CHALMERS

Development of Test System for Distribution System Reliability Analysis, Integration of Electric Vehicles into the Distribution System

Master's Thesis in the Master's Electric Power Engineering

PRAMOD BANGALORE

Department of Energy and Environment
Division of Electric Power Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2011
Masters Thesis

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ABSTRACT

This master thesis project aims to work in parallel with an IEEE Task Force on Distribution System Reliability – development of test systems (DRTS). Over the years the electric power system has seen an exponential growth in terms of size and technology. A similar growth and development has taken place in the terms of probabilistic applications used to analyze the power systems. An extensive literature survey has been done as a part of the work to analyze the existing widely used test systems; IEEE RTS and RBTS. Conclusions have been drawn towards how these test systems might be updated or modified to be sufficient with respect to the modern power systems "Smart Grid".

The thesis has been divided into two main parts. The first part focuses on review of publications, which use test systems for probabilistic applications. In the second part Bus-2 distribution system of RBTS has been considered and extensions to the same have been proposed for integration of EVs to the system. The main contribution of work is the proposed extension of the test RBTS test system with integration of EVs.

Contents

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Pramod Bangalore,
Chalmers University of Technology,
Gothenburg,
April, 2011

Definitions

SAIDI: System Average Interruption Duration Index [min/yr]

SAIDI= $\frac{sum\ of\ customer\ interruption\ durations}{total\ number\ of\ customers}$

SAIFI: System Average Interruption Frequency Index [1/yr]

SAIFI=$\frac{total\ number\ of\ customer\ interruptions}{total\ number\ of\ customers\ served}$

CAIDI: Customer Average Interruption Duration Index [h]

CAIDI= $\frac{Sum\ of\ customer\ initerruption\ durations}{total\ number\ of\ customer\ interruptions}$

ASAI: Average Service Availability Index [%]

ASAI= $\frac{customer\ hours\ of\ available\ service}{customer\ hours\ demanded}$

ABBREVIATIONS

AC OPF – AC Optimal Power Flow

BEV – Battery Electric Vehicle

EDS – Electrical Distribution System

ENS – Energy Not Supplied

EPS – Electrical Power System

EV – Electric Vehicle

G4V – Grid for Vehicle

HVDC – High Voltage Direct Current

ICT – Information & Control Technology

IEEE RTS – IEEE Reliability Test System

PHEV – Plug in Hybrid Electric Vehicle

RBTS – Roy Billinton Test System

SOC – State Of Charge

TSO – Transmission System Operator

V2G – Vehicle to Grid

VSC – Voltage Source Converter

1 Chapter One

1.1 Introduction

Reliability in general can be understood as the ability of a component or a system as a whole to perform the designated task under defined conditions for a specific period of time. The concept of reliability applied to power systems generally means maintaining the continuity of supply to the customers.

Electric power systems have developed over the years and one of the main focuses has been reliability assessment. Various concepts like redundancy in supply, regular maintenance of the equipment have resulted in high reliability in the power systems. However, improvement of reliability comes at a cost and it can be said that reliability of a system and the investment cost go hand in hand.

Test systems are fictitious systems, which are used as a bench mark tool for various kinds of studies. These systems are made to resemble an actual system but at the same time are sufficiently general so as to be able to cater different needs for different studies. In case of reliability, IEEE RTS and RBTS are two widely used test systems for electric power system analysis.

1.2 Background of the Project

This master thesis project aims to work in parallel with an IEEE Task Force on Distribution System Reliability – development of test systems (DRTS) . The Task Force is within the Power System Analysis Computing and Economics Committee (PSACEC), the Reliability, Risk, and Probability Applications (RRPA) Subcommittee within the IEEE Power & Energy Society (PES). This group has an annual meeting in July during the general meeting when the TF group meets.

A presentation about the proposed work was made in Minneapolis during the conference in July 2010. Various ideas were expressed by the participants of the meeting and the same have been summarized as follow:

- There was an overall consensus that test systems should be flexible and sufficiently general.
- It was suggested that the most important feature that could be included in the test system is wind power generation.
- It was suggested that in case of extending RBTS with models of wind power generation, the input data should be given together with identified techniques of reliability calculation.
- It was pointed out that there may be a problem with the present RTS system with respect to AC OPF studies. The solution does not converge for congestion study with N-1 contingency with thermal limitations.
- It was suggested that very specific system (for e.g.: particular configuration of HVDC) should not be included in the test system to keep it more general and user friendly.
- It was requested to include the load trends and load modeling at the distribution system level, while developing the test system.

1.3 Scope and Aim of Project

Over the years the reliability test systems such as the IEEE Reliability Test System (RTS) and Roy Billinton Test System (RBTS) have been used extensively by researchers, as a bench mark system, for reliability assessment and other developments in the field of probabilistic applications in power systems. In the past few decades the electric power system has seen tremendous growth both in the terms of size and technology. Such developments mainly include wind energy, increased use of HVDC transmission, integration of plug in hybrid electric vehicles (PHEV) and electric vehicles (EV) and the state–of- the-art communication systems applied to power systems.

The master thesis project has been divided into two main parts. The first part concentrates on the literature survey of publications using test systems. The second part concentrates on the development of the test system to include the integration of PHEV and EV in a distribution system.

1.4 Methodology Adopted for the Project

The methodology adopted for the thesis project can be summarized by the following steps:

Step 1: Literature Survey

- Selecting journals
- Selecting publications using test system from the selected journals
- Analyzing the publications to find out which test system has been used, where are these test systems being used, who is using them and the purpose of use of test systems.
- Based on the analysis results are presented and conclusions are drawn.

Step 2: Familiarizing to the Software NEPLAN

NEPLAN software shall be used to do the reliability analysis. However, before starting a short study has been done to understand the working of the software. Reliability analysis for RBTS test system has been performed on the software.

Step 3: Extension of the RBTS Bus-2 Distribution Test System

An existing test system has been selected and extension has been done to include the integration of PHEV and BEV in the distribution network. Reliability analysis and sensitivity analysis for the same has been done using NEPLAN.

1.5 Introduction to Electric Vehicles

Electric vehicles have been around for more than 150 years. One of the first electric vehicles was developed in 1830. Electric vehicles were the preferred option till the early 20th century as driving range was not an issue during that time. They had distinct advantages over the gas version. Electric vehicles were free from noise and smell, the gear system was simpler and there were no cranking handles to start the vehicle [11].

After the discovery of huge reserves of oil and the subsequent reduction in its price, the gas version of vehicles became lucrative. The development in combustion engine technology and the mass production of gasoline vehicles finally led to demise of supremacy of electric vehicles in the market [12].

In recent years, the growing concerns about global warming have generated a renewed interest in fuel efficient and less polluting vehicles. A legislative and regulatory reform was passed in United States in 1990 which started the process of resurrection of electric vehicles [18]. Though this effort was not long lasting but due to recent developments in technology electric vehicles are being considered seriously again.

A range of electric vehicles are available today. Two main types of electric vehicles are plug in hybrid electric vehicle (PHEV) and battery electric vehicle (BEV). As the name suggest the hybrid electric vehicle is a combination of internal combustion engine (ICE) and an electric motor. Based on the configuration of the vehicle the role of ICE and electric motor may be different. However, generally the electric motor is used more within the cities where the vehicle starts and stops more often. Whereas the gasoline engine is used for longer drives giving the same range for the vehicle.

Battery electric vehicles derive the complete power from the stored energy of the batteries. These vehicles are completely emission free. Various models are available in the market today. Tesla motors introduced an electric car named "Tesla roadster", which has a range of 350 kilometres and a top speed of 210 kmph [19].

Electric vehicles present an excellent source of energy storage. For maximizing the utilization of renewable sources of energy such as wind and solar power, integration of electric vehicles might be very necessary. The vehicle to grid (V2G) concept of electric vehicles allows the supply of power from the vehicle to grid. With V2G electric vehicles could be used to provide ancillary service like up and down regulation. The advantage of electric vehicles over conventional power plants used for regulation is that electric vehicles have an extremely fast response time and can act as a load or a generator depending on the requirement thereby giving both up regulation and down regulation [12].

However, there are still a lot of challenges to accomplish a full scale integration of electric vehicles. A robust network to support large number of electric vehicles, a competitive market structure, affordability and range of these vehicles are some of the most important issues being addressed recently.

The power system infrastructure in Europe and America are aging. A lot of research has been carried out to study the impact of large scale integration of electric vehicles into the existing power system [13][14]. One of the major issues is the imminent overload on the distribution transformers and cables due to charging of many electric vehicles at the same time. Strategies like coordinated charging to reduce this overloading have been suggested by researchers [15][16].

1.6 Basics of EVs

There are two main configurations of PHEVs, series and parallel configurations. As seen from the below Figures the series hybrid vehicle has an internal combustion engine which can charge the battery. Under normal condition the engine is not used very often but can be started during long journeys to maintain the SOC of the batteries.

Parallel hybrid configuration has an ICE connected to the wheel drive through special gears. The electric motor is used for frequent start and stop of the vehicle and the engine is engaged when the speed increases above a specified value. The motor supplies energy back to the battery during braking of the vehicle.

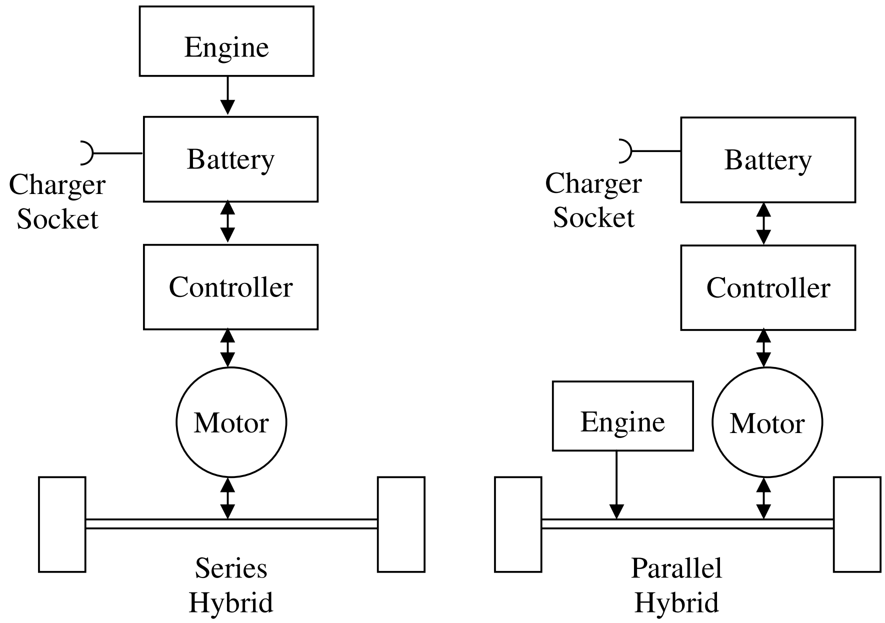

Figure 1.1 Series and Parallel Hybrid vehicles [11]

The battery electric vehicles do not have an internal combustion engine. The energy from the socket is stored in the batteries and used to drive the electric motor. Energy is given back to the batteries during braking operation of the vehicle through regeneration.

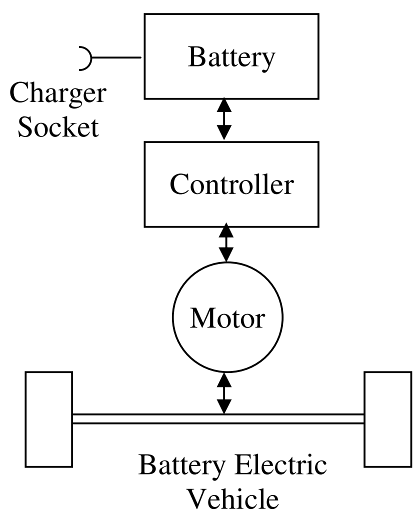

Figure 1.2 Battery electric vehicle [11]

1.7 Vehicle 2 Grid Model for Electric Vehicles

Vehicle to Grid systems (V2G) are equipped with bi-directional power flow capabilities. This will enable the vehicles connected to the sockets at home and at commercials buildings to supply electricity from the car batteries [12].

The concept is still under research and a lot of changes in the electric power system infrastructure are needed to accomplish the same. An intermediate entity called the aggregator might be required to accomplish V2G power supply. The aggregator will be responsible for a fleet of electric vehicles. The charging and discharging of the vehicles can be accomplished by internet or mobile communication. To the TSO the aggregator will be a well regulated load and as a controllable generation [17].

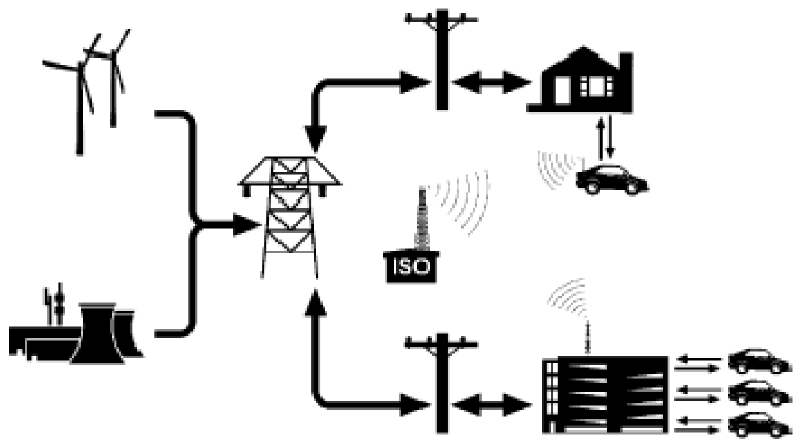

Figure 1.3 V2G concept [17]

It is difficult to predict how much support each electric vehicle will be able to provide when the direction of supply is from vehicle to grid. The support from electric vehicle will depend on the state of charge of battery, which depends how much the vehicle has travelled and how much charge is left in the batteries. Moreover, the customers might also impose a limit on the amount minimum charge to be left in the batteries. Considering a large fleet of vehicles a prediction can be made with accepTable accuracy. As opposed to a conventional power plant the electric vehicle supply is much more reliable. This can be said as failure of one electric vehicle would not make any major difference in the capacity of the entire fleet. For this study the capacity for a time frame is considered to be constant.

1.8 Outline of Thesis

In Chapter 2 the literature survey has been presented, which investigates how the test systems have been used and some conclusions are drawn about how the extension of the test system might be required.

In Chapter 3 short theory about reliability is provided and introduction to the software NEPLAN is given. Reliability analysis on a sample system has been done and the results have been presented.

In Chapter 4 Bus 2 distribution test system has been defined and extensions to the same are presented with respect to integration of electric vehicles in to the system.

In Chapter 5 a sample study has been performed on the extended test system and the results of the same have been presented

In Chapter 6 the proposed extensions to the test system have been enlisted and conclusion of the work has been presented.

PART-1 LITERATURE SURVEY

2 Chapter Two

Literature Survey

2.1 Introduction

Over the years reliability test systems such as the IEEE Reliability Test System (RTS) and Roy Billinton Test System (RBTS) have been used extensively by researchers, as a bench mark system, for reliability assessment and other developments in the field of probabilistic applications in power systems. In the past few decades the electric power system has seen tremendous growth both in the terms of size and technology. Such developments mainly include wind energy, increased use of HVDC transmission, integration of plug in hybrid electric vehicles (PHEV) and electric vehicles (EV) and the state–of- the-art communication systems applied to power systems.

There is a large technology development in the electric power system which could be related to the traditional areas of electric power generation, transmission and consumption.

In the generation sector, the most significant changes are the introduction of distributed generation and more specifically, the introduction of intermittent generation from renewable energy sources.

Lately, the users of electricity become more active, which can act as both the consumers as well as the producers of electricity. This is often expressed as the new concept of prosumer. This could, e.g. involve the connection of electrical vehicles to the grid with the future vision that the electrical vehicles can both draw and inject (support) power from the grid. At the customer side, smart meters give the customers new possibilities to make decisions on their use of electricity. The introduction of the prosumers also result in that the distribution system needs to handle bi-directional power flow and the distribution system needs to be made more advanced, and rather similar to the transmission systems.

In the transmission area, the technology development has led to the new features with increasing use of HVDC transmission. HVDC transmissions can be used as a DC grid (e.g., for large off-shore wind farm applications) or embedded in the existing AC interconnected systems (e.g., Sweden will introduce multi-terminals voltage source converters VSC-HVDC in its high voltage transmission system to increase transfer capability and controllability of the system.

These different developments and changes in the electric power system, together with the increased use of information and communication technology (ICT), automatic control methods, etc., are reflected in the concept of Smart Grid.

As a part of the thesis a comprehensive literature survey was done looking at publications using the mentioned test systems and also other test systems. This section presents the results of the survey and tries to analyse the same.

2.2 RTS & RBTS Test System

In this Section, the two most commonly used test systems (i.e. the IEEE RTS and the RBTS) are briefly described. They have been mainly used for reliability analysis and probabilistic applications to electric power systems.

A. IEEE RTS

The first IEEE-RTS introduced in 1979 consists of 24 buses and 32 generator units. The system is divided into two parts. The northern part has a voltage level of 230 kV and the southern part has the voltage level of 138 kV. The total installed capacity of generation units is 3405 MW and the total peak load of 2850 MW. The southern part is a power deficit area while the northern part is a power surplus area. Figure. 2.1 shows the original single line diagram of the IEEE-RTS (1979).

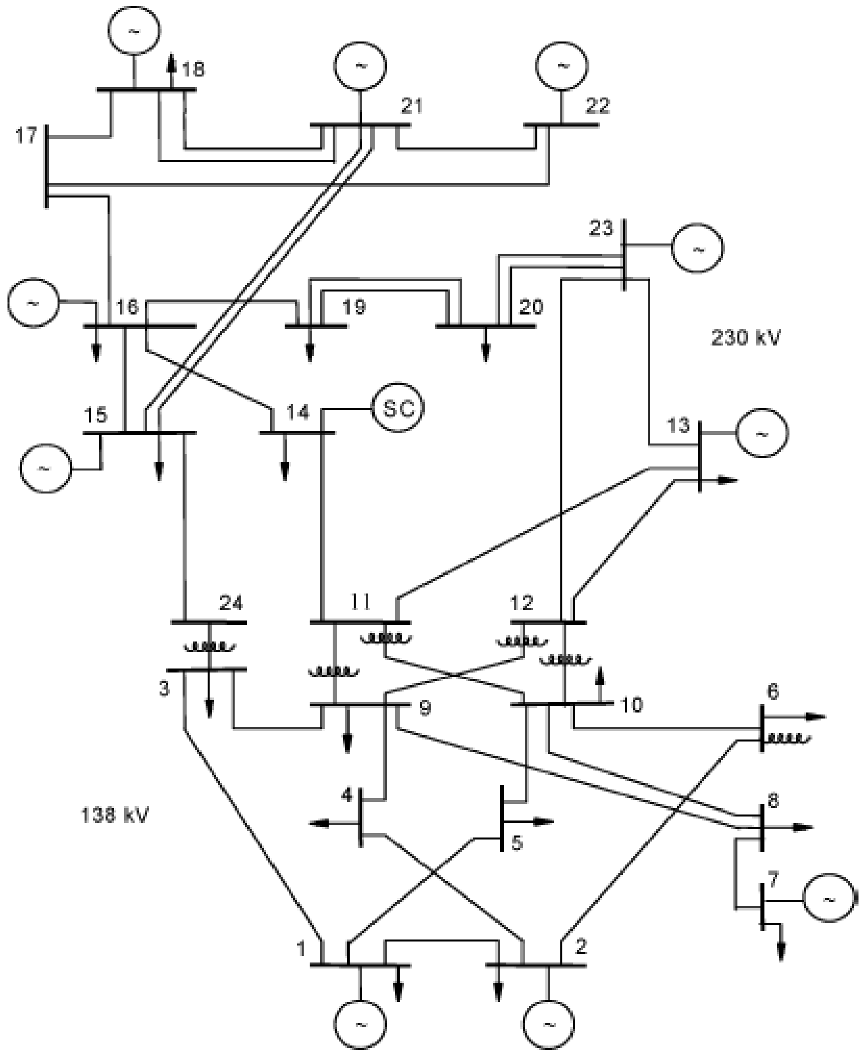

Figure 2.1 IEEE RTS 24 bus test system [162]

RTS has been used for various kinds of studies. In recent times integration of wind power to the system has been the most studied topic in the generation sector. RTS has been used in many cases for this kind of study. One limitation of RTS is that no data regarding distribution system has been provided within the existing test system. Hence, many studies on distribution system reliability analysis have been done using self-developed test system or actual distribution system connected to the RTS.

B. RBTS

RBTS was developed at University of Saskatchewan for educational purposes and research [24]. RBTS includes 6 buses and 11 generator units. The transmission voltage is 230 kV and the total installed capacity is 240 MW with a system peak load of 185 MW. Figure. 2.2 shows the single line diagram of RBTS. RBTS is a smaller test system as compared to RTS. However, data for a distribution system has been defined for the existing RBTS. This makes it very convenient for applications on distribution system reliability analysis and similar studies. RBTS has also been used for a variety of similar studies as RTS. The area of research where it has been used the most is introducing and testing new techniques for probabilistic applications. Another advantage of RBTS is that it is very easy to modify the test system due to its size.

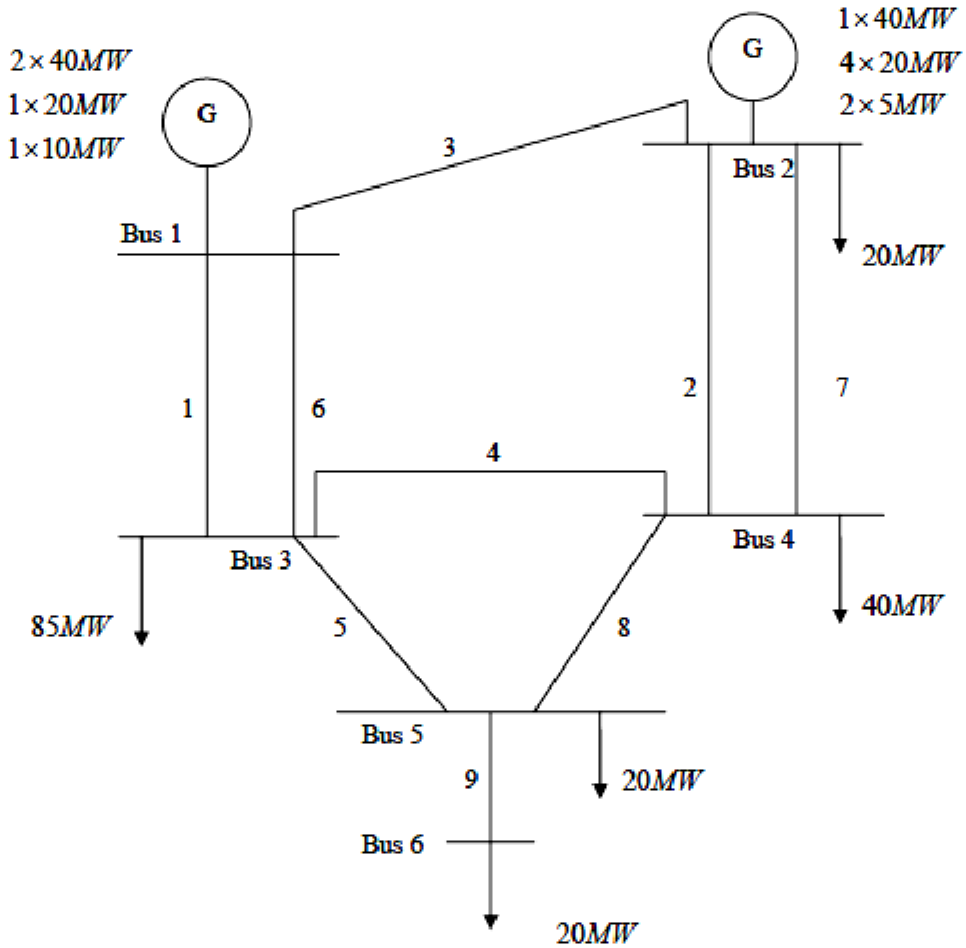

Figure 2.2 6 bus RBTS test system [24]

2.3 Approach for Literature Survey

The approach for the performed literature study can be summarized as follows:

1. Selecting journals

2. Identifying publications using test systems:

a) Publications using IEEE RTS or RBTS

b) Publications using other test systems for reliability analysis of electric power systems.

3. Various questions to be investigated:

a) Which test systems have been used?

b) Who has used these test systems?

c) Where have the test systems been used?

d) What is the purpose of using these test systems?

2.4 Literature Survey

A. Selecting Journals

In the first step, the following journals were selected for the study:

- IEEE Transactions on Energy Conversion (Transaction from 2010 to 1986)
- IEEE Transactions on Power Delivery (Transaction from 2010 to 1986)
- IEEE Transactions on Power Systems (Transaction from 2010 to 1986)
- IEEE Transactions on Smart Grid (new transaction, introduced in 2010)
- IEEE Transactions on Sustainable Energy (new transaction, introduced in 2010)

B. Selecting Publications

A total of 240 publications, as listed in Appendix A, were selected from the journal papers listed above. **The publications selected used the RTS, the RBTS or other test systems for reliability studies**. Under this Appendix, the publications can be found in different categories according to aspects of reliability analyses.

C. Investigating Questions

Fig. 2.3 shows 'Which' test systems have been used. It can be seen from the Figure that that more than half of the selected journal papers used the RTS or the RBTS for analysis. Moreover, the RTS was used with 36% of the cases. In many of these publications, modifications have been made to the RTS to fit the purpose of the study.

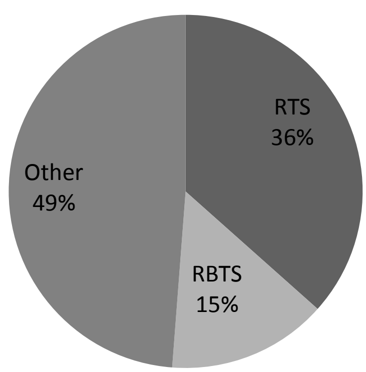

Figure 2.3 General trend of usage of test systems

Fig. 2.4 presents results grouping the journal papers according to the affiliation of the authors. It is interesting to observe that the RTS system is not only used by the academic world (around 80% of the studies), the industry has also made used of the test systems in their studies (around 20% of the studies).

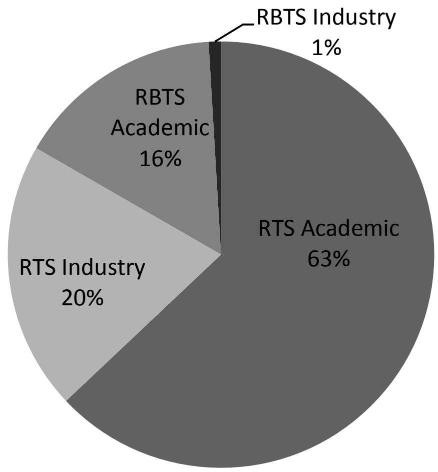

Figure 2.4 The use of the RTS and the RBTS by Academics and Industry

Fig. 2.5 shows results from analyzing where the different studies using the test systems have been made. It can be seen that Canada and USA are the places where the RTS and the RBTS have been used the most. Due to the origin of the RBTS from Canada, this is expected. A main result is that the test systems have been widely used worldwide.

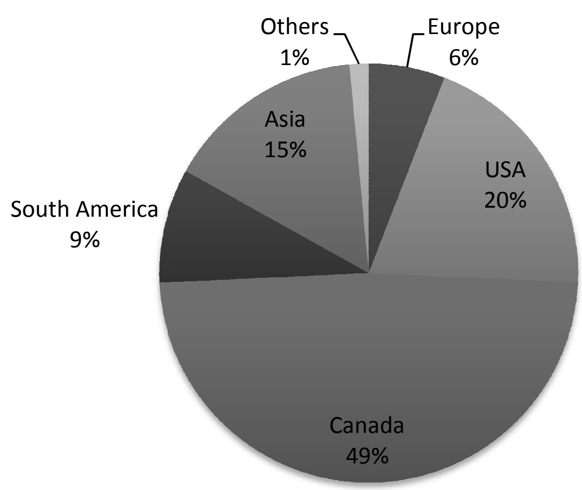

Figure 2.5 Usage of RTS & RBTS worldwide

Investigation has been made of the purpose of the use of the different test systems. Fig. 2.6 and Fig. 2.7 shows the result investigating the purpose of the studies made using the RTS respectively the RBTS. The Figures have been divided into five sections depending of different aspects of reliability analyses as follows:

A. Reliability analysis and Planning, Generation

B. Reliability analysis and Planning, Transmission

C. Power System Economics and Optimization

D. Reliability analysis and Planning, Distribution

E. New techniques for reliability analysis

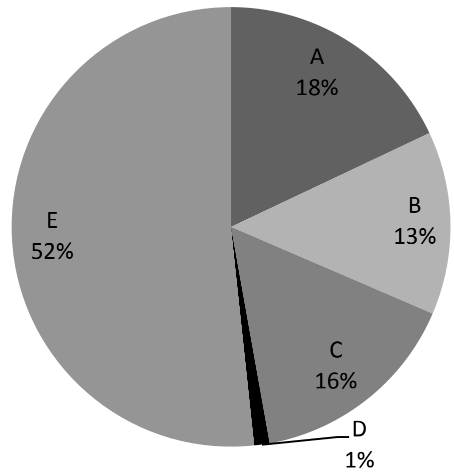

Figure 2.6 The RTS used for different type of reliability studies

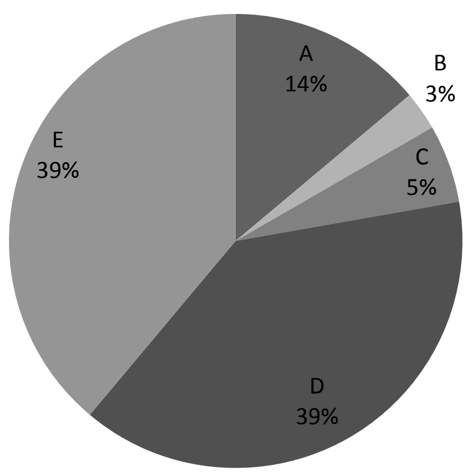

Figure 2.7 The RBTS used for different type of reliability studies

It can be seen from the Figure 2.6 and Fig. 2.7 that the test systems have been used for a variety of studies. Figure 2.6 shows that in just about half of the studies the RTS was used for analyzing the introduction of new techniques for reliability analysis. Fig. 2.7 shows that almost 80% of the studies have focused on reliability analysis with focus on distribution systems or introduction of new techniques. Another conclusion is that economic studies have been made more using the RTS than the RBTS system. In summary both the RTS and the RBTS have been used to analysis a wide range of questions related to reliability analysis.

2.5 Conclusion

This section has presented first results from an IEEE TF on test systems, investigating further developments for reliability analysis of the future smart electric power systems. A bibliography study has been made identifying 240 journal papers using test systems for reliability analysis which have been further analyzed. Of these, around 50% of the studies were made using the test systems RTS or RBTS. The study shows that these two test systems have been used worldwide and by both the industry and the academia, although almost 80% of the studies presented came from the academia. The RBTS system is more adopted for distribution system studies. Both of the systems have been used of around 50% to investigate reliability questions for distribution systems or introduction of new techniques. For analysis of economic questions, the RTS system has been more widely used than the RTS. In summary, this survey indicates the success of using the RTS and the RBTS for reliability analysis. For further work, it will be investigated how these test systems could be adopted to investigate the features for the new developments of the electric power systems, e.g. connection of large scale wind power or plug in electric cars to the grid. This work will be continued within the IEEE TF on Test System.

The results from this study will be presented in a panel meeting at IEEE PES General Meeting to be held in July, 2011.

2.6 Bibliography

Table 2.1 List of publications from IEEE Transactions

Transaction	References
IEEE Transactions on Power Systems	[1] to [19], [24] to [41], [43] to [53], [55] to [63], [71] to [90], [94] to [101], [110] to [121], [152] to [234]
IEEE Transactions on Power Delivery	[20] to [23], [42], [54], [64] to [70], [91] to [93], [102] to [109], [122] to [151], [235] to [240]

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PART-2 EXTENSIONS TO THE DISTRIBUTION TEST SYSTEM

3 Reliability Theory and NEPLAN Software

3.1 Reliability Theory

Reliability of a system can be defined as the ability of the system to perform the desired function. When applied to the electric power system, reliability is mainly concerned with the ability of the system to supply the load demands. Reliability evaluation of an electric power system can be divided into two main categories, system adequacy evaluation and system security evaluation. System adequacy is concerned with the evaluation of adequacy of resources to supply the demanded load, whereas system security is concerned with the response of system to disturbances[30].

Electric power systems are complex and large systems. It is difficult to analyze the entire system at once. For this reason the power system is generally divided into three main hierarchy levels for reliability evaluation[30].

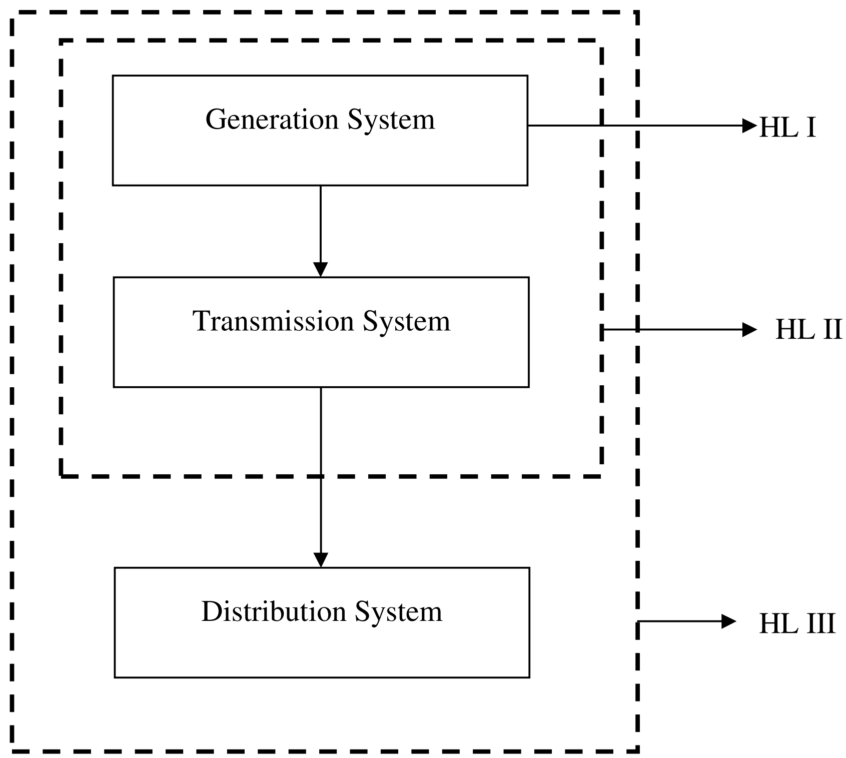


Figure 3.1 Hierarchy Levels defined for reliability evaluation [30]

HLI are concerned with the reliability evaluation of generation systems. The main indices analyzed in this study are loss of load expectation (LOLE), loss of energy expectation (LOEE), failure frequency and failure duration. In this study only the generation systems are considered and the effect of transmission and distribution systems on reliability are neglected.

HLII studies constitute of both the generation and the transmission systems. This study can be used to assess the reliability of an existing system or a proposed system. These studies give two main outputs, one related to each bus and the other for overall system. The main indices considered here are failure frequency and failure duration.

HLIII constitutes of the entire power system consisting of generation, transmission and distribution. Due to the complexity of such a system, evaluation of the entire system is not done. The reliability analysis of distribution system is done separately, wherein the indices from HLII evaluation are inputs to the reliability evaluation of the distribution system. The main indices to be considered in this evaluation are SAIFI, SAIDI and CAIDI.

Reliability evaluation of a system can be classified into two broad categories, deterministic and probabilistic. The electric power system is stochastic in nature and hence the probabilistic evaluation of the system is preferred for objective analysis. However, deterministic technique is computationally faster and requires less data. Due to the advancement of technology and computational techniques, over the years, probabilistic reliability evaluation has become possible and is being practiced widely.

3.2 Introduction to NEPLAN

NEPLAN is a software used for analysis of electric power systems by BCP group in Switzerland. The main features of the software include optimal power flow, transient stability, load flow, short circuit and reliability evaluation. NEPLAN can provide reliability indices for individual load points and the overall system. The working of the software can be summarized in the simple diagram of Figure 3.2.

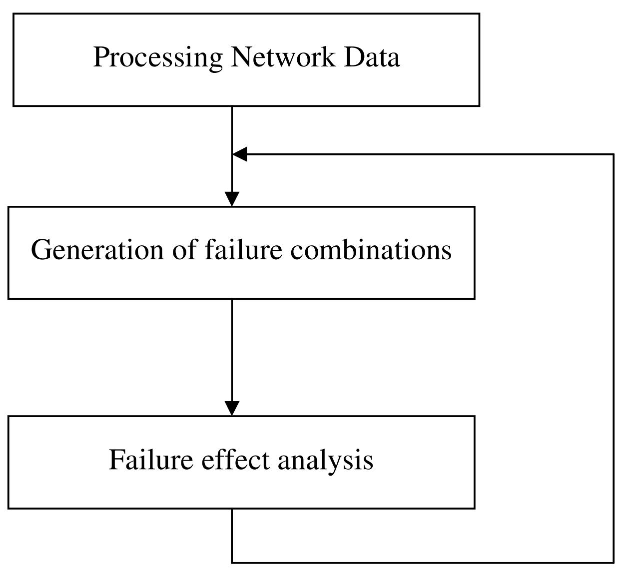


Figure 3.2 Block diagram representing working of NEPLAN

The first step is to analyse the network data for load flow analysis and the data for reliability evaluation. In the next step the software generates failure combinations. The failure combinations can be either individual failure or simultaneous multiple failures. The first order failures or individual failures consider a failure of only one component in the system. The second order or multiple failures consider simultaneous failure of two components in the system.

In the next step failure effect analysis is performed on each failure combination. Processing of a failure combination produces a value for the contribution of that combination to the reliability characteristics of the network, expressed as a probability. For each load node, Figures are generated for the frequency and duration of non-supply or undersupply. The contribution of this failure combination is added to the factors already identified, so that after processing all relevant failure combinations, a detailed picture is obtained of the interruptions occurring at each load node.

3.3 Application of NEPLAN

As a part of the thesis the software was proposed to be used. To understand the working of the software a sample study has been done and results for various scenarios have been presented here. RBTS system mentioned in Section 2.2 has been used for the sample study. Figure 3.3 shows RBTS system designed in NEPLAN software.

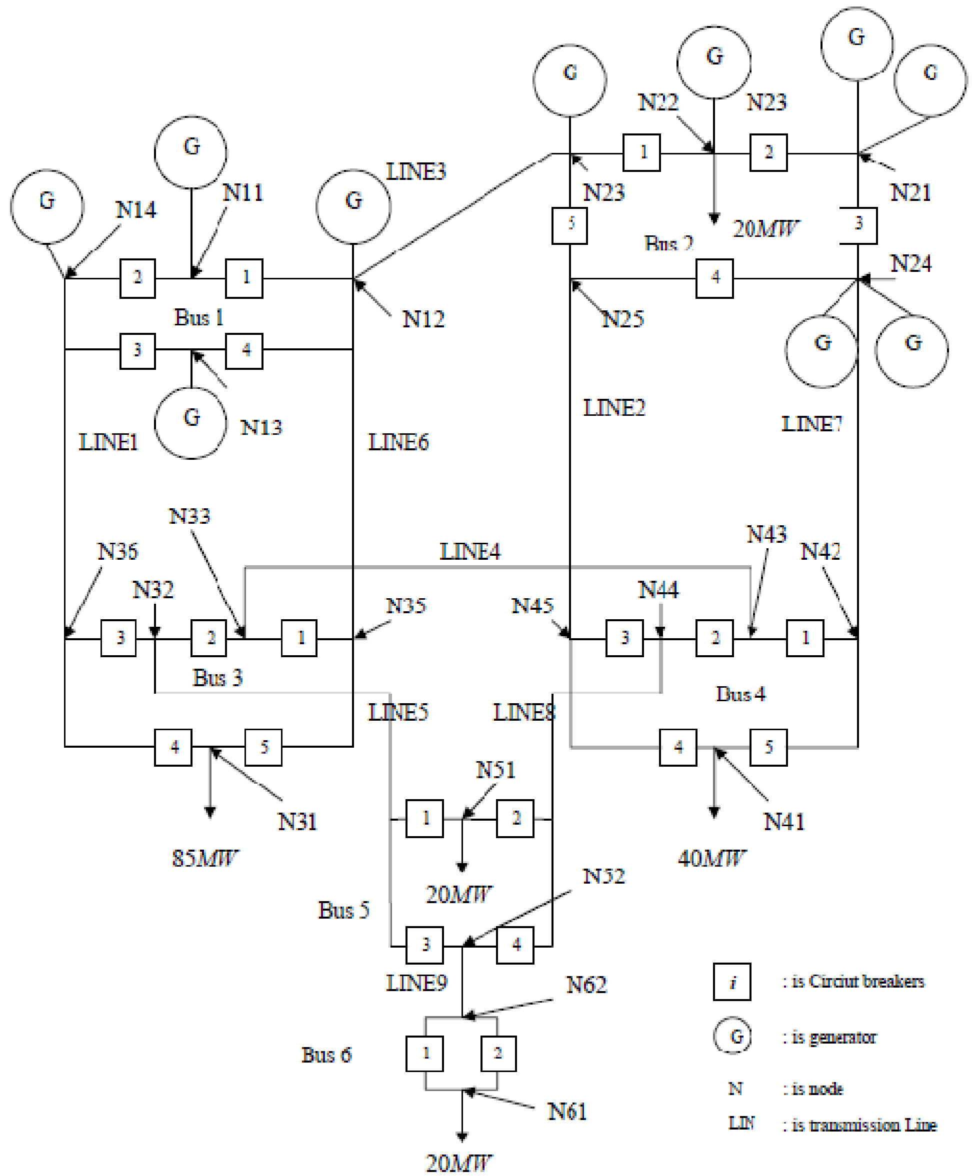


Figure 3.3 RBTS System modelled in NEPLAN[3]

The station configuration has been simplified to only one circuit breaker. The load point indices have been calculated assuming a constant peak load. The study has been performed step wise to see the effect of each input data on the overall system reliability. This can be understood as a sensitivity analysis. For the base case study the substation elements have been considered to be ideal. This means that no station originated outage has been considered and also no common mode outages have been considered.

3.4 Base Case Study

As mentioned earlier the base case study does not consider station originated and common mode outages. Both load indices and the overall system indices can be calculated using NEPLAN and the same have been presented in the following Tables.

Table 3.1 Load indices for base case

Load at	Failure Frequency [1/yr]	Duration [h]	Probability [min/yr]	Power not supplied [MW/yr]	Energy not supplied [MWh/yr]
Bus 2	0.47	1	28.19	9.397	9.397
Bus 3	0.066	1	3.955	5.604	5.604
Bus 4	0.355	1	21.301	14.201	14.201
Bus 5	0.002	5	0.685	0.046	0.228
Bus 6	1.002	9.989	600.68	20.046	200.228

We can observe from the above Figures that the load at bus 6 has the least reliability. This can be attributed to the fact also that it is being supplied by only one transmission line. If there is a fault on this transmission line all the load at bus 6 has to be curtailed.

Table 3.2 System Indices for Base case

System Indices	
SAIFI [1/yr]	0.379
SAIDI [min/yr]	130.964
CAIDI [h]	5.758
ASAI (%)	99.975
F [1/yr]	1.893
T [h]	5.759
Pr [min/yr]	654.134
P [MW/yr]	49.293
W [MWh/yr]	229.658

3.5 Study considering common mode outages

Common mode outages are those outages, which are related to each other. In this case two transmission lines on the same tower are considered. It means that if one of the line fails the other is also shutdown or both the lines fail together. As defined in [1] two common mode outages have been considered in this study.

Table 3.3 Common mode data for circuits on a common right of way [1]

Line	Common Length (km)	Outage rate per year	Outage duration (hours)
1	75	0.15	16
6	75		
2	250	0.5	16
7	250		

Considering the above common outages the load indices and the system indices have been calculated once again and presented in the Tables below.

Table 3.4 Load indices considering Common Mode outages

Load at	Failure Frequency [1/yr]	Duration [h]	Probability [min/yr]	Power not supplied [MW/yr]	Energy not supplied [MWh/yr]
Bus 2	0.47	1	28.19	9.397	9.397
Bus 3	0.216	1	12.955	18.35	5.604
Bus 4	0.855	1	51.301	34.201	14.201
Bus 5	0.002	5	0.685	0.046	0.228
Bus 6	1.002	9.989	600.68	20.046	200.228

We can observe from the above Figures that due to the common mode outages the reliability for load on bus 4 has reduced compared to the base case.

3.6 Study considering station originated outages

For the previous cases the substation components were considered to be ideal. However, this is an approximation which is rarely true. There is a major difference in the reliability of the entire system when the station originated outages are considered. The below Tables and Figures provide the reliability indices considering station originated outages.

Table 3.5 Load Indices considering station originated outages

Load at	Failure Frequency [1/yr]	Duration [h]	Probability [min/yr]	Power not supplied [MW/yr]	Energy not supplied [MWh/yr]
Bus 2	2.217	1.893	251.834	44.345	83.945
Bus 3	0.775	3.556	165.322	65.686	234.206
Bus 4	0.562	1	33.738	22.249	22.492
Bus 5	0.223	9.924	133.019	4.468	4.468
Bus 6	1.662	9.995	996.468	33.231	332.156

Table 3.6 System Indices considering station originated outages

System Indices	
SAIFI [1/yr]	1.088
SAIDI [min/yr]	316.076
CAIDI [h]	4.482
ASAI (%)	99.940
F [1/yr]	5.436
T [h]	4.842
Pr [min/yr]	1579.862
P [MW/yr]	170.404
W [MWh/yr]	717.139

3.7 Conclusion

In this section a brief theory about reliability has been provided. NEPLAN software has been introduced and reliability analysis for a sample system has been performed. Sensitivity analysis has been done on the sample system to understand the behaviour of the system due to different kinds of failures. Results of reliability evaluation for each case has been provided and short observations on these results has been presented.

4 Chapter Four

The Distribution Test System

4.1 Introduction to the Distribution Test System

Two distribution test systems have been defined within RBTS[10] . RBTS is a six bus test system, within RBTS distribution system has been defined on Bus 2 and Bus 4. These distribution systems are general and follow general utility principles. In this section reliability analysis for both these distribution systems has been performed using NEPLAN and the results have been presented.

4.2 Bus 2 Distribution Test System

The distribution system for Bus 2 is supplied by two 33/11 kV, 16 MVA transformers. Further distribution of the supply is done from the 11 kV switchgear. The distribution system has both high voltage and low voltage customers. The 0.415 kV low voltage customers are supplied via 11/0.415 kV transformers and the 11 kV customers are supplied directly. For the reliability analysis the 33 kV supply has been considered 100% reliable. Figure 4.1 shows the single line diagram for the distribution system.

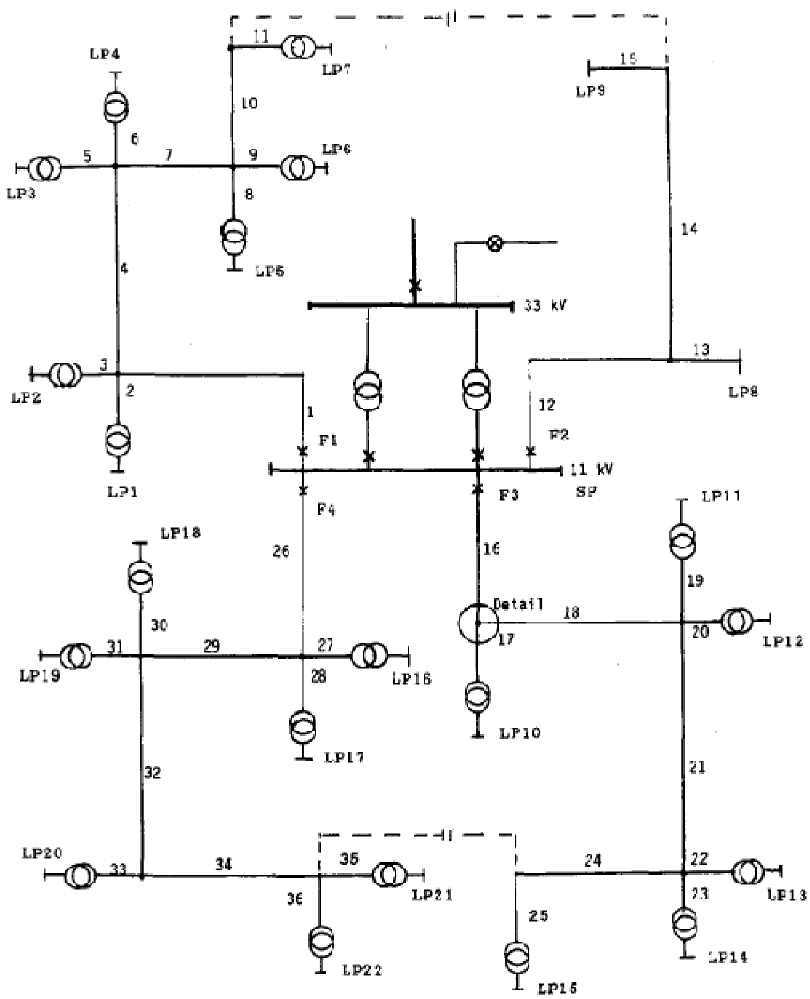


Figure 4.1 RBTS Bus 2 distribution system [10]

There are in total 22 load points supplying various kinds of customers. The customers have been divided in to four categories and they are residential, small users, government/institutions and commercial. The transformers for customers being supplied at 11 kV level are not considered for reliability evaluation as the metering for these customers is done at 11 kV level.

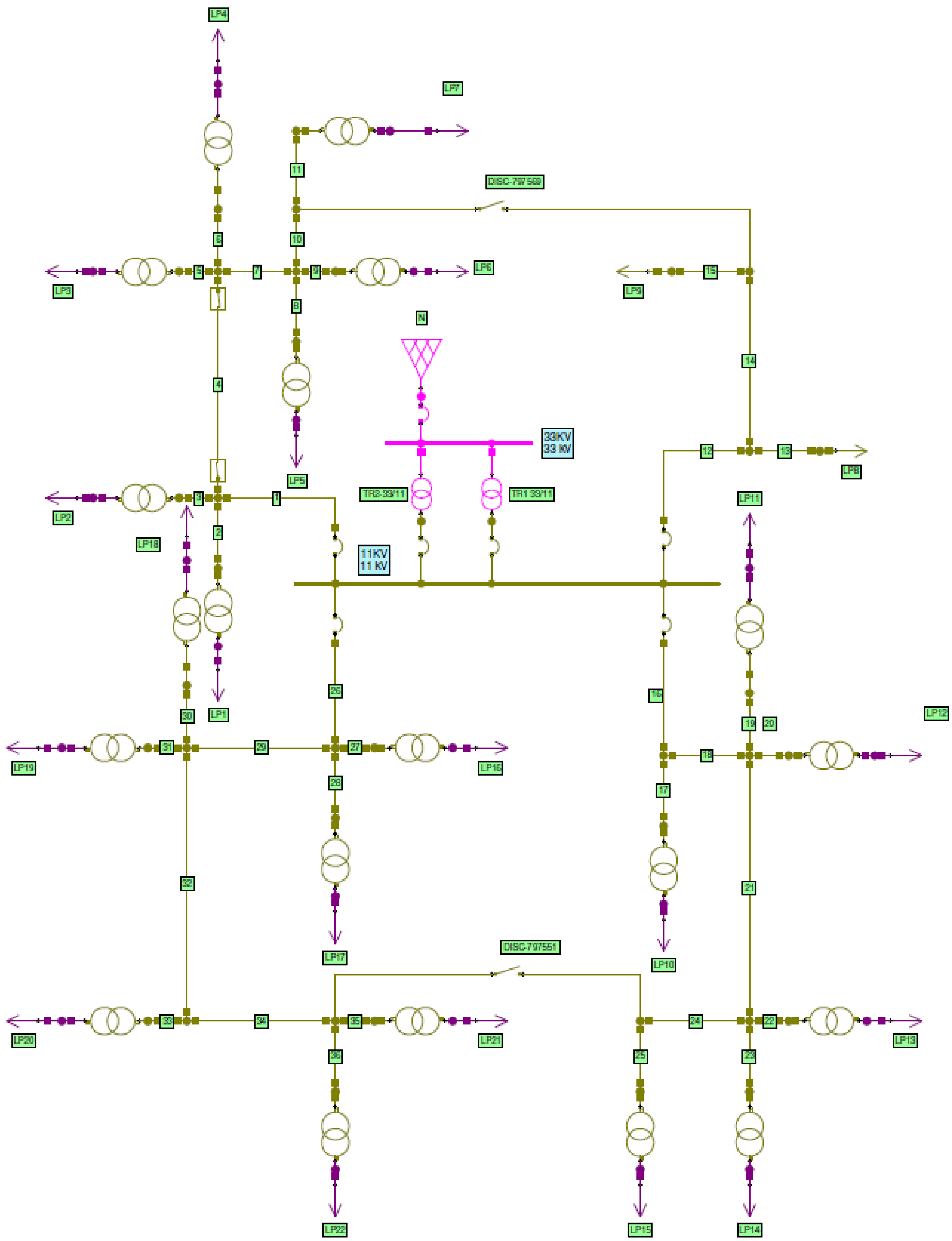


Figure 4.2 Bus 2 Distribution System Model in NEPLAN

The results for the reliability analysis for the distribution system are presented below.

Table 4.1 System Indices for Bus 2 Dist System

System Indices		Units
SAIFI	0.657	[1/yr]
SAIDI	565.642	[min/yr]
CAIDI	14.399	[h]
ASAI	99.892	(%)
F	2.752	[1/yr]
T	59.303	[h]
Pr	9793.382	[min/yr]
P	7.364	[MW/yr]
W	101.855	[MWh/yr]

4.3 Extension to Bus 2 Distribution Test System

The focus in this section is to extend the test system so as to be able to study the impact of integration of electric vehicles into the electric distribution system. Availability of proper data is imperative for an accurate reliability analysis. However, due to unavailability of required data, assumptions have to be made in this case.

Following questions have to be investigated to study the impact of EV integration into the system.

1. What is the geographical profile of the test system?
2. How many vehicles are connected to the system at given point of time?
3. What are the driving habits of the customers?
4. What is the daily load variation?
5. What kind of electric vehicles are being used?
6. How much energy is left in the car at any given point of time, when connected to the system and discharging?

The following sub sections provide the answers to the questions above and also enlists some extensions to the test system.

4.3.1 Classification of Loads

To decide the geography of the test system, the location of each load has to be decided. For this purpose the loads have been classified based on their assumed geographical locations. Loads R1, R2 and R3 are called residential loads and are the loads of residential complexes. Similarly loads C1, C2 and C3 are classified as commercial loads and signify the loads of commercial complexes and other institutions. Residential load R1 has three different load points LP1, LP2 and LP3. This means that there are three different distribution transformers in area R1 each supplying a set of residential customers. However, from geographical point of view these loads can be located in a single area.

Table 4.2 Classification of loads in the DTS

Load Point	Area Designation	Type of Customer	Dist. Transformer Rating [KVA]	Peak Load (MW)	Number of customers
LP1	R1	Residential	1200	0.866	210
LP2		Residential	1200	0.866	210
LP3		Residential	1200	0.866	210
LP4	C1	Govt/Inst	1200	0.9167	1
LP5		Govt/Inst	1200	0.9167	1
LP6		Commercial	1000	0.75	10
LP7		Commercial	1000	0.75	10
LP8		Small User	--	1.628	1
LP9		Small User	--	1.872	1
LP10	R2	Residential	1200	0.866	210
LP11		Residential	1200	0.866	210
LP12		Residential	1000	0.729	200
LP13	C2	Govt/Inst	1200	0.916	1
LP14		Govt/Inst	1200	0.916	1
LP15		Commercial	1000	0.75	10
LP16		Commercial	1000	0.75	10
LP17	R3	Residential	1000	0.729	200
LP18		Residential	1000	0.729	200
LP19		Residential	1000	0.729	200
LP20	C3	Govt/Inst	1200	0.916	1
LP21		Govt/Inst	1200	0.916	1
LP22		Commercial	1000	0.75	10

4.3.2 Geography of Distribution Test System

Based on the grouping of the loads in the test system a simple geography for the same has been presented in Figure 4.3. Each area has a set of customers as defined in Table 4.2.

The following assumptions are made regarding EVs:

- The residential customers travel to the commercial complexes and the govt/inst area for work during the weekdays and use the shortest path from home to work.

- During night all electric vehicles in the residential complex are connected to the system and during the day all vehicles travel to the commercial complexes where they are connected to the plug in points available.
- The number of EVs and their travelling distances are specified in the following sub section.

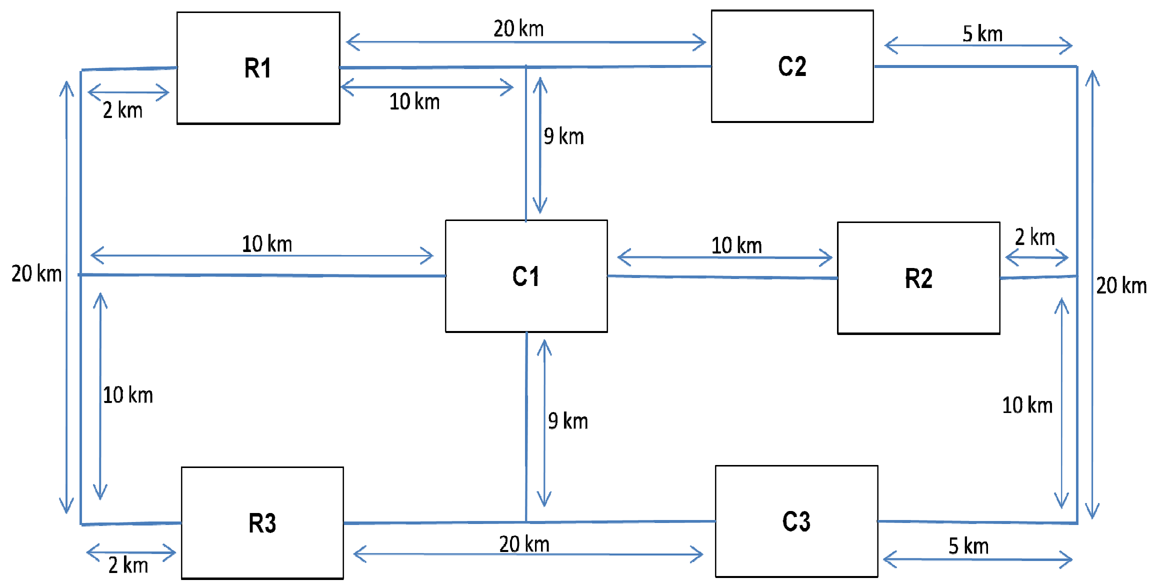


Figure 4.3 Geography for the selected electrical distribution system

4.3.3 Number of EVs in the Distribution Test System

The environment conservation agenda is pushing countries towards shifting to green technology all throughout the world. Many countries have set ambitious targets towards use of EVs in the coming years. Figure 4.4 shows the targets set by different countries in this regard.

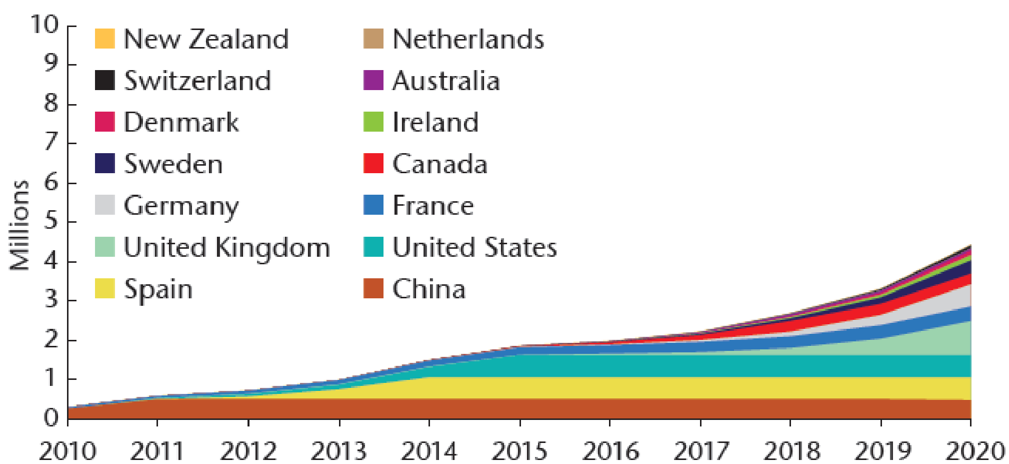


Figure 4.4 Sales target set by different countries for sale of EVs [17]

The number of vehicles that are considered in the test system depends on what scenario is being studied. There can be many cases ranging from 10% penetration to a 100% penetration of EVs. In this thesis two such cases have been considered:

- **Case 1: 30% Penetration of EVs**
- **Case 2: 100 % Penetration of EVs**

4.3.4 Number of EVs in the Distribution Test System: Case 1 (30% EV penetration)

In this case 30% penetration of EVs has been considered. This means that 30% of the total consumers use an electric vehicle.

There are in total 630 customers in residential areas R1 & R2 and 600 customers in residential area R3. Considering 30% of the total customers have EVs there are total 210 EVs in areas R1 & R2 and 200 EVs in R3. The travelling distance of these EVs and the number of EVs travelling from one destination to the other have been shown in Table 4.3.

Table 4.3 Assumed driving distance between two locations (Case 1)

Route	Distance (km)	Number of vehicles travelling	Total Number of Vehicles
R1 to C1	19	70	210
R1 to C2	20	70	
R1 to C3	38	70	
R2 to C1	10	70	210
R2 to C2	17	70	
R2 to C3	17	70	
R3 to C1	19	60	200
R3 to C2	38	60	
R3 to C3	20	80	

4.3.5 Number of EVs in the Distribution Test System: Case 2

In this case 100% penetration of EVs has been considered. This means that 100% of the total consumers use an electric vehicle.

There are in total 630 customers in residential areas R1 & R2 and 600 customers in residential area R3. Considering 100% of the total customers have EVs there are total 630 EVs in areas R1 & R2 and 600 EVs in R3. Table 4.4 shows the travelling distance of these EVs and the number of EVs travelling from one destination to the .

Table 4.4 Assumed number of vehicles and travelling distance (Case 2)

Route	Distance (km)	Number of vehicles travelling	Total Number of Vehicles
R1 to C1	19	210	630
R1 to C2	20	210	
R1 to C3	38	210	
R2 to C1	10	210	630
R2 to C2	17	210	
R2 to C3	17	210	
R3 to C1	19	200	600
R3 to C2	38	200	
R3 to C3	20	200	

4.3.6 Load Curve and Cost Data

For all kind of customers the requirement of power varies on hourly basis over each day of the week. This variation depends on various factors like location, psychology of the customers, economic status etc. Here two major classifications have been made for deciding the load curve, residential and non residential customers. Loads designated R1, R2 and R3 are considered residential loads and C1, C2 and C3 are considered non-residential loads. Figure 4.5 shows the daily load curve for residential and non-residential customers on a weekday. The load curve shows the variation of load as a percentage of peak load over a period of 24 hours. Based on the load curve the load variation over a period of 24 hrs for residential customer R1 is presented in Table 4.5 as an example.

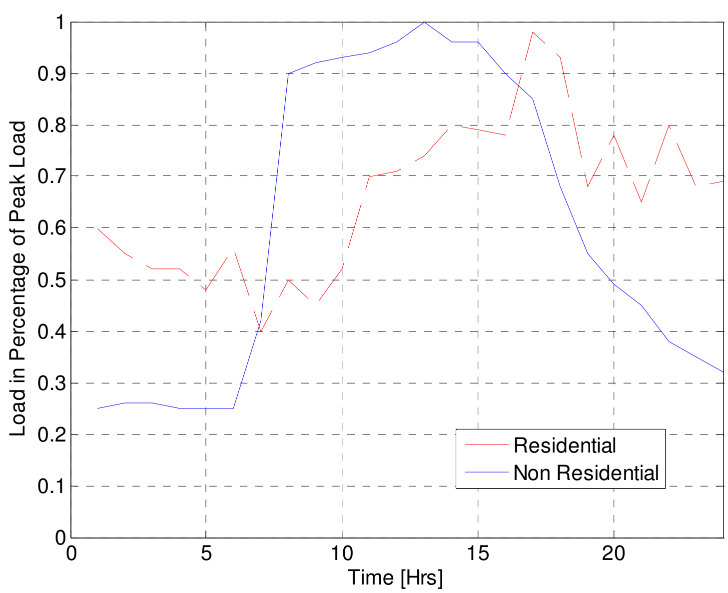


Figure 4.5 Daily Load Curve without Electric Vehicles [28]

Table 4.5 Load data for customer R1 for a period of 24 hrs

Time Period	Load [MW]	Time Period	Load [MW]
00:00 – 01:00	0.52	12:00 – 13:00	0.641
01:00 – 02:00	0.476	13:00 – 14:00	0.693
02:00 – 03:00	0.450	14:00 – 15:00	0.684
03:00 – 04:00	0.450	15:00 – 16:00	0.676
04:00 – 05:00	0.416	16:00 – 17:00	0.849
05:00 – 06:00	0.485	17:00 – 18:00	0.806
06:00 – 07:00	0.346	18:00 – 19:00	0.589
07:00 – 08:00	0.433	19:00 – 20:00	0.676
08:00 – 09:00	0.39	20:00 – 21:00	0.5653
09:00 – 10:00	0.45	21:00 – 22:00	0.693
10:00 – 11:00	0.606	22:00 – 23:00	0.589
11:00 – 12:00	0.615	23:00 – 00:00	0.598

The data shown in Table 4.5 has been calculated considering the peak load residential customer R1.

The cost of electricity also varies over time during a day and is also dependent on the season. To associate an economic benefit with the current study, time varying cost data has been assumed. This data has been extracted from Nord Pool website [26] and gives the variation of cost over one particular day. Here two cases are considered one showing a huge variation in the price over a period of the day and the other in which the variation of price is much lower

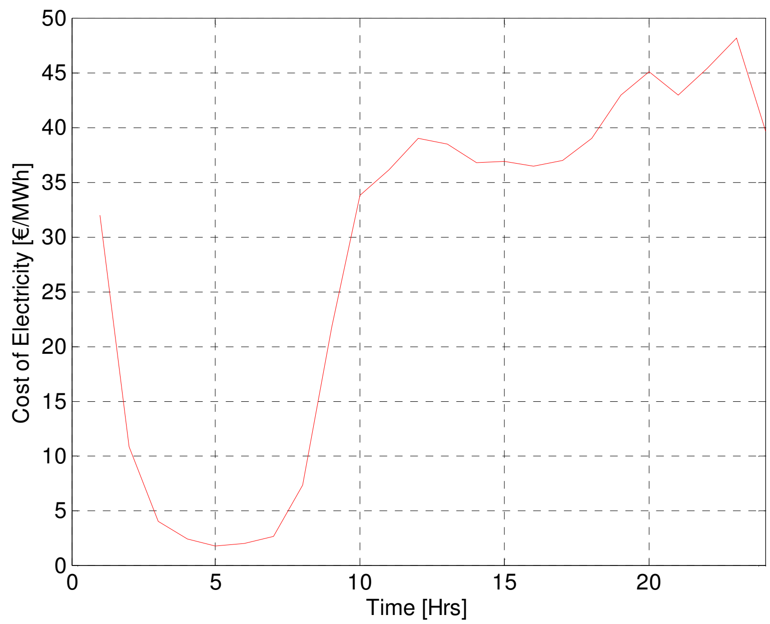


Figure 4.6 Hourly cost data during summer time (13th June 2010) [26]

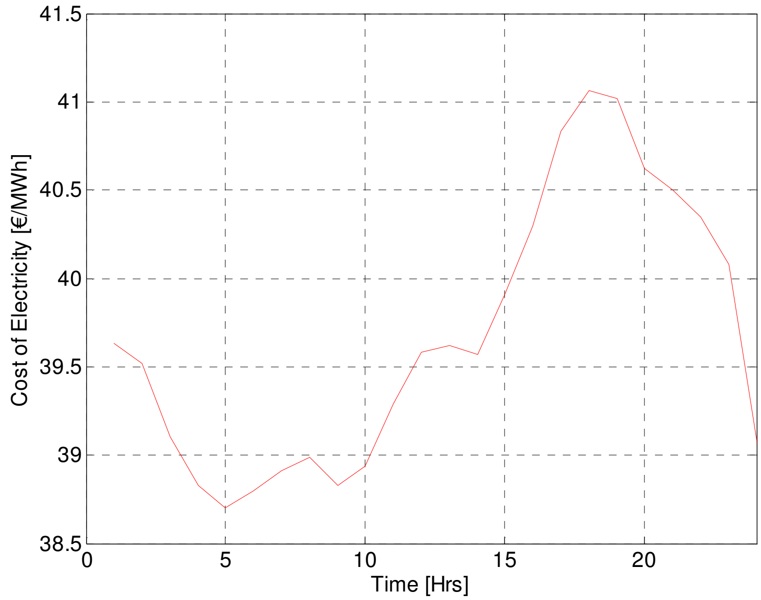


Figure 4.7 Hourly cost data during winter time (4th Jan 2010) [26]

4.4 Electric Vehicles Case Study

Various different types of PHEVs and EVs are available in the market today. With increasing demand new variations of electric vehicles with different range and performance will be available in coming times. For purpose of study three different kind of vehicles have been considered as mentioned in Table 4.6. This data has been taken from website of "*Grid 4 Vehicles*" project. The objective of G4V is to develop an analytical method to evaluate the impact of a large scale introduction of EV and PHEV on the grid infrastructure and a visionary "road map" for the year 2020 and beyond, taking into account all stakeholders and generating fast and openly available results. Chalmers is a part of this project, which is run in collaboration with other universities and industries from all over Europe.

Table 4.6 Details of Electric Vehicles

Type of Car	**Battery Capacity (kWh)**	**Energy Consumption (kWh/km) [29]**	**Composition in Market (%)**
BEV	35	0.20	37
City-BEV	16	0.12	10
PHEV90	18	0.20	53

For the purpose of simplification, here only one size of battery is assumed for all kinds of vehicles. This can be achieved by considering the average size of battery for all the vehicles. In this case the average battery size is 24.1 kWh. Here the simple average calculation has been done and not weighted average as per market composition.

The energy consumption by an EV depends on the driving cycle. The starts and stops and also on the ups and downs in the road. However this kind of data will vary due to various reasons like geography, traffic rules etc. In this case an average value of energy consumption is considered which is 0.17 kWh/km.

4.5 Charging of Vehicles

Electric vehicles can be charged by conduction, induction or by using battery swapping stations [29]. However, the investment needed to achieve each of these charging methods is very different.

Conductive charging is by far the simplest method of charging the electric vehicles. It means simply connecting the electric vehicles to the plug in points available in the system. From an investment point of view this may be the cheapest method as the existing lines can be used for the purpose of charging.

Inductive charging on the other hand does not need any physical connection to the grid. Charging can be possible just by parking the vehicle in the parking lot equipped with the facility of inductive charging. However, at present the efficiency of such a charging technique is very poor and new installations are required, which calls in for extra investments.

Battery swapping stations are a quick way of charging the vehicle. These are stations where the batteries of the vehicle will be swapped with fully charged batteries. However, to accomplish this method, standardization in battery types across all manufacturers is imperative.

As in this case we are studying the impact of electric vehicles on the electric distribution system, only the conductive charging is considered.

Time needed by the vehicle to charge depends on the size of the vehicle, type of charger used and the type of batteries. Various manufacturers have variety of solutions and consequently different battery charging times. The data for charging times has been considered from G4V project results [29].

Table 4.7 Details for battery charging

Type of Charging	Kms/hr of charging at Max Power	Maximum Power during Charging [kW/h]	Approximate Charge Time to full capacity [Hrs]
Slow Charging	21	3.7	6
Fast Charging	64	11.0	2

5 Chapter Five

Application of the Extended Test System

5.1 EV Integration within RBTS Bus-2 Distribution System

Electric vehicles could be considered as new type of loads, which will be added to the electrical distribution system in future. The transformers in the electrical distribution system have not been rated to cater to this new load. For this reason it has to be taken care that the transformers are not overloaded due to the charging of vehicles. In present case coordinated charging has been considered based on the calculated spare capacity available in the distribution transformer. Coordinated charging can be achieved by central control by aggregator, who sends signals to the connected electric vehicles to start or stop charging. Table 4.2 shows the spare capacity available in the transformer based on the rating and load profile.

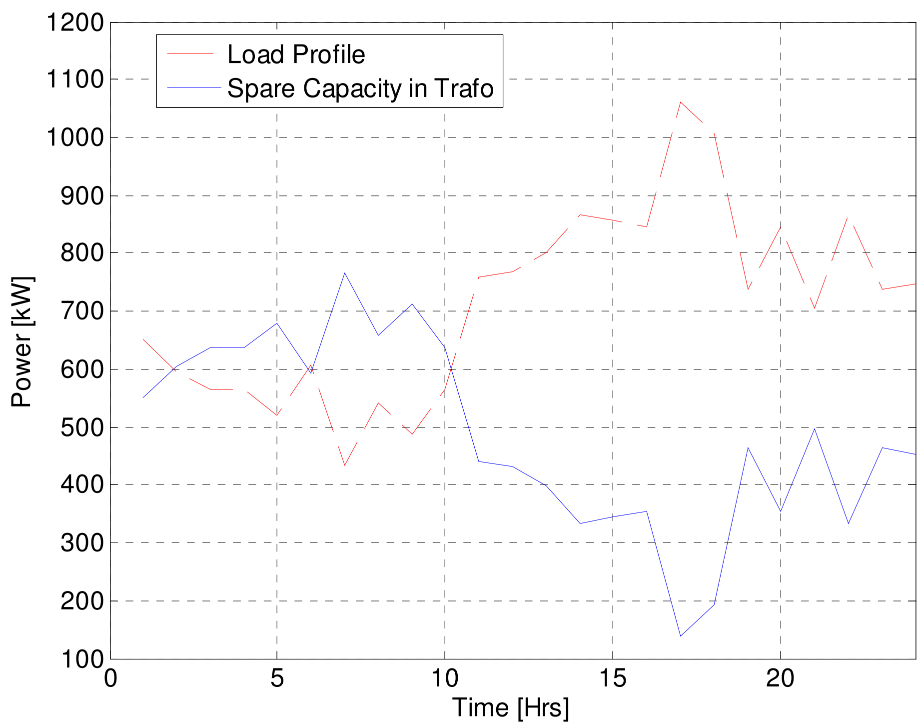


Figure 5.1 Load profile of load point and spare capacity available in transformer (1200 kVA)

As has been stated earlier, it is assumed that the vehicles will be charged at the residential complex during the night time. This charging will be coordinated based on the spare capacity available in the transformer shown in Figure 5.1. As defined in Table 4.7 two cases of charging have to be considered, fast charging and slow charging.

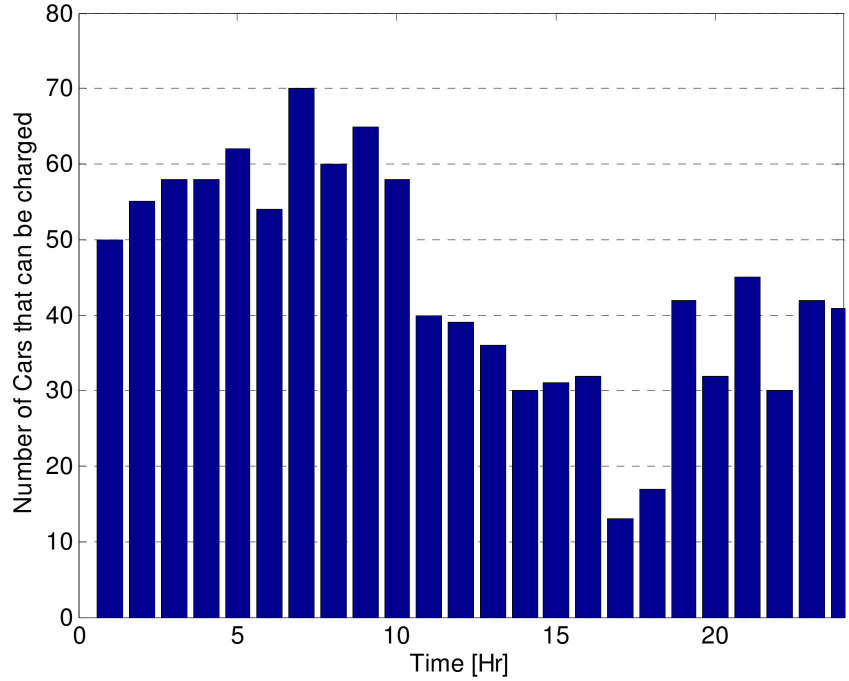


Figure 5.2 Number of vehicles that can be charged in the residential complex using Fast Charging based on transformer spare capacity (1200 kVA)

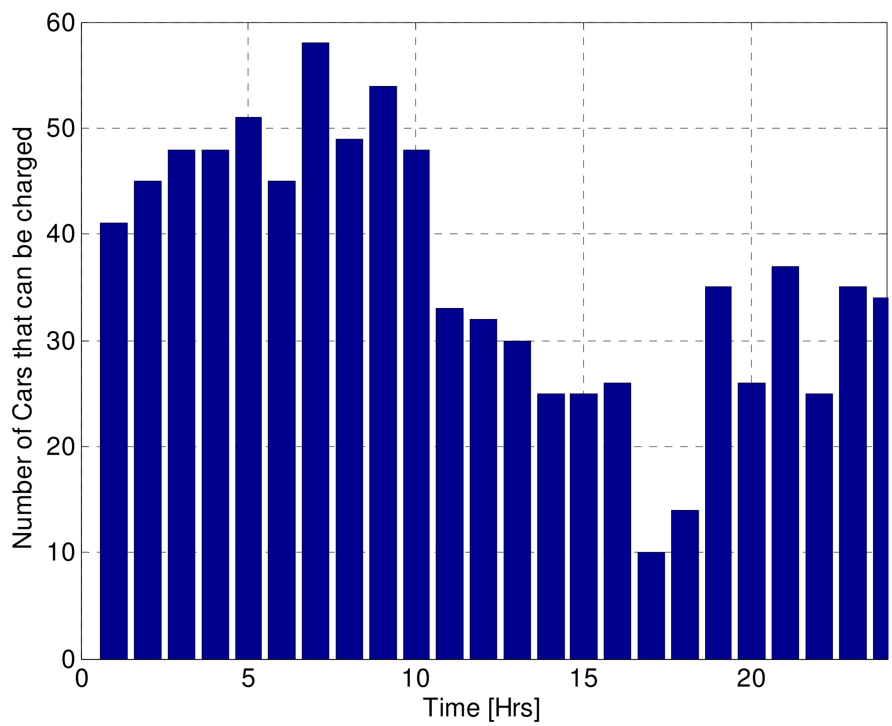


Figure 5.3 Number of vehicles that can be charged in residential complex using Fast Charging based on transformer spare capacity (1000 kVA)

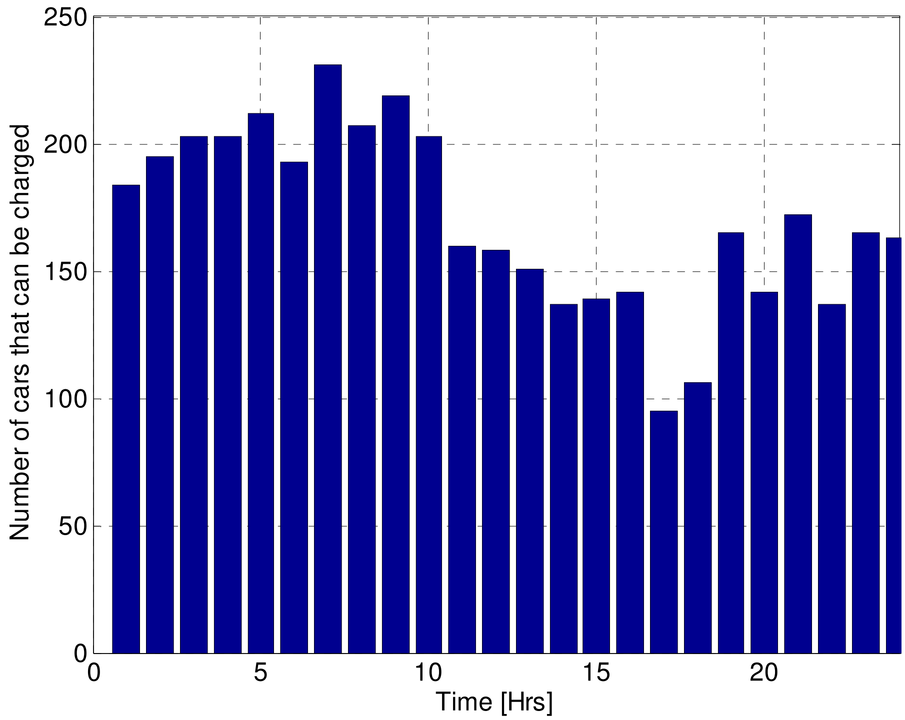


Figure 5.4 Number of vehicles that can be charged in the residential complex using Slow Charging based on transformer spare capacity (1200 kVA)

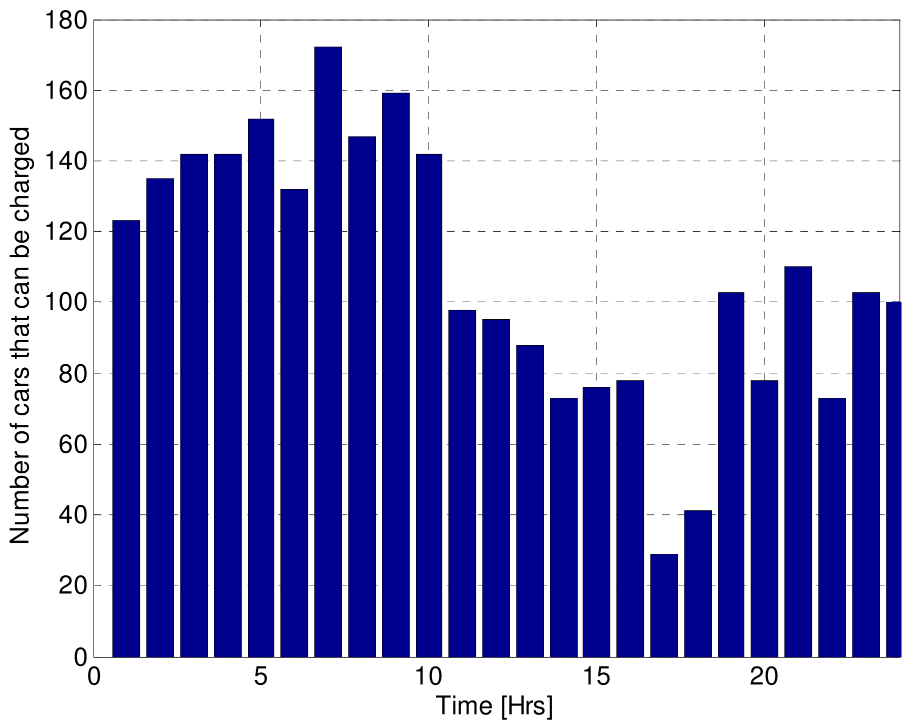


Figure 5.5 Number of vehicles that can be charged in residential complex using Slow Charging based on transformer spare capacity (1000 kVA)

Figures 5.2 – 5.5 present the maximum number of EVs that can be charged during each hour based on the charging method and the available spare capacity in the transformers.

The next step is to find out how many vehicles will be charging in which area during the night hours. For this we need to consider the two cases of EV penetration as defined earlier, 30% penetration and 100 % penetration.

<u>Case 1: 30% EV Penetration</u>

Area R1 has total 210 EVs to be charged distributed over three transformers rated 1200 kVA each. Area R2 has total 210 EVs to be charged distributed over two transformers rated 1200 kVA each and one transformer rated 1000 kVA. Similarly area R3 has 200 EVs to be charged distributed over three transformers rated 1000 kVA each.

Table 5.1 Number of cars charging per hour considering Fast Charging

Time frame	Area R1			Area R2			Area R3		
	LP1	**LP2**	**LP3**	**LP10**	**LP11**	**LP12**	**LP17**	**LP18**	**LP19**
01 – 02	55	55	55	55	55	34	34	34	34
02 – 03	55	55	55	55	55	34	34	34	34
03 – 04	15	15	15	15	15	36	26	26	46
04 – 05	15	15	15	15	15	36	26	26	46
Total	**70**	**70**	**70**	**70**	**70**	**70**	**60**	**60**	**80**

Table 5.2 Number of cars charging per hour considering Slow Charging

Time frame	Area R1			Area R2			Area R3		
	LP1	**LP2**	**LP3**	**LP10**	**LP11**	**LP12**	**LP17**	**LP18**	**LP19**
00 – 01	70	70	70	70	70	70	60	60	80
01 – 02	70	70	70	70	70	70	60	60	80
02– 03	70	70	70	70	70	70	60	60	80
03 – 04	70	70	70	70	70	70	60	60	80
04 – 05	70	70	70	70	70	70	60	60	80
05 – 06	70	70	70	70	70	70	60	60	80
Total	**70**	**70**	**70**	**70**	**70**	**70**	**60**	**60**	**80**

Case 2: 100% EV Penetration

In this case area R1 and R2 have 630 EVs and area R3 has 600 EVs in total. The aim is again to be able to charge all the EVs without overloading the distribution transformer.

Table 5.3 Number of cars charging per hour considering Fast Charging

Time frame	Area R1			Area R2			Area R3		
	LP1	**LP2**	**LP3**	**LP10**	**LP11**	**LP12**	**LP17**	**LP18**	**LP19**
22 – 23	55	55	55	55	55	30	30	30	30
23 – 00	55	55	55	55	55	30	30	30	30
00 – 01	60	60	60	60	60	40	40	40	40
01 – 02	60	60	60	60	60	40	40	40	40
02– 03	65	65	65	65	65	45	45	45	45
03 – 04	65	65	65	65	65	45	45	45	45
04 – 05	30	30	30	30	30	45	45	45	45
05 – 06	30	30	30	30	30	45	45	45	45
06 - 07	-	-	-	-	-	50	40	40	40
07 - 08	-	-	-	-	-	50	40	40	40
Total	**210**	**210**	**210**	**210**	**210**	**210**	**200**	**200**	**200**

Table 5.4 Number of cars charging per hour considering Slow Charging

Time frame	Area R1			Area R2			Area R3		
	LP1	**LP2**	**LP3**	**LP10**	**LP11**	**LP12**	**LP17**	**LP18**	**LP19**
20 - 21	50	50	50	50	50	70	70	70	70
21 - 22	50	50	50	50	50	70	70	70	70
22 – 23	50	50	50	50	50	70	70	70	70
23 – 00	50	50	50	50	50	70	70	70	70
00 – 01	50	50	50	50	50	70	70	70	70

Time frame	Area R1			Area R2			Area R3		
	LP1	**LP2**	**LP3**	**LP10**	**LP11**	**LP12**	**LP17**	**LP18**	**LP19**
01 – 02	50	50	50	50	50	70	70	70	70
02– 03	160	160	160	160	160	140	130	130	130
03 – 04	160	160	160	160	160	140	130	130	130
04 – 05	160	160	160	160	160	140	130	130	130
05 – 06	160	160	160	160	160	140	130	130	130
06 - 07	160	160	160	160	160	140	130	130	130
07 - 08	160	160	160	160	160	140	130	130	130
Total	**210**	**210**	**210**	**210**	**210**	**210**	**200**	**200**	**200**

In case of slow charging, the EVs have to start charging from 20:00 in the evening as this type of charging takes six hours and all the EVs cannot be charged at the same time due to limitation in the transformer capacity. However, a case has been considered where less number of EVs are being charged during the early night hours when the prices are still high and maximum number of EVs are charged during late night hours when the price of electricity is low, the sequence of charging is shown in Table 5.4.

5.2 Modelling of Electric Vehicles

To carry out the study EVs have been modelled as a combination of load and a generator as shown in Figure 5.6.

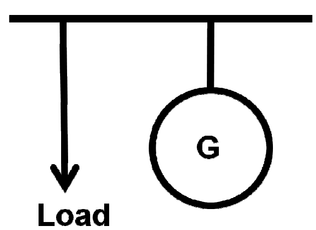


Figure 5.6 Modelling of Electric Vehicles

The load in Figure 5.6 signifies the charging of electric vehicles and is calculated based on the number of electric vehicles charging at any particular hour. The generator part are the vehicles connected to the system, which are capable of providing support to grid. In case of generator, the capacity support that can be provided will depend upon the state of charge of batteries. The reliability of generators in this case has been considered to be 100%. This is a valid assumption as failure of one vehicle will not have any major impact on the capacity of the fleet of vehicles.

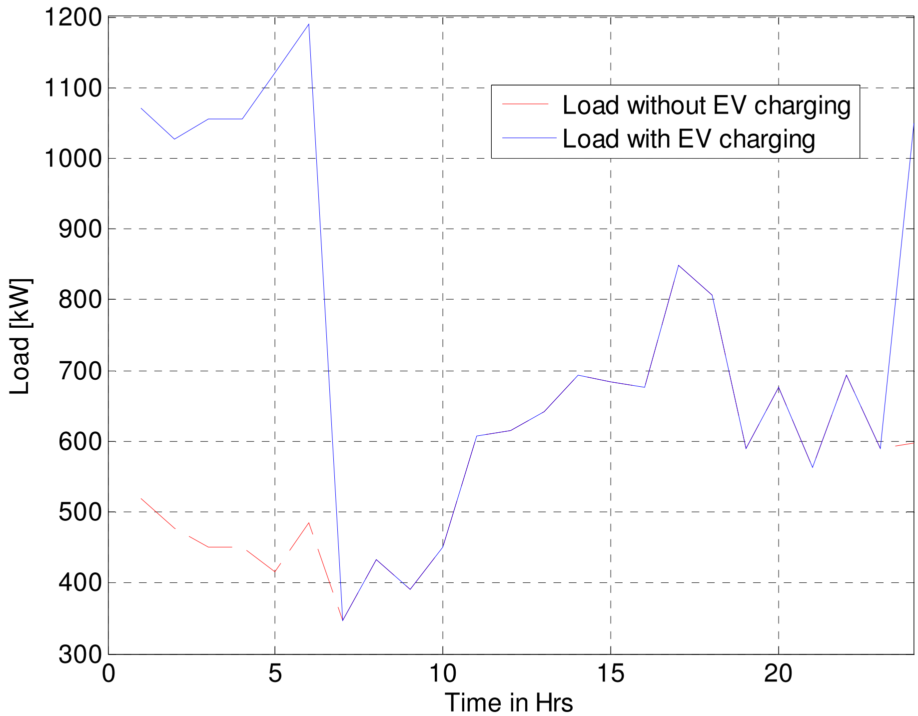
The load at each point has been calculated based on the number of EVs connected during a particular hour. Table 5.5 shows the EV load connected to the residential areas during the period of charging.

Table 5.5 Load of connected EVs sample calculation for load point LP1

Time frame	EV load in area R1 (LP1) considering Fast Charging (100 % EV Penetration) [kW]	EV load in area R1 (LP1) considering Slow Charging (100 % EV Penetration) [kW]
22 – 23	55 * 11 = 605	50 * 3.7 = 185
23 – 00	55 * 11 = 605	50 * 3.7 = 185
00 – 01	60 * 11 = 660	50 * 3.7 = 185
01 – 02	60 * 11 = 660	50 * 3.7 = 185
02 – 03	65 * 11 = 715	50 * 3.7 = 185
03 – 04	65 * 11 = 715	50 * 3.7 = 185
04 – 05	30 * 11 = 330	160 = 592
05 – 06	30 * 11 = 330	160 = 592
06 - 07	-	160 = 592
07 - 08	-	160 = 592

5.3 Load Profile Considering Electric Vehicle Integration

As depicted in Table 5.1 to 5.4 a specified number of vehicles will be charging during the off peak, low cost period at the residential complexes. This will change the load cycle for these areas. As stated earlier in Section 4.5, each vehicle will consume either 11 kW or 3.7 kW from the grid per hour while charging, depending on the type of charging being used. Based on this data the new load curve has been presented in Figure 5.7.



5.7 Load curve with and without EV integration for LP1 with 30% EV Penetration

It can be observed from the Figure 5.7 that the charging of EV is done in such a way that the transformer is never overloaded. Based on this criterion load profile for each load point has been calculated. There are two cases to be considered here, the first without any V2G and one with V2G power flow. In the former case it is assumed that the vehicles are connected to the grid during the day at the commercial complexes but they neither charge nor discharge. In the latter case it is assumed that the EVs connected at the commercial complexes give capacity support to the grid during the day.

5.4 Vehicle to Grid

To calculate the capacity support that can be provided by a fleet of electric vehicles, it is necessary to know the capacity available for supply in the batteries, when it is connected to the system. To achieve this few assumptions have to be made.

The energy available in the EV at any given point of time depends on the following factors:

1. How much has the vehicle travelled from the time when the battery was fully charged?
2. What are the limiting requirements put by the consumer?
3. What are the specifications for the EV?

To answer the first question one has to look at the geography of the current test system and the assumed driving habits of the customers. Tables 3.3.2 and 3.3.3 give details of the number of vehicles coming to each commercial complex during the day and the amount of distance they travel to reach there. The same Tables have been presented here in a different way for easy reference.

5.6 Vehicles coming to each commercial complex for Case 1

Commercial Complex	Area R1		Area R2		Area R3	
	Number of EVs [n]	Distance [km]	Number of EVs [n]	Distance [km]	Number of EVs [n]	Distance [km]
C1	70	19	70	10	60	19
C2	70	20	70	17	60	38
C3	70	38	70	17	80	20

5.7 Vehicles coming to each commercial complex for Case 2

Commercial Complex	Area R1		Area R2		Area R3	
	Number of EVs [n]	Distance [km]	Number of EVs [n]	Distance [km]	Number of EVs [n]	Distance [km]
C1	210	19	210	10	200	19
C2	210	20	210	17	200	38
C3	210	38	210	17	200	20

The following assumptions have been made:

1. The vehicles are charged for 2 hours during the night considering fast charging or 6 hours considering slow charging.
2. Each vehicle has a travelling distance of maximum 128 km.
3. The total energy of the battery has been considered as 24.1 kWh.
4. The average energy consumption of EV is 0.17 kWh/km.

To calculate the energy left in the battery the following method has been used:

Energy Available in EV:

From the data available, it is known that the EV has been charged so that it can travel a maximum of 128 km. The energy used in travelling 1 km is 0.17 kWh. Hence the calculated maximum energy available in the EV can be calculated as follows:

Energy Available in EV before travel = D_{max} * E1

Where,

D_{max} = Maximum Distance that can be travelled

E1= Energy required to travel 1 km

Energy Available in EV after travel = Ebt – Eut

Where,

Ebt= Energy Available in EV before travel

Eut= Energy used by EV for travelling

Energy Used for Travelling:

The energy used in travelling can be calculated using the simple equation as follows:

Energy Used in Travelling = D * E1

Where,

D= Distance Travelled

Spare Energy Required:

The spare energy required in the EV depends on customer preference. In worst case scenario the customer might not be willing to provide energy to the grid. However, an assumption has been made here for the purpose of study as follows:

Spare Energy Required = 25% of maximum capacity + Enb

Where,

Enb= Energy required to travel back

Capacity Available For Supply:

The capacity available for supplying back to the grid can be calculated as follows:

Capacity Available =Eat – SpCap

Where,

Eat= Energy Available in EV after travel

SpCap = Spare Capacity required

Based on the assumptions and calculations above, Table 5.4.3 gives the energy that will be available in the electric vehicles when connected at the commercial complexes.

- Energy available in EV before travel – 21.76 kWh
- EVs travelling from R1 to C1 - distance of travel is 19 km
- Energy used in Travelling – 3.23 kWh
- Energy available after travel – 18.53 kWh
- Spare energy required – 8.67 kWh
- Capacity available for supply – 9.8 kWh

5.8 Energy available in EV for supply to grid for Case 1

Commercial Complex	Area R1		Area R2		Area R3	
	Number of EVs [n]	Capacity Available in each EV [kWh]	Number of EVs [n]	Capacity Available in each EV [kWh]	Number of EVs [n]	Capacity Available in each EV [kWh]
C1	70	9.8	70	11.39	70	9.8
C2	70	9.6	70	10.2	70	6.6
C3	70	6.6	60	10.2	80	9.6

Based on Table 5.8 the total energy available in each commercial complex has been estimated and presented in Table 5.9.

5.9 Total energy available from EVs in the commercial complexes for Case 1

Commercial Complex	Total Energy Available [kWh]
C1	2169
C2	1848
C3	1842

5.10 Energy available in EV for supply to grid for Case 2

Commercial Complex	Area R1		Area R2		Area R3	
	Number of EVs [n]	Capacity Available in each EV [kWh]	Number of EVs [n]	Capacity Available in each EV [kWh]	Number of EVs [n]	Capacity Available in each EV [kWh]
C1	210	9.8	210	11.39	200	9.8
C2	210	9.6	210	10.2	200	6.6
C3	210	6.6	210	10.2	200	9.6

5.11 Total energy available from EVs in the commercial complexes for Case 2

Commercial Complex	Total Energy Available [kWh]
C1	6410
C2	5478
C3	5448

The aggregator will be responsible to use the energy available in EVs. In ideal situation the energy will be used to supply back to the grid when the price is high giving maximum benefit to the customers. In this study it is considered that the stored energy available in the EV will be used during the day, when the price of electricity is high. This would be the ideal situation for the use of energy from the EV. Table 5.12 and 5.13 show how the energy is distributed over these three hours.

Table 5.12 Distribution of energy available in EV over a period of three hours (Case 1)

Commercial Complex	Energy Used between 10:00 – 11:00 [kWh]	Energy Used between 11:00 – 12:00 [kWh]	Energy Used between 12:00 – 13:00 [kWh]
C1	763	763	763
C2	546	546	546
C3	531	531	531

Table 5.13 Distribution of energy available in EV over a period of six hours (Case 2)

Commercial Complex	Energy Used between 10:00 – 11:00 [kWh]	Energy Used between 11:00 – 12:00 [kWh]	Energy Used between 12:00 – 13:00 [kWh]	Energy Used between 13:00 – 14:00 [kWh]	Energy Used between 14:00 – 15:00 [kWh]	Energy Used between 15:00 – 16:00 [kWh]
C1	1068	1068	1068	1068	1068	1068
C2	913	913	913	913	913	913
C3	908	908	908	908	908	908

The number of EVs are less in Case-1 compared to Case-2. For this reason the total energy in Case-1 is distributed over a period of three hours, whereas for Case-2 it is distributed over a period of six hours.

5.5 Results of Application

Various kinds of studies can be performed with the test system described above. In this case analysis has been done to assess the effect of V2G supply on the ENS. Two cases have been considered here, one with V2G supply and one without V2G supply for individual complexes and the effect of V2G supply on the ENS of entire system has been studied for case with fast charging and slow charging.

Case 1: 30 % EV penetration in to EDS

Figure 5.8 shows the ENS for the commercial complexes without any V2G supply. Figure 5.9 shows the ENS for the commercial complexes with V2G supply. As can be observed from these Figures the value of ENS is reduced in case of V2G supply.

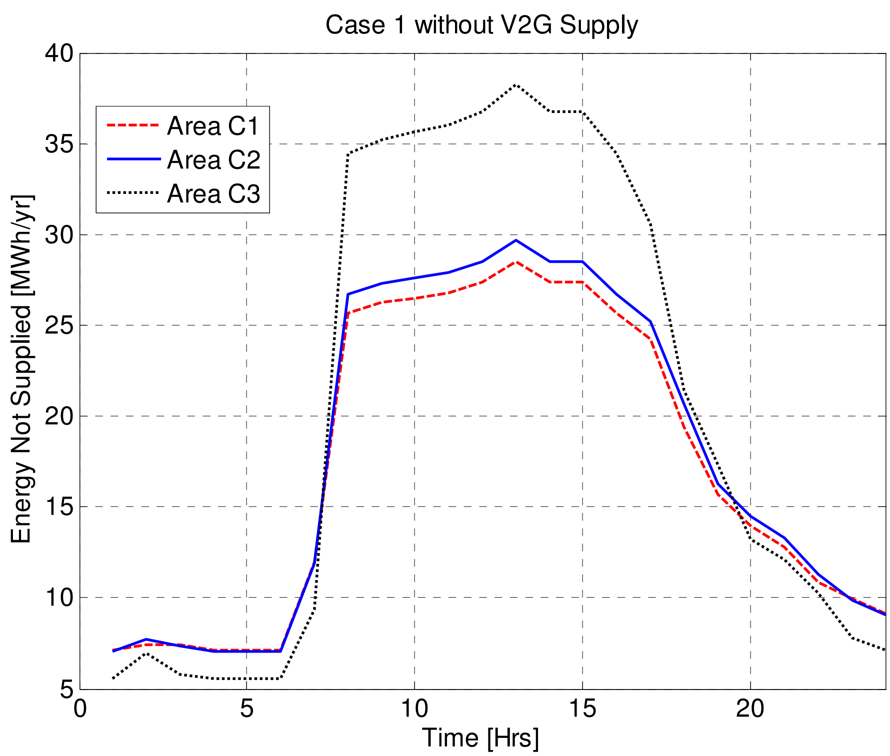


Figure 5.8 ENS for Commercial Complexes (Case 1 without V2G Supply)

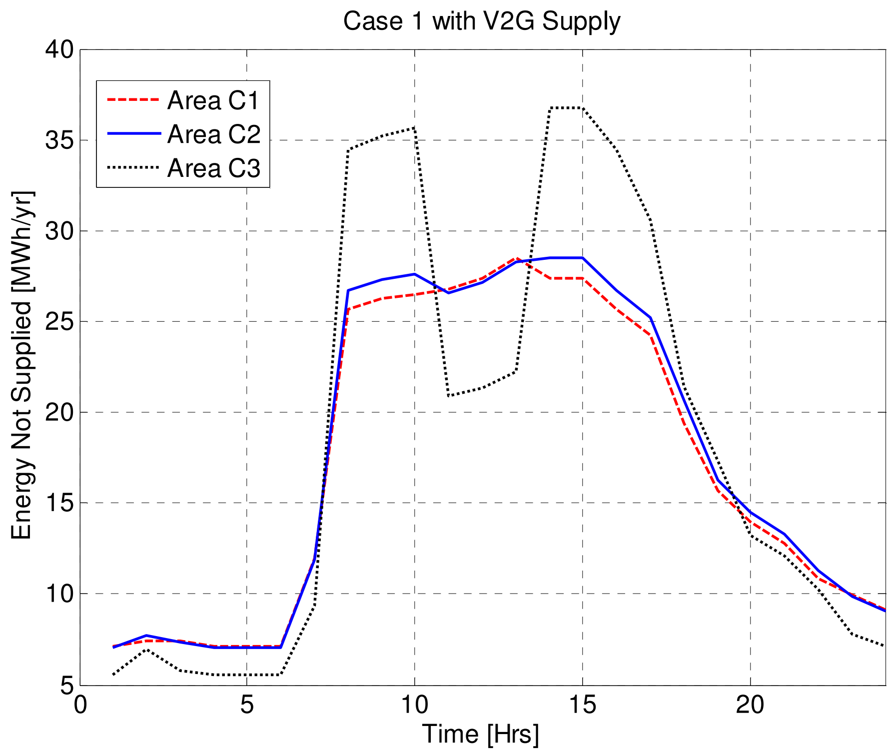


Figure 5.9 ENS for Commercial Complexes (Case 1 with V2G Supply)

Figure 5.10 shows the ENS for entire system with and without V2G supply, when the case of fast charging is considered for 30% EV penetration into the EDS. Average value for ENS for a load variation over one day is presented as below:

Average ENS without V2G = 108 MWh/yr

Average ENS with V2G = 105 MWh/yr

There is cost associated with this ENS. As mentioned in Figures 3.6 and 3.7 two cost curves have been considered one showing the variation of cost in winter and the other showing variation in summer over a period of one day.

Average Cost of ENS during summer period without V2G = 3280 Euros

Average Cost of ENS during summer period with V2G = 3178 Euros

Average Cost of ENS during winter period without V2G = 4306 Euros

Average Cost of ENS during winter period with V2G = 4200 Euros

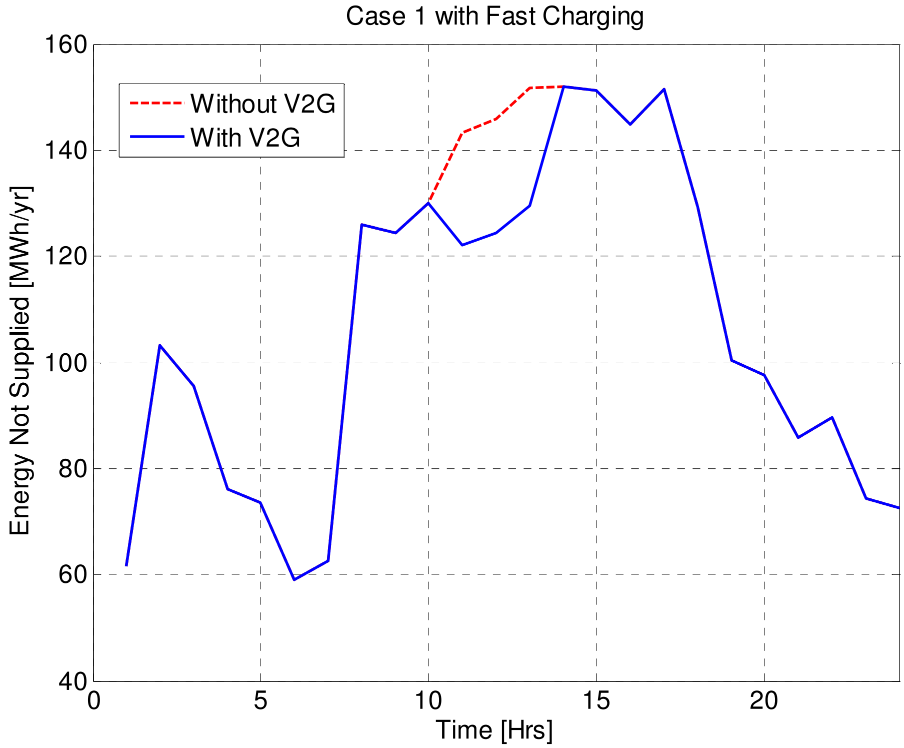


Figure 5.10 ENS for Total System (Case 1 Fast Charging)

Figure 5.11 shows the ENS for entire system with and without V2G supply, when the case of slow charging is considered with 30% of EV penetration into the EDS. Average value for ENS for a load variation over one day is presented as below:

Average ENS without V2G = 109 MWh/yr

Average ENS with V2G = 106 MWh/yr

There is cost associated with this ENS. As mentioned in Figures 3.6 and 3.7 two cost curves have been considered one showing the variation of cost in winter and the other showing variation in summer over a period of one day.

Average Cost of ENS during summer period without V2G = 3329 Euros

Average Cost of ENS during summer period with V2G = 3327 Euros

Average Cost of ENS during winter period without V2G = 4326 Euros

Average Cost of ENS during winter period with V2G = 4220 Euros

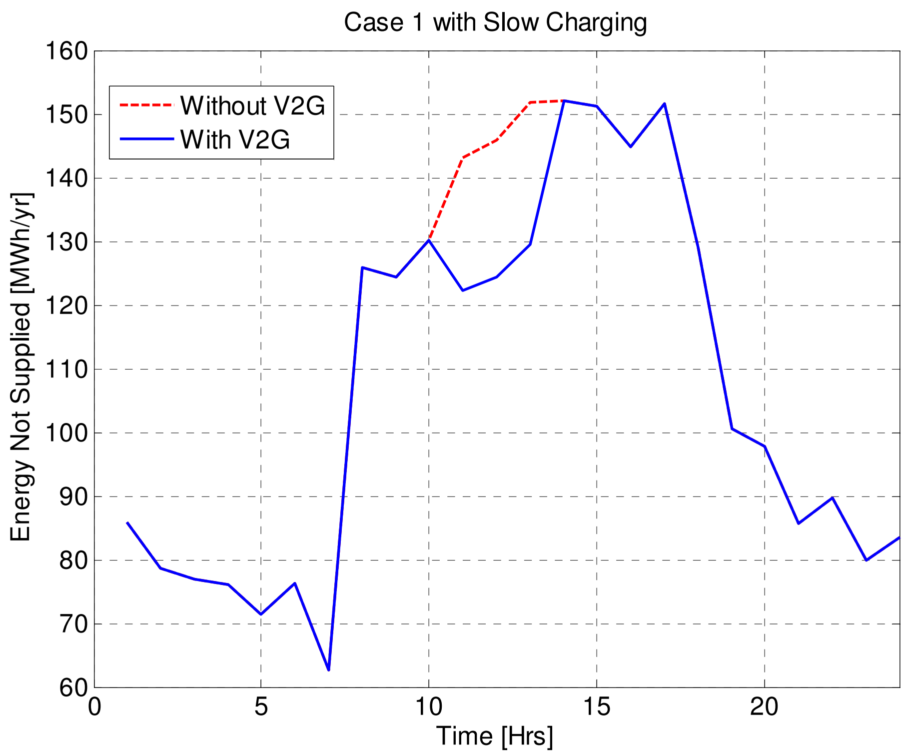


Figure 5.11 ENS for Total System (Case 1 Slow Charging)

<u>Case 2: 100 % EV penetration in to EDS</u>

Figure 5.12 shows the ENS for the commercial complexes without any V2G supply. Figure 5.13 shows the ENS for the commercial complexes with V2G supply. As can be observed from these Figures the value of ENS is reduced in case of V2G supply.

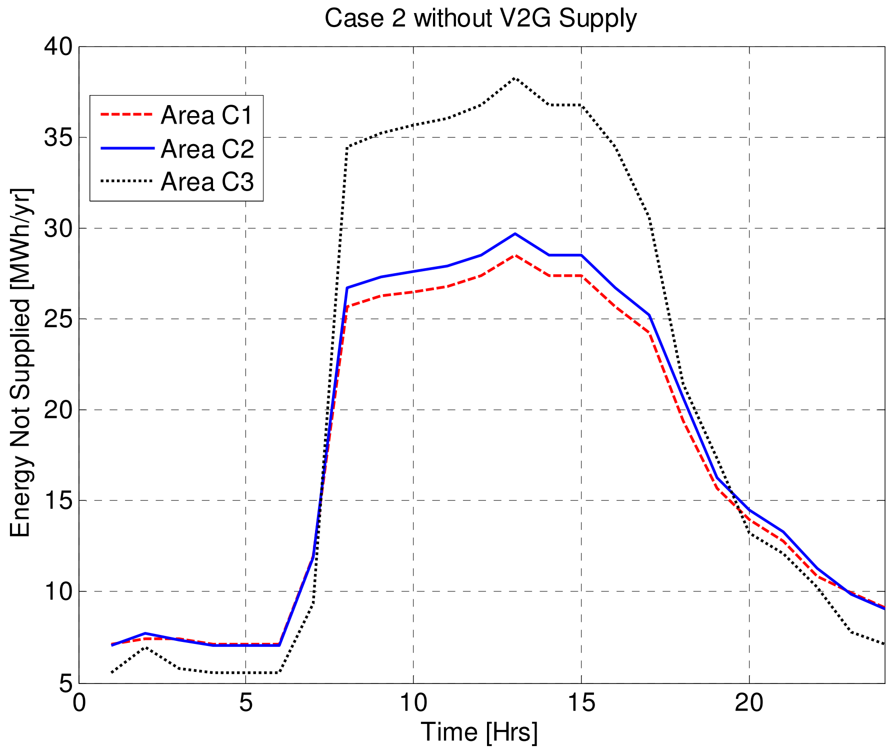


Figure 5.12 ENS for Commercial Complexes (Case 2 without V2G Supply)

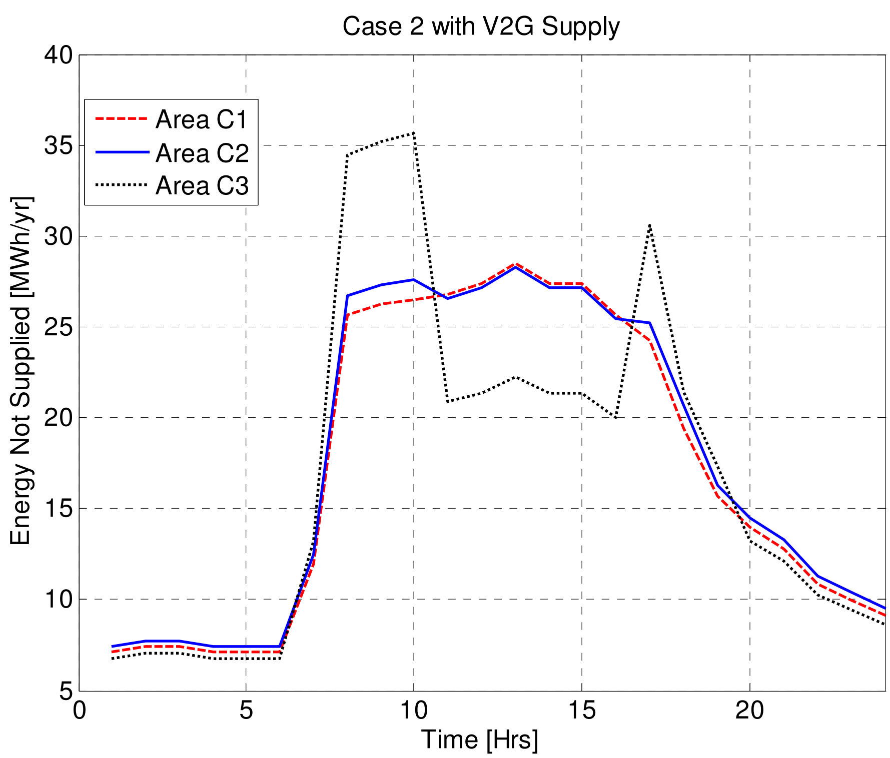


Figure 5.13 ENS for Commercial Complexes (Case 2 with V2G Supply)

Figure 5.14 shows the ENS for entire system with and without V2G supply, when the case of fast charging is considered for 100% EV penetration into the EDS. Average value for ENS for a load variation over one day is presented as below:

Average ENS without V2G = 120 MWh/yr

Average ENS with V2G = 114 MWh/yr

There is cost associated with this ENS. As mentioned in Figures 3.6 and 3.7 two cost curves have been considered one showing the variation of cost in winter and the other showing variation in summer over a period of one day.

Average Cost of ENS during summer period without V2G = 3508 Euros

Average Cost of ENS during summer period with V2G = 3307 Euros

Average Cost of ENS during winter period without V2G = 4768 Euros

Average Cost of ENS during winter period with V2G = 4554 Euros

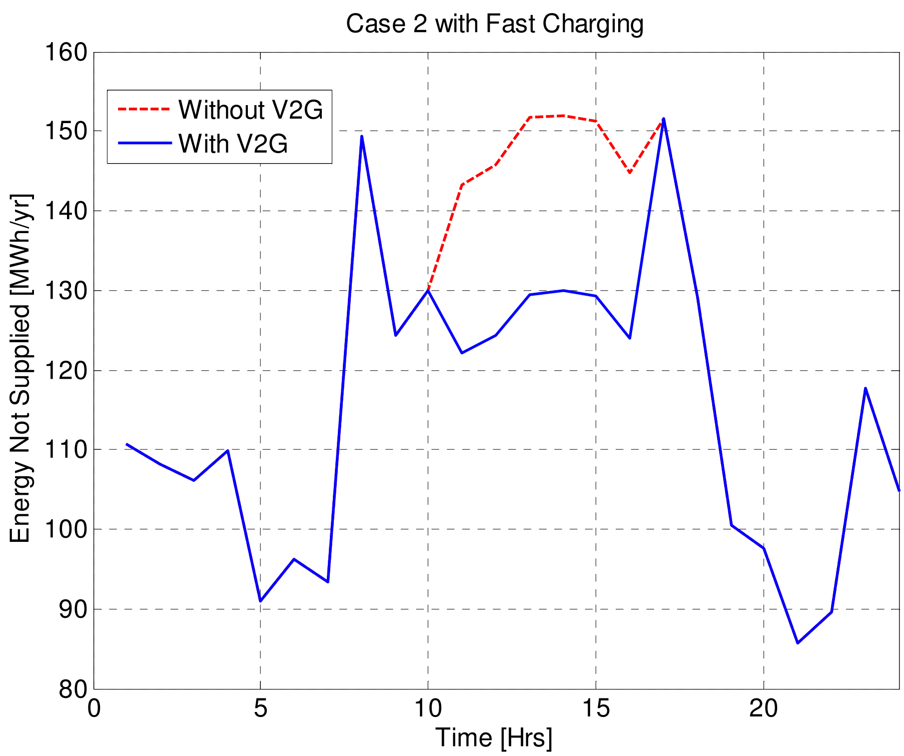


Figure 5.14 ENS for Total System (Case 2 Fast Charging)

Figure 5.15 shows the ENS for entire system with and without V2G supply, when the case of slow charging is considered for 100% EV penetration into the EDS. Average value for ENS for a load variation over one day is presented as below:

Average ENS without V2G = 120 MWh/yr

Average ENS with V2G = 115 MWh/yr

There is cost associated with this ENS. As mentioned in Figures 3.6 and 3.7 two cost curves have been considered one showing the variation of cost in winter and the other showing variation in summer over a period of one day.

Average Cost of ENS during summer period without V2G = 3472 Euros

Average Cost of ENS during summer period with V2G = 3270 Euros

Average Cost of ENS during winter period without V2G = 4780 Euros

Average Cost of ENS during winter period with V2G = 4565 Euros

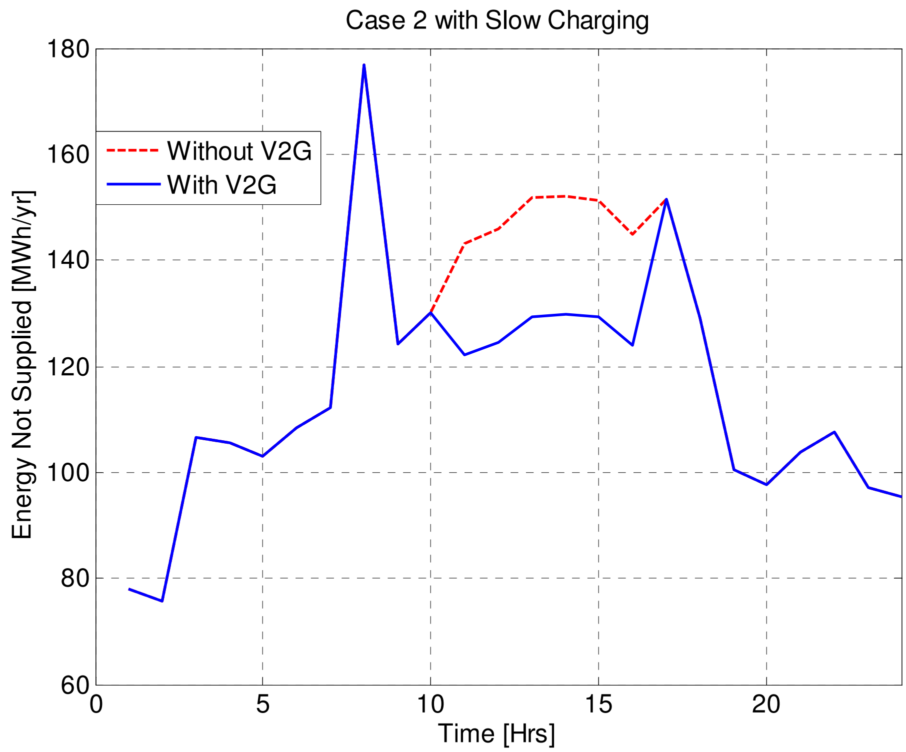


Figure 5.15 ENS for Total System (Case 2 Slow Charging)

5.6 Conclusion and Summary of Results

The extended test system has been used here to perform a sample study. The study focuses on finding out the variation in value of ENS for different conditions and the cost associated with the same. The different cases considered are fast charging and slow charging and two different cost one for summer and the other for winter are considered. It has been assumed in this study that during the summer the cost of electricity is low and the variation during the day is large and the winter costs are high and the variation of cost is not large. These are two extreme cases considered to analyze the effect of cost variation on the system.

Table 5.14 presents the summary of results. A variety of conclusions can be drawn from the same. The potential saving in case of 30% EV penetration is not significant even when the prices are high. This means that the investment in infrastructure for V2G will have a long return period. However, a significant increase in the potential saving is seen when the penetration of EVs has reached a full 100%.

Table 5.14 Summary of results for the conducted study on the extended RBTS Test System

Study Case		Av. ENS w/o V2G [MWh/yr]	Av. ENS with V2G [MWh/yr]	Av. Cost of ENS Summer w/o V2G [Euros]	Av. Cost of ENS Summer with V2G [Euros]	Potential Saving [Euros]	Av. Cost of ENS Winter w/o V2G [Euros]	Av. Cost of ENS Winter with V2G [Euros]	Potential Saving [Euros]
Case 1	Fast Charging	108	105	3280	3178	2	4306	4200	106
	Slow Charging	109	106	3329	3327	2	4326	4220	106
Case 2	Fast Charging	120	114	3508	3307	201	4768	4554	214
	Slow Charging	120	115	3472	3270	202	4780	4565	215

6 Chapter Five

6.1 Proposed Extensions to the Test System

Chapters 3 and 4 describe the proposed extensions to the distribution test system. These extensions and the assumptions considered therein are presented here as a summary.

A. <u>Extensions to RBTS:</u>

1. Geography for the test system has been proposed. A simple geography is assumed with flat land profile. Distances between different complexes have been defined. The geography of the test system has been presented in Figure 4.3.
2. Grouping of loads as per geographic location has been done. The loads have been grouped into different categories. The main categories are residential loads and commercial loads. There are three groups of residential loads R1, R2 and R3 and three groups of commercial loads C1, C2 and C3. Each group of loads has different load points as defined in Table 4.2. The rating of distribution transformers has been given for each load point and provided in Table 4.2. Two cost curves have been provided with cost variation over a period of one day. One of the cost curve is for cost of electricity during the winter season and the other is during summer season.
3. Load curve for both the residential and the commercial complexes has been defined over a period of 24 hours.
4. Different types of EVs have been defined and an average battery size has been provided. Based on this average battery size the two charging scenarios have been defined. Fast charging and slow charging. The power drawn and the time taken for the batter to attain full charge have been provided. Number of EVs within the test system has been defined. Two cases have been considered with 30% EV penetration and 100% EV penetration. The first case considers that 30% of the total customers have some kind of electric vehicle and the second case considers that all the customers have electric vehicles.

B. <u>Assumptions done for sample study to Extended RBTS test system:</u>

1. Coordinated charging of EVs has been considered and the philosophy for such charging is defined. The number of EVs charging in each hour for 30% and 100% penetration case for both fast and slow charging has been provided.
2. A simple model for electric vehicles has been presented. An assumption is made that the reliability of a fleet of vehicles is 100%, as the failure of one vehicle will not affect the capacity of entire fleet of vehicles.
3. Depending on the driving habits of customers the energy available in EVs for supply to grid, when parked at the commercial complexes has been calculated.
4. It is assumed that the capacity support provided by EVs is distributed evenly over a period of three hours for 30% penetration case and a period of six hours for 100% penetration case. This can vary depending on the philosophy adopted by the user. Relevant data for such a variation has been provided.

6.2 Conclusion and Future Work

Huge impetus is being given to electric vehicles as it presents a carbon free form of transportation. In such a scenario analyzing the effect of integration of huge number of electric vehicles in to the grid is of prime importance. An effort has been made to define a simple electrical distribution test system with integration of EVs. The existing electrical distribution test system within RBTS has been adopted for the study and extensions made to the same. The system has been kept simple and flexible so as to give opportunity to make changes easily for different kinds of studies.

Various kinds of studies can be performed with the test system. However, a sample reliability study has been performed on the extended test system and the results of the same have been presented in the report.

A future work in this direction could be to integrate distributed wind power generation in the test system. This would enable one to see the usefulness of EVs as energy storage devices.

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