an attempt is done in each loop to find the consecutive feeder. Each time if some destination bus is found in origin bus position of another segment, the [segcon] vector is updated with the destination bus of the new segment with the segment code. On the other hand, if the destination bus of any segment is already in [segcon] vector, the exchange of bus is done along with rearranging of the coordinates of the segment. In this process, only the segments which are not already in the [segcon] vector are checked. At the end of every loop, check for connection with the fuse element is done. A vector [closed_fuse] is created with both origin and destination bus of all closed

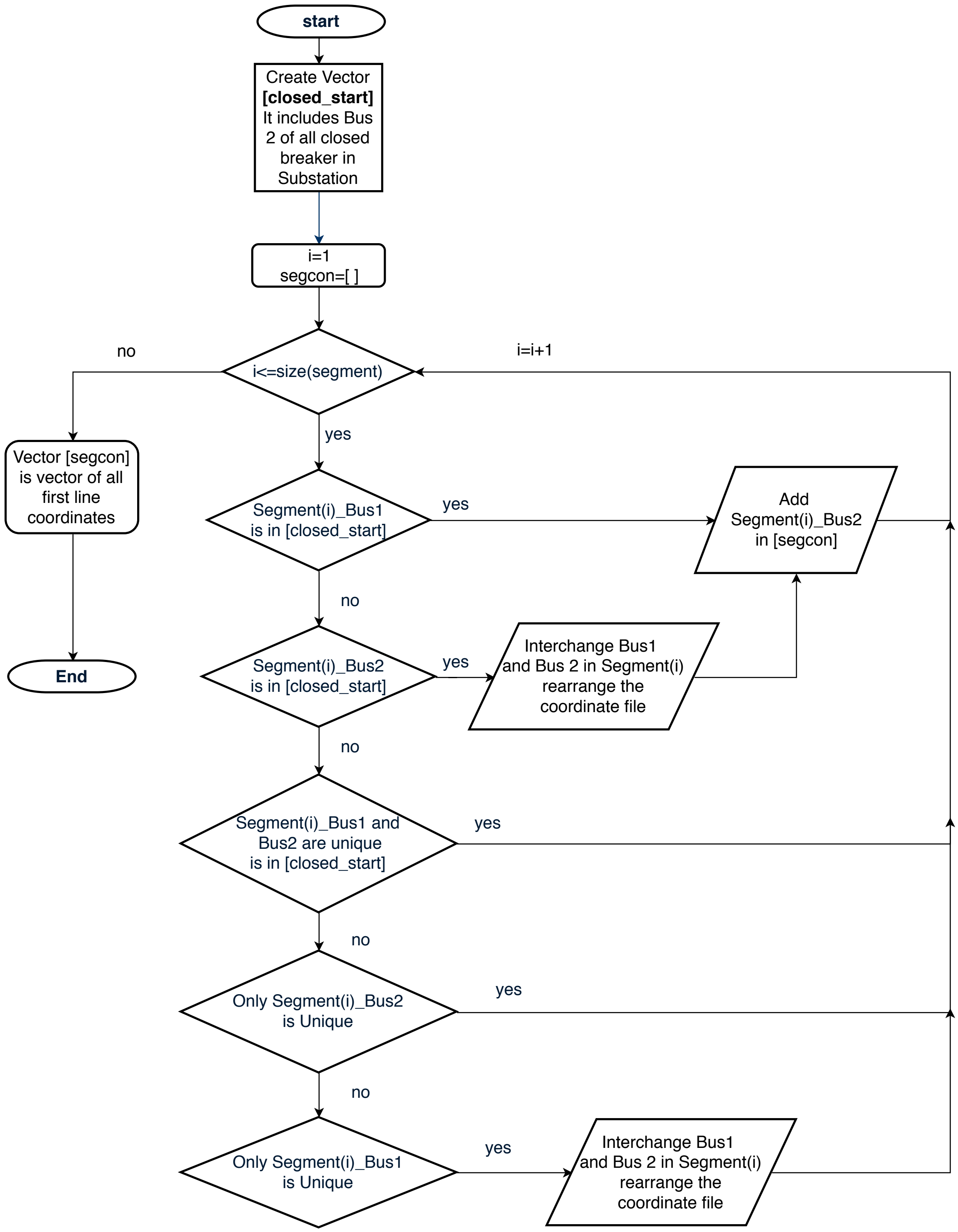

Figure 5-14: Flowchart to link the circuit breaker with first point of line segment

circuit breaker in the network. When either of the buses is found in [segcon], the other bus is updated in [segcon] with the segment code as 0. The loop continues until

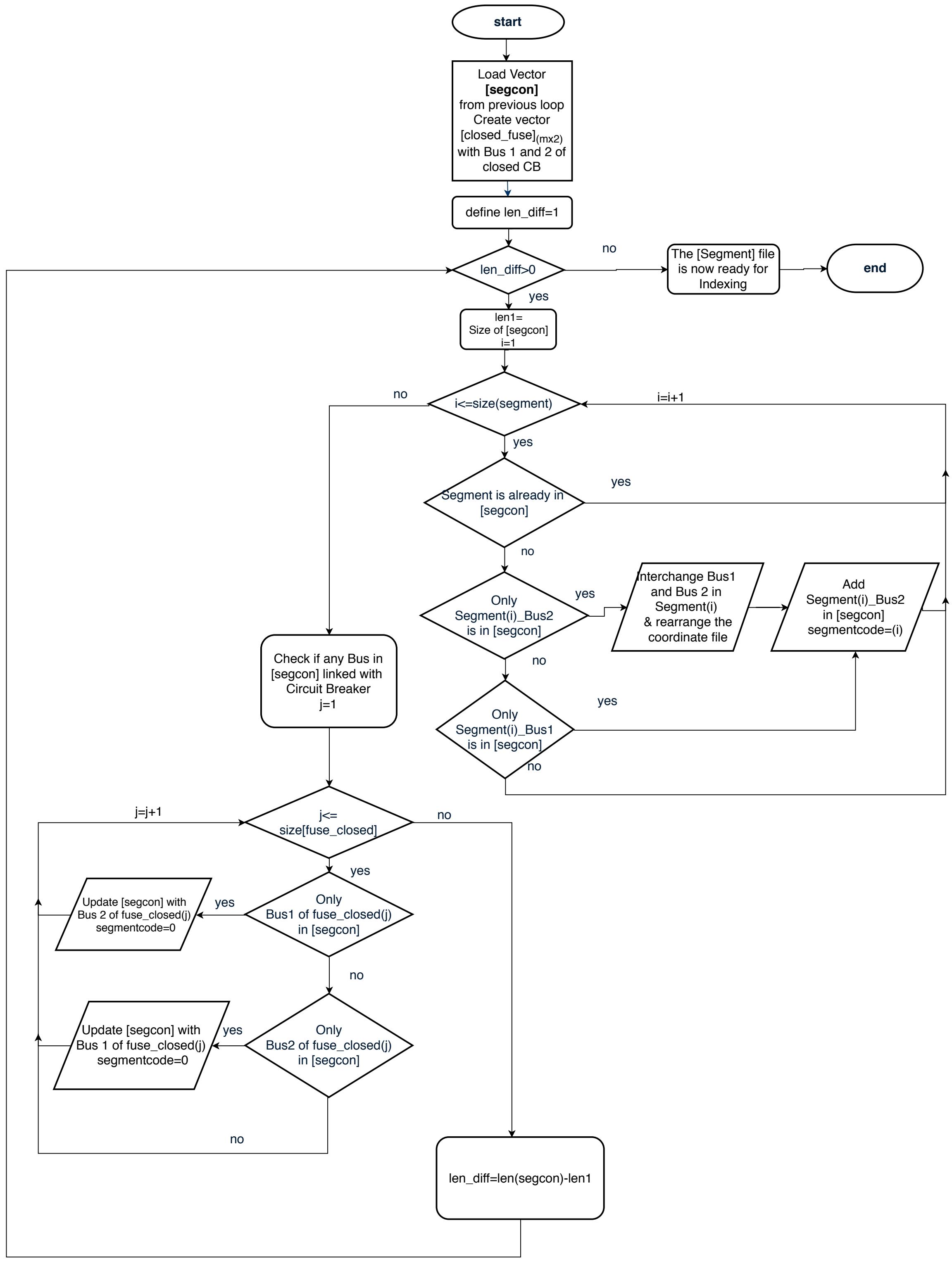

Figure 5-15: Algorithm for arranging Bus 1 and Bus 2 of Line Segment correctly

the size of [segcon] stops increasing.

Table 5.4: Working of Algorithm to check the position of Bus

	Original Data		Loop 1			Loop 2		
Seg	Bus 1	Bus 2	Bus 1	Bus 2	[Segcon]	Bus 1	Bus 2	[Segcon]
b	3	2	2	3	[2,3]			
a	1	2			[2,3]			
c	10	2	2	10	[2,3,10]			
d	4	3	3	4	[2,3,10,4]			
e	3	11	3	11	[2,3,10,4,11]			
i	7	6			[2,3,10,4,11]	6	7	[2,3,10,4,11,6,7]
g	6	4	4	6	[2,3,10,4,11,6]			

The algorithm is used to explain the arranging of the data given in Table 5.3 assuming the [segcon] has already the data of segment a. So, the initial value of [segcon] will be ['2']. The algorithm will check in sequence to see if any Bus 1 or Bus 2 value is already in [segcon] vector. When it reaches first entry, which has Bus1='3' and Bus2='2'. Since '2' is already in [segcon], the bus name of Segment 'b' is swapped with Bus1='2' and Bus2='3'. [segcon] will be updated with newly discovered destination bus '3', i.e., [segcon]=['2','3']. The second segment is neglected as it is already in [segcon]. Similar things happen in the third and fourth segment, where Bus 1 and Bus 2 are swapped with an update in [segcon]. In the fifth segment, it is seen that the Bus1 is in [segcon] vector. So in this case, the Bus1 and Bus2 are not swapped but keep as it is while [segcon] vector is updated with Destination Bus '11' of this segment. At the sixth segment, neither Bus 1 nor Bus 2 is in [segcon] so this segment is skipped. In the seventh segment, again Bus 2 is in [segcon] so swapping of Bus 1 and Bus 2 is done and Bus'6' is updated in [segcon]. In the second loop, all the segments except 'i' are neglected as they have been all updated. Now, in the sixth segment, Bus '6' is in [segcon] so swapping of Bus1 and Bus2 is done with an update in [segcon].

The other vector in used is [fuse_closed], which has data of all Bus1 and Bus2 of the closed circuit breaker. At end of every loop, the elements of [fuse_closed] are compared with the destination bus stored in [segcon]to find any linking bus. This process incorporates the segment after the circuit-breaker to arrange them with the proper origin and destination feeder to re-annotate the bus name and line name correctly. The whole loop continues until the size of the vector [segcon] is increasing.

Algorithm for Load Indexing

As discussed in the previous section, load data had few problems which need to be sorted out for the proper running of simulations. The following method was used to rectify those issues and create a working model.

- **Phase missing**: The phase data obtained from the field was not complete especially due to the changing loads or meter as well as lack of a proper database on utility. Phase identification of the load in the distribution network itself is a huge topic with many researchers working on it [56, 57]. It is an important aspect of real modeling but was not included in the scope of the thesis. For approximately 5% of cases where load phase data was not available, a random phase was given.

- **Floating Load**: Few cases of loads and line segment which were freely floating without connections to any source was found. This cases requires field survey and updating in the GIS model. Since there were only less than 5 cases in a network with 8087 loads and 12,000 nodes, these were manually removed based on the Isolated node report generated by OpenDSS.

- **Non-Smart meter**: There were still a few meters which were not smart. Those meters had no load data for hourly consumption. For now, the consumption of such meter is considered to be 0 kWh for simplicity. But it is expected that all the meters will be the smart meter in near future.

5.5 Program Structure for Data Extraction

A modular script in MATLAB was created to convert the GIS data file into the indexed OpenDSS file for the whole network. The MATLAB script was divided into two basic parts; first to generate the constant part of network, i.e., transformer, distribution lines, breaker and load. The second part was to extract more variable parameters of load consumption from smart meter record.

5.5.1 Network Data

The network data file can be extracted and converted into OpenDSS format by `shortcut.m` which contains the files to extract the data from GIS file and create indexed OpenDSS network file as shown following:

```
%shortcut.m %Set of File to Generate OpenDSS files
[transformer, Line, lnraw, Segment, Segraw, buscord, loadbus,txID, fuse,
    fuseraw, load_loc, load_loc_raw, phaseraw]=filename;
linecode;%generates line code for existing type of feeder
bus_cord_modified; %Indexing of Bus number before rearrangement
Seg_crazy; %arranges BUS 1 and BUS 2 in proper order
bus_cord_modified; %Indexing of Bus number after rearrangement
line_indexed; %OpenDSS file generator for LV_line
bus_cord_indexed; %OpenDSS file Generator for Bus Coordinate
source_ind; %OpenDSS file Generator for MV line from source to transformer
fuse_indexed; %OpenDSS file Generator for Circuit Breaker in LV network
reactor_neutral; %OpenDSS file generator for Transformer
transformer_indexed; %OpenDSS file Generator for transformer
energymeter; %OpenDSS file Generator for Energy Meter
load_indexed; % OpenDSS File Generator for Load
```

The different functions used in the `shortcut.m` are explained below:

1. **`filename.m`**: This function is meant for extracting data from the excel file in MATLAB. The function has three variables, 'file_master' (Network file),

'file_load' (Smart Meter File) and 'file_phase' (Load Phase File) to give the file name of raw file on 5-1 manually. These files pointers are used to access those excel files and their sub-files.

2. **`linecode.m`**: This function gives the `linecode.txt` file which has linecode of all type of line described in Line Segments (*Segmento BT*). We attempted to make a universal file by the inclusion of all possible distribution cable type in Spain. The line code is generated in 4×4 format to include the neutral point and all mutual impedance are neglected.

3. **`Seg_crazy.m`**: This file is meant for re-arranging the wrongly placed bus. It reshuffles the origin and destination buses in line segments where it is wrong based on the algorithm discussed in figure 5-14 and 5-15.

4. **`bus_cord_modified.m`**: This .m file is used for indexing the bus name. The file takes all the bus name from line segments and removes the duplicates. Then indexing of the segments is done as mentioned in table 5.1. This code is run twice, before the arrangement and after the arrangement. The second run is for making the line index and index bus 2 of that line same as discussed in section 5.2 to make easier in monitoring.

5. **`line_indexed.m`**:This file is meant for generating LV line details including the substation breaker and LV feeder. This file generates all the sub-segment of the line segment to give its length, line codes and connecting bus as per the indexing pattern discussed in section 5.2. Further, it also incorporates the 4 lines, including the isolated neutral which allow the return path for the unbalanced current. At the same time, it also generates monitor file for each feeder at the substation and all bus in the LV network.

6. **`bus_cord_indexed.m`**: This file generates the bus coordinates of all the LV buses based on the coordinates in the raw data file and the name as per the new indexing.

7. **source_ind.m**:This file is to generate the MV lines in our circuit. In this simulation, MV lines of 5 m each from a common source to all the transformer are generated. The effective resistance of MV lines is assumed to be very low i.e., $2.5 \times e^{-6}\Omega$ in this simulation as we are interested in LV part only. At the same time, it also generates the monitors for MV lines.

8. **fuse_indexed.m**: This file is to create the file for all circuit breaker in the middle of the LV network. The data is extracted from *fusible* file and indexed according to the indexing rule. The effective resistance of the circuit breaker is assumed to be $25e^{-6}\Omega$.

9. **reactor_neutral.m**: This file generates circuit objects used in the neutral grounding. It is assumed that the transformer neutral is grounded with the resistance of 5 Ω and very nominal impedance. This incorporates our assumption of the grounded neutral at the substation and isolated neutral outside the substation.

10. **transformer_indexed.m**: This file generates the OpenDSS file for transformer component. It incorporates currently the wye-delta configurations only as they are the general type of transformer in the distribution system and three phase as European Distribution system usually do not have single phase transformers. It incorporates the idea of 4-wires LV distribution system.

11. **energymeter.m**: This defines an energy-meter element file for OpenDSS for every MV line of the transformer. It provides us a chance to study the voltage profile from that point in OpenDSS.

12. **load_indexed.m**: This file generates an OpenDSS file for the load element of the network. It incorporates the type of the load (single-phase or three-phase), connected phase for single-phase load, connected bus and load shape.

5.5.2 Load Data

The load data from smart meter data was extracted to load shape file using this set of codes in MATLAB listed in `shortcut_loadshape.m` and was linked with the load in network data file. The shape file consists of 20 days per hour data for each load while the Loadshape file links the Load name with Load shape.

```
%shortcut_loadshape.m %it calls all program for creating loadshape file
days=20 %no of days of load
fileno=7 % no of loadfile
loadshape_ind; %file to Generate Loadshape file for OpenDSS
loadshapeextraction;%%Extracts load from the csv file and saves in vector
save_loadshape; %saves the extracted load in csv file
```

The variable 'days' and 'fileno' is to signify no of days in which we are interested to extract data and number of files having the data. Since we are dealing with huge data all load data will be in more than 1 file and we renamed all load data files by file1, file2, etc. The different files called in the script above are discussed below:

1. **`loadshape_ind.m`**: It generates an OpenDSS file to link the Load element with the Loadshape. It gives the file name and location of respective loadshape. It has also provision for changing number of load points in load shape.

2. **`loadshapeextraction.m`**: This file checks the smart meter data file and stores it in a vector [shape] as per the indexing rule of Load in Load extraction module. For example *shape(1).hrs* will contain 481 load points for 20 days for LOAD1 indexed in Network extraction file.

3. **`loadshapeextraction.m`**: This file is for converting the [shape] vector to .csv file for OpenDSS program. The load shapes are saved is with name *shape_1.csv, shape_2.csv,...* etc for LOAD1, LOAD2,.. as indexed in `load_indexed.m` in network data.

The European LV test network thus built up by using the above data extraction tool is discussed in next chapter.

Chapter 6

European Standard Distribution Network

The indexing scheme and data extraction scheme discussed in chapter 5 is now used to generate a European LV test network representing a distribution network of the European style.

This is the first network in the literature which includes the network data of whole city re-annotated and representing typical European type distribution system. The set of files would be made available publicly so that the researchers can use it for different studies in large-scale distribution system. It has also the provisions for change in LV Network as well as the change in the number of days of study through modification in quasi-static load data days. Further, it includes the all type of feeders from highly loaded to sparsely loaded and all type of transformers with sparse and dense loading. This network includes the multiple feeders originating from a transformer as well as reserve feeders with circuit breakers to change the network configuration. Further, it also has circuit breakers in middle of the LV networks which can be used to modify the load flow in Distribution Network. The load in this network is a mixture of both 3 phase and 1 phase. In this master thesis, the system has been simulated using the existing feature in OpenDSS software but to deal with this sort of network, the software should have a robust power flow engine like OpenDSS and a better visual representation like Power World Simulator[1] which can be used to operate the circuit breakers to see the effect in load-flow. The data will also play a vital role in working in distribution system software with better visual representation and interactive in nature to assist distribution utility to have better visibility of network and controllable to an extent. Further, this system is very complete to do the various economic study as it covers a wide area with all type of load.

6.1 Introduction to Test Network

As discussed in the previous chapter, the current test feeders are mostly found in the North American style. The existing European LV test feeder are also not complete and does not represent actual European style feeder in terms of 4 line system with isolated neutral, neutral grounding only in substation, different load type (1 phase or 3 phase), integration with smart meter data and inclusion of multiple feeder in a single transformer which has been discussed in detail in section 4.2.

With the evolution of DERs and increased penetration in the distribution network, distribution system operators need more tools for visualization of the LV networks. The European style network discussed in this thesis network provides the data which can be used to test a software which supports utilities in future to control various variables and manage DERs and storage systems more profitably. It can also be used to test the various applications based on the smart meter data including the inclusion of the smart meters in future SCADA making Distribution System more controllable.

The major feature of this network are:

1. The test network has LV voltage level of 416 V and frequency 50 Hz.

2. The LV network has been modeled as 4-wires system with neutral grounded only in substation. The neutral voltage can be monitored at every bus and neutral is isolated from consumer ground.

[1] https://www.powerworld.com/

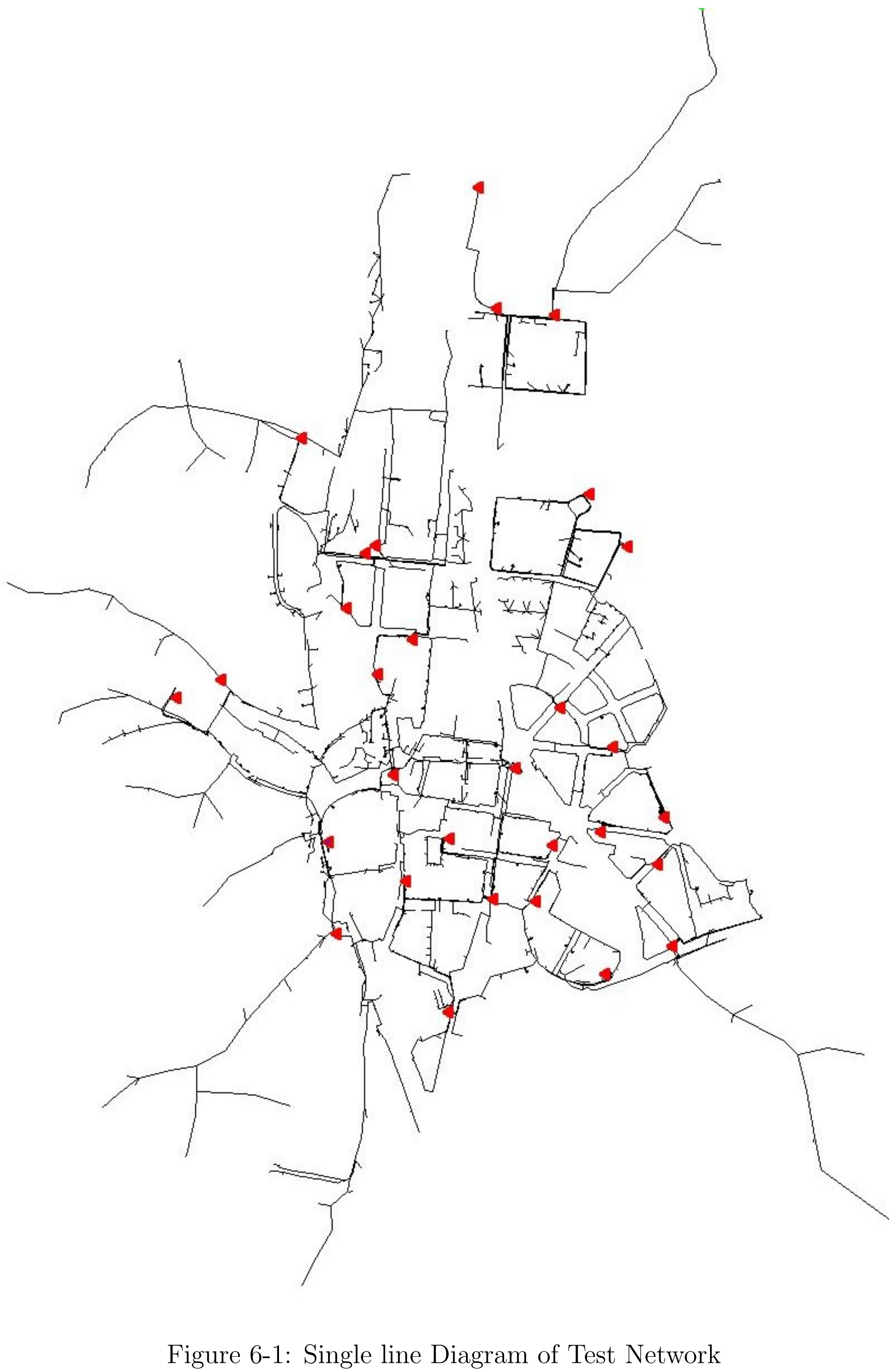

Figure 6-1: Single line Diagram of Test Network

3. The network consists of 8087 loads and 30 Distribution transformer which represents a load of a small city. Out of 8087 loads only 31 were non-smart meters.

4. The network consists of 10290 buses of which 2681 buses are only monitored.

5. The load is in time-series form for 20 days and every hour. The load being obtained from smart meter directly can be modified as per need for more or fewer days.

6.2 Network Description

The figure 6-1 shows the single line diagram of the whole network. The various circuit elements to define the network are discussed below with the corresponding OpenDSS file in Brackets.

Voltage Source

The **source** is defined by the short circuit current in three phase and 1 phase like in IEEE European Test Feeder. But the voltage level in this system is 22 kV.

```
#source Impedance
edit Vsource.Source bus1=source basekv=22 pu=1.0001 phases=3 ISC3=9000
    ISC1=5000
```

MV Lines (`source2txline_ind.txt`)

The Imaginary **MV lines** are created to connect the source with the transformer. Each MV line is assumed of very low resistance of $25 \times e^{-6}\Omega$ to neglect the MV lines. They are three wire system and connected to the delta side of the transformer. These lines are named mv1, mv2,...,mvn based on the number of transformers and given in `source2txline_ind.txt`.

```
#MV lines
```

```
New Line.mv1 Bus1=Source Bus2=1 phases=3 Linecode=101 Length=5 Units=m
New Line.mv2 Bus1=Source Bus2=2 phases=3 Linecode=101 Length=5 Units=m
New Line.mv3 Bus1=Source Bus2=3 phases=3 Linecode=101 Length=5 Units=m
```

Transformers (`Transformer_ind.txt`)

The **distribution transformers** are in the distribution substation marked by red delta mark in 6-1. All of the 30 transformers in network are delta-wye. The voltage rating of the transformer are 22/0.420 kV and power rating are either 250, 630 or 1000 kVA. The reactance of the transformer winding is considered to be 4% for all the transformer. The data of transformer is given in `Transformer_ind.txt` of which a part is as below:

```
New Transformer.TD401346 windings=2 Buses=[1 31.1.2.3.4] Conns=[Delta Wye]
    kVs=[22 0.420] kVAs=[630 630] XHL=4.0 sub=y
New Transformer.TD400291 windings=2 Buses=[2 32.1.2.3.4] Conns=[Delta Wye]
    kVs=[22 0.420] kVAs=[1000 1000] XHL=4.0 sub=y
New Transformer.TD000653 windings=2 Buses=[3 33.1.2.3.4] Conns=[Delta Wye]
    kVs=[22 0.420] kVAs=[630 630] XHL=4.0 sub=y
```

LV Network (`Line_indexed_check.txt`)

The **feeder** and **circuit breaker** in the substation is defined as line element with nomenclature as [feeder00] and [cktbk00] and is listed in `Line_indexed_check.txt` file, which also contains the description of the all LV network. It models the LV network as four-wires system with isolated neutral from consumer ground. The neutral wire provides return path to the all unbalanced current. The code below shows the representative description of the feeder, circuit breaker, and LV Networks:

```
!LV Feeder from Transformer to the Circuit Breaker
New Line.feeder1 Bus1=31.1.2.3.4 Bus2=31_1.1.2.3.4 phases=4 Linecode=205
    Length=4.340 Units=m
```

```
! LV substation Circuit Breaker
New Line.cktbk1 Bus1=31_1.1.2.3.4 Bus2=2684.1.2.3.4 phases=4 Linecode=102
    Length=1.000 Units=m
```

```
!LV Lines Description
New Line.67_0 Bus1=66.1.2.3.4 Bus2=67_1.1.2.3.4 phases=4 Linecode=316
    Length=4.658 Units=m
New Line.67_1 Bus1=67_1.1.2.3.4 Bus2=67_2.1.2.3.4 phases=4 Linecode=316
    Length=2.265 Units=m
New Line.67 Bus1=67_5.1.2.3.4 Bus2=67.1.2.3.4 phases=4 Linecode=316
    Length=3.922 Units=m
```

The **Line Codes** are defined by the 4×4 matrix of R and X for LV lines and 3×3 matrix for the MV lines and is represented in OpenDSS file in `linecode.txt`. The cross-section of the distribution cable is used to find the resistance and inductance. Since the ground return-path concept is rejected in this model and the LV cables are generally twisted insulated cables, the mutual couplings are neglected. The unique line code is assigned for all type of cable which has been listed in A.2. The codes below represent the way in which Line code is represented for 4-phase system.

```
!Line code 4x4 for LV lines
New LineCode.201 nphases=4 baseFreq=50 units=km
~ rmatrix = [1.230000 | 0  1.230000 |  0  0   1.230000 | 0  0  0 1.230000]
~ xmatrix = [ 0.080000| 0  0.080000 |  0  0   0.080000| 0  0  0 0.080000]
```

Load (`Load_indexed.txt`)

The **Load** file is linked to the LV network by using `Load_indexed.txt` file. There are 8087 loads in the network which are indexed to hide the details of the consumer. The loads are either one-phase or three-phase. In this network, the constant PQ load with P given by load shape file and Power factor as constant 0.95 is modeled. The loads are connected to the respective phase and the neutral of the distribution lines represented by .4 which ensures that the neutral current flows back to the distribution line neutral not ground. In this test case, 12 loads are in comments as the proper mapping of those load was not done in GIS file and are floating without any connected bus. This would be corrected once the utility provides the corrected connection in GIS.

```
!Load Description File
New Load.LOAD1 Phases=1 Bus1=1233.3.4 kV=0.23 kW=1 PF=0.95 daily=Shape_1
New Load.LOAD382 Phases=3 Bus1=1222.1.2.3.4 kV=0.4 kW=1 PF=0.95
    daily=Shape_382
```

The data of **Loadshape** is given in `Loadshape.txt` file and it links with the .csv file consisting the load data for 481 hours of 20 days. Each load profiles for 20 days is given in file `shape_1.csv, shape_2.csv`, etc linked with LOAD1, LOAD2, etc respectively. The load profile is for the time interval of 1 hours.

```
!LoadShape
New Loadshape.Shape_1 npts=481 minterval=60
    mult=(file=day_20_profile\shape_1.csv) useactual=true
New Loadshape.Shape_2 npts=481 minterval=60
    mult=(file=day_20_profile\shape_2.csv) useactual=true
```

Circuit Breaker in LV Networks (`fuse_indexed.txt`)

The **Circuit Breaker** element in the middle of LV Network is the special feature of this network. These circuit breakers are used to change the LV network configuration. In this model, we have assumed the circuit breaker as line element with $25e^{-6}\Omega$ effective resistance. To change the LV configuration, the change should be first done in GIS representation and the extraction loop has to be run again. The visual representation of the breaker is important in this case to understand the sequence of operation. One of the limitations of OpenDSS is that the system cannot be simulated when part of the component is disconnected from the source. So, this raw data can be used to create a new distribution system software which can also simulate the disconnected load without any problem. The other problem with handling fuse data is to ensure the radial nature of the feeder for which also a better software is required with the ability of better power flow visualization. The circuit-breaker counts are 2,4,5.. in the example below, which means that fuse1, fuse3,.. and other missing one are circuit breakers which are open. The open circuit breakers are commented by using '!' at the beginning in the OpenDSS file.

```
!Circuitbreaker at Middle of LV network for changing configurations
New Line.fuse2 Bus1=2677.1.2.3.4 Bus2=1099.1.2.3.4 phases=4 Linecode=102
   Length=0.5 Units=m
New Line.fuse4 Bus1=1540.1.2.3.4 Bus2=2724.1.2.3.4 phases=4 Linecode=102
   Length=0.5 Units=m
New Line.fuse5 Bus1=2727.1.2.3.4 Bus2=1526.1.2.3.4 phases=4 Linecode=102
   Length=0.5 Units=m
```

Reactor for Neutral Grounding (`neutral_ind.txt`)

This file represents the resistance grounding of transformer neutral in TT grounding system adopted in European distribution system. The reactor for all transformer neutral is described in the `neutral_ind.txt` file. Each neutral is grounded with the resistance of 5 Ω. The `.4` phase of the transformer neutral is grounded with `.0` phase which represents the earth. This grounding is required to maintain voltage balance during extremely unbalance condition.

```
!Neutral Grounding of Transformer
New Reactor.grnd1 phases=1 bus1=31.4 bus2=31.0 R=5 X=0.01
New Reactor.grnd2 phases=1 bus1=32.4 bus2=32.0 R=5 X=0.01
```

Monitors

The **monitor** elements are used to monitor the voltage, current, active power and reactive power of the bus 2 of the line segment monitored. This is the reason why name of bus 2 and line segment were synchronized during data extraction. The OpenDSS file of the network consists of three files, `MVmon.txt, monitor_feeder.txt` and `monitor_line.txt` to monitor the MV side of the transformer, individual LV feeders in the substation and all observable bus in LV network respectively. The monitoring of MV lines will give the aggregate power of the transformer, monitoring of LV feeders give the aggregate power of individual feeders and monitoring of the Bus is helpful to understand the state of the bus in form of voltage, current, and power in each phase.

```
!MV MOnitor
New Monitor.MV1_PQ_vs_Time Line.mv1 2 Mode=1 ppolar=0
New Monitor.MV1_VI_vs_Time Line.mv1 2 Mode=0
!LV feeder Monitor
New Monitor.feeder1_PQ_vs_Time Line.feeder1 2 Mode=1 ppolar=0
New Monitor.feeder1_VI_vs_Time Line.feeder1 2 Mode=0
!LV Line Monitor
New Monitor.LINE61_PQ_vs_Time Line.61 2 Mode=1 ppolar=0
New Monitor.LINE61_VI_vs_Time Line.61 2 Mode=0
```

Energymeter (`energymeter_ind.txt`)

The energy meter is kept at MV line to keep the record of the energy consumed in all transformers and is stored in `energymeter_ind.txt`. It also separates the zones of each transformer and helps to acquire the voltage and power profile of the feeders.

```
New energymeter.m1 LINE.mv1 1
New energymeter.m2 LINE.mv2 1
```

Bus Coordinates (**Buscord_indexed.txt**)

The bus coordinates represented in OpenDSS format in `Buscord_indexed.txt` has the coordinates of all buses in the network. The file is required to represent the feeders visually in the network plot. The text file has the bus name and X and Y coordinates. The bus coordinate of Source is not included as the MV lines are imaginary.

```
!Bus Coordinates
1     284345.890000 4807588.080000
1382  284097.950000 4807649.960000
661_1  284533.640000 4807934.090000
661_2  284538.330000 4807933.180000
```

Master File (**Master.dss**)

The master file in OpenDSS is required to compile all the Distribution elements. The `Master.dss` links all the individual files of different elements described above.

```
Clear
!! Test case
Set DefaultBaseFrequency=50 ! for European system
new circuit.test
edit Vsource.Source bus1=source basekv=22 pu=1.0001 phases=3 ISC3=9000
   ISC1=5000 !Defination of Voltage Source
!LINE CODES
redirect linecode.txt !linecodes
redirect Line_indexed_check.txt !LV Lines
redirect source2txline_ind.txt !MV Lines
redirect fuse_indexed.txt !Circuit Breaker in Circuit
redirect neutral_ind.txt !Neutral Grounding
redirect Transformer_ind.txt !!Transformer Definition
solve
redirect LoadShape.txt !Load Shape Defination
```

```
batchedit loadshape..* useactual=no
redirect Load_indexed.txt !Load Defination
redirect monitor_feeder.txt !Feeder Monitor
redirect monitor_line.txt !LV Bus Monitor
redirect MVmon.txt !MV lines Monitor
Set Voltagebases=[22.0, 0.420]
calcv
BusCoords Buscord_indexed.txt
set casename=myckt
redirect energymeter_ind.txt
set mode=Daily number=481 stepsize=60m !Daily Power Flow Simulation for
   481 hrs
solve
closedi
```

6.2.1 Use of MATLAB for Simulation

The `Master.dss` was compiled in our simulation using COM Interface in MATLAB. The MATLAB codes consist of two files one to compile and other to observe different bus as described below:

1. **`Testnetwork_monitorall.m`**: This file compiles the `Master.dss` file explained in the previous section and extracts the monitor data from OpenDSS to the Matlab and saves it in `bus.mat`. The buses which are not monitored are listed in `'notmonitored.mat'` and includes the floating buses which were excluded during the data extraction as they are not connected to the network in consideration. This file makes use of COM interface to use access OpenDSS engine for Power Flow of Distribution Network.

2. **`plot_curve.m`**: This file is the function to plot the various parameters of the bus under interest after observing it in OpenDSS plot. The command structure is `plot_curve(bus,busno,day1,nodays)`, where 'bus' refers to the observed

data of all bus, 'busno' refers to the bus under observation and 'day1' and 'nodays' refers to the first day under consideration and the number of days after that respectively. The example of the output is given in B-2, which includes active and reactive power, phase voltage and current and neutral voltage and current.

The output file consists of **`bus.mat`** which is a structure with the bus number and day. The day is further structured with voltage, current, active power and reactive power for 20 days.

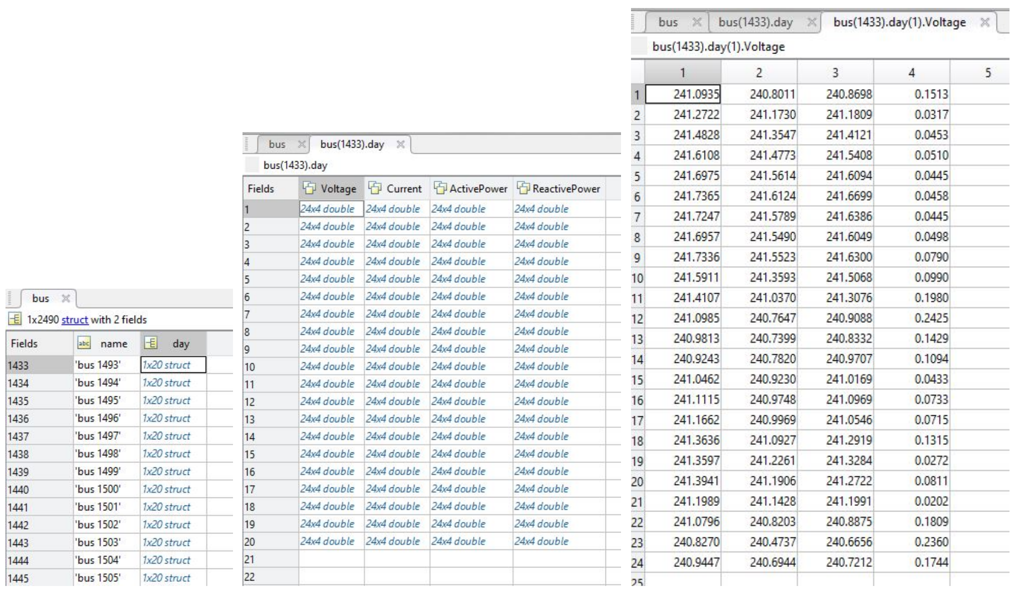

Figure 6-2: Output of the Power Flow Simulation of Test Network (from left) (a) Structure `'bus'` as Output (b) Expansion of structure `'bus(1443).day'` (c) Expansion of Structure `'bus(1443).day(1).Voltage'`

The figure 6-2 shows the format in which the output of power flow simulation as observed by monitors are stored in MATLAB structure. The data thus obtained can be used to observe various parameters of a distribution network.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This master thesis aimed at creating a more complete test network for smart grid applications for distribution system operator and has been able to achieve so in following ways:

- The European LV networks being TT grounded, the 3 line model represented through Kron's reduction does not completely represent the actual distribution system. So, the modified IEEE European LV test feeder is presented in chapter 4 which represents the real European feeder with unbalanced current returning from neutral conductor instead of ground.

- With the increased penetration of smart meter and other data logging devices, different style of time series load profile can be obtained. A new load profile with per-second time series data was proposed in section 4.3.2 for IEEE European test feeder. The load data was obtained from the actual household of Austria and scaled to the consumption of the load of European test feeder.

- A sequence of code for converting the GIS data and smart meter data for defining the network and load data in OpenDSS format was proposed in chapter 5. This module also indexes the bus and line to make it handle more easily for the purpose of monitoring the bus. It also takes care of all the bus coordinates making visual representation easier. The module further takes care of the possible changes in LV network through the operation of the circuit breaker in the sub-station and/or on LV network.

- In chapter 6, a real European test network is proposed which represents the data of whole city re-annotated to easier name and hidden private data. The network has 8087 loads and 10290 bus. The observed bus is reduced to 2681 to exclude the line segment which has almost similar power flow. This model represents the 4-wires model with the possibility of observing the neutral voltage and actual phase-neutral voltage obtained by the consumer. Also, it has the real time-series data of consumers for 20 days in the interval of 1 hour.

- Many studies are being done in high voltage level to generate a synthetic test bus with more than 70,000 bus [58, 59]. This network provides a base to compare the similar synthetic network for the LV system of bigger cities or the whole nation.

7.2 Future Works

The test network proposed in this thesis attempts to represent the real European distribution system better than any other test system in the literature. But to make it complete and robust work has to be done in few other features of software as well as the test network.

- The current test system only simulates the LV network. The layer of MV network can be added to it in future to represent the sub-transmission level and also to study the effect of the change in the network configuration in the MV network.

- The OpenDSS software provides a robust engine for power flow simulation of a distribution network with 10,290 bus. But it lacks in term of visual representation. The provision of multiple switches in LV network and their control by the utility would be easier if the simulation software has interactive visual programming with script based program in the base.

- The voltage and reactive power control elements are not currently used in the test network. The test network can be used to design the software which provides better controllability to the DSOs either in the planning stage or in real time by the use of available reactive power control resources in LV network.

- The smart meter data can be used to analyze the LV network status in hourly basis or even in lesser duration to solve the problem of optimal power flow in the distribution network with more percentage of renewable generators, storage devices, and electric vehicles.

- The test network provides a base network for various economic analysis of future electrical distribution system in a real city as well as the study of state estimation in distribution network by combining SCADA and smart-meter data.

- The module to create OpenDSS file can be extended to other GIS platforms for making a universal converter.

Appendix A

Tables

A.1 Resistance and Impedance of Cross Section

Table A.1: Resistance and Impedance

Cross-section	R(Aerial)	X(A)	R(UG)	X(UG)
2 mm Cu	9.9	0.075	9.9	0.075
4 mm Cu	4.95	0.075	4.95	0.075
6 mm Cu	3.30	0.075	3.30	0.075
16 mm CU	1.23	0.08	1.23	0.08
16 mm Al	2.14	0.09	2.14	0.09
25 mm Cu	1.34	0.097	1.538	0.095
35 mm Al	0.907	0.095	0.907	0.095
50 mm Al	0.718	0.093	0.718	0.093
54.6 mm Al	0.658	0.09	0.658	0.09
70 mm AL	0.454	0.091	0.515	0.085
80 mm Al	0.39	0.090	0.450	0.084
95 mm Al	0.3587	0.089	0.410	0.083
150 mm Al	0.231	0.085	0.264	0.082
240 mm Al	0.160	0.079	0.160	0.079
Desconcido	0.210	0.075	0.21	0.075

A.2 Line Types and Line Code

Table A.2: Line Code for Different types of Lines used along with Circuit Breaker

LV Cable Type	Aerial	Underground	Special
BT - MANGUERA	201	301	-
BT - RV 0,6/1 KV 2*16 KAL	202	302	-
BT - RV 0,6/1 KV 2*25 KAL	203	303	-
BT - RV 0,6/1 KV 3(1*150 KAL) + 1*95 KAL	204	304	-
BT - RV 0,6/1 KV 3(1*240 KAL) + 1*150 KAL	205	305	-
BT - RV 0,6/1 KV 3(1*240 KAL) + 1*95 KAL	206	306	-
BT - RV 0,6/1 KV 4*25 KAL	207	307	-
BT - RV 0,6/1 KV 4*50 KAL	208	308	-
BT - RV 0,6/1 KV 4*95 KAL	209	309	-
BT - RX 0,6/1 KV 2*16 Cu	210	310	-
BT - RX 0,6/1 KV 2*2 Cu	211	311	-
BT - RX 0,6/1 KV 2*4 Cu	212	312	-
BT - RX 0,6/1 KV 2*6 Cu	213	313	-
BT - RZ 0,6/1 KV 2*16 AL	214	314	-
BT - RZ 0,6/1 KV 3*150 AL/80 ALM	215	315	-
BT - RZ 0,6/1 KV 3*150 AL/95 ALM	216	316	-
BT - RZ 0,6/1 KV 3*25 AL/54,6 ALM	217	317	-
BT - RZ 0,6/1 KV 3*35 AL/54,6 ALM	218	318	-
BT - RZ 0,6/1 KV 3*50 AL/54,6 ALM	219	319	-
BT - RZ 0,6/1 KV 3*70 ALM/54,6 AL	220	320	-
BT - RZ 0,6/1 KV 3*95 AL/54,6 ALM	221	321	-
BT - RZ 0,6/1 KV 4*16 AL	222	322	-
BT - Desconocido BT	250	350	-
HV Line	-	-	101
LV Circuit Breaker	-	-	102

Appendix B

Figures

B.1 Isolated Element Report From OpenDSS

```
ISOLATED CIRCUIT ELEMENT REPORT

|
***  THE FOLLOWING BUSES HAVE NO CONNECTION TO THE SOURCE ***

"2553"
"2552"

***********  THE FOLLOWING SUB NETWORKS ARE ISOLATED ************


***********  THE FOLLOWING ENABLED ELEMENTS ARE ISOLATED ************

"Load.load7900"  Buses:  "2553.1.2.3.4"
"Load.load8070"  Buses:  "2552.1.2.3.4"

***  THE FOLLOWING BUSES ARE NOT CONNECTED TO ANY POWER DELIVERY ELEMENT ***

"2553"
"2552"

***********  CONNECTED CIRCUIT ELEMENT TREE ************
```

Figure B-1: Isolated Circuit Element Report

Note: The isolated circuit report of the OpenDSS has to be observed now to see if there is any floating point in the OpenDSS network. These are the incorrectly Indexed elements in GIS and should be corrected by utility in their network.

B.2 Example of Output by `plot_curve()`

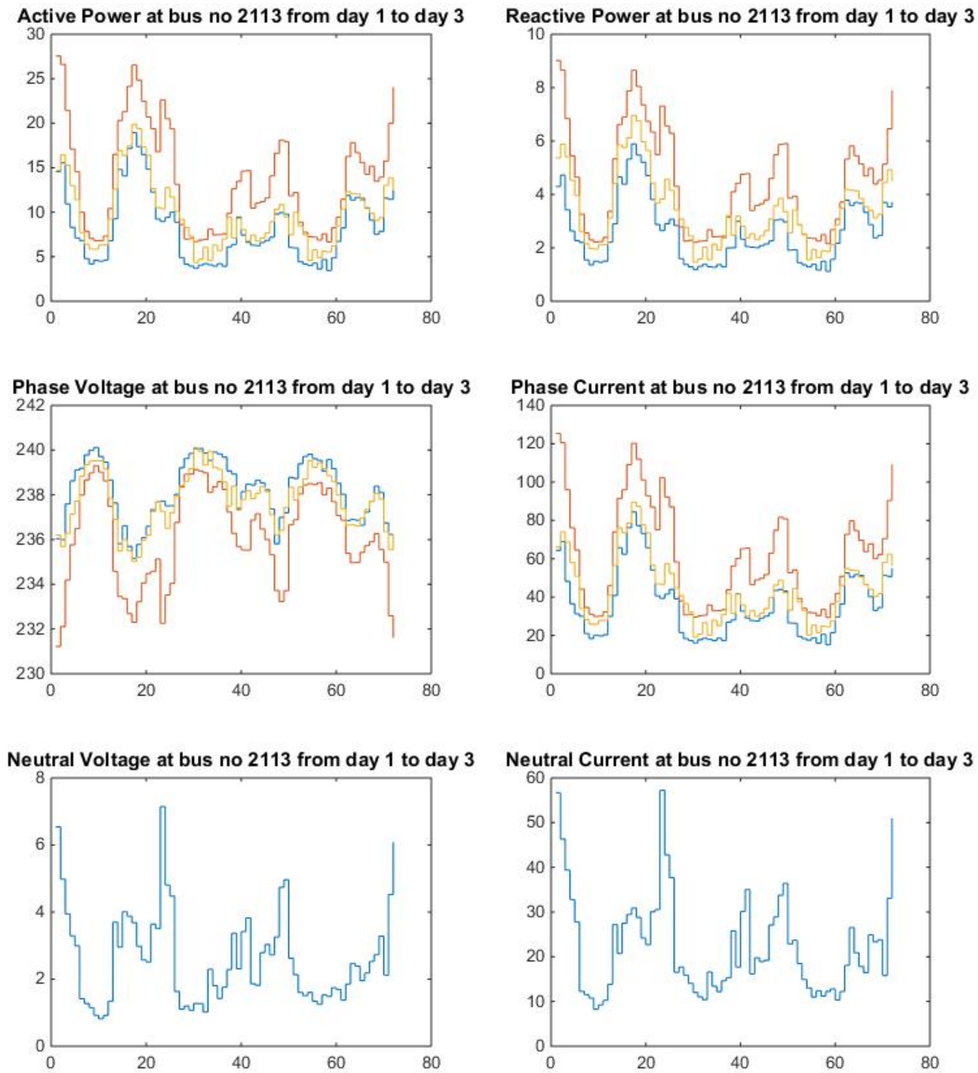

Figure B-2: The Output file of Power Flow simulator given by `plot_curve(bus,2113,1,3)`

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