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Plug-in Hybrid Electric Vehicles and Distributed Generations in Power Systems: Effects and Penetration Level Studies

Master of Science Thesis in Electric Power Engineering

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Göteborg, Sweden, 2010

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Abstract

Major part of this master thesis deals with impact of plug-in hybrid electric vehicles (PHEVs) on the power system. First a brief review of the technical challenges in the power system due to mass introduction of the PHEVs in the transmission sector is given. Then the Master thesis shows on an analysis of the overloading effects of PHEVs on the distribution system with normal charging and quick charging of PHEVs for an IEEE 13-node distribution test system using power flow analysis. The results of the study on the IEEE 13-node distribution test system show that introduction of PHEVs in the transportation sector will lead to overloading of distribution system and cause voltage problems at the end-users. Then the impact of PHEVs is tested on a real distribution network in Gothenburg. Two areas have been selected one commercial and one residential area. In the 400 V network, there is a few numbers of overloaded line due to PHEVs charging while the under voltage effect on the end users is negligible providing that voltage of main busbar set higher than 1 pu which is the real case. In the real sample 10 kV network in the Gothenburg, where, there are number of 10 to 0.4 kV substations that are supplying vehicles with required charging power besides their regular daily load, over loading of line is observed at peak load. Then maximum possible vehicles that can be charged without any violations in a reliable manner is calculated both for residential and commercial areas.

The Master thesis also analyzes the effects of PHEVs in the transmission system, using one test transmission network (10-Bus transmission system) and the Nordic 32-bus test system. The study results show that the overloading problem is not prominent. Introduction specific penetration of vehicles leads to under voltage in the 10-Bus transmission test system, while one interesting and important result happens in the Nordic 32-bus test system and that is PHEVs may lead to over voltages in some buses in the transmission system which requires the voltage control measures. PHEVs would also lead to increased number of network violations in the contingency analysis.

The Master thesis also analyzes maximization of the DGs penetration in the existing distribution networks. First a brief review of voltage rise effect in the networks equipped with DGs is given. Then this effect is simulated on the modified IEEE 13-Nodes test system and finally one nonlinear programming with GAMS is presented to maximize DGs penetration in the lightly load distribution network with Power curtailment as a solution to mitigate over voltage.

Keywords: PHEV, simulation, distribution network, transmission network, charging, violation, iterative method, distributed generation, voltage rise effect.

Preface

This work has been done at the Division of Electric Power Engineering, Department of Energy and Environment at Chalmers University of Technology.

I would like to express my sincere gratitude to my supervisor and examiner Dr. Tuan le for doing this master thesis. He gave me valuable help and direction during this work. I gratefully thank David Steen for providing me with required data and also giving me direction in one Chapter of this master thesis. I would like to thank all the people at Master thesis room for providing really nice and friendly atmosphere specially my friend Francisco Montes for his kind help whenever I had problem with one of my software.

My last and most gratitude goes to my parents, Ali Babaei and Nahid Chaparchi, because of their endless love, patient and support.

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Chapter 1

1. Introduction

1.1.Background and Motivations

High penetration of plug-in hybrid electric vehicles (PHEVs) in the transportation sector will likely be envisioned by the transportation authority as well as energy authority in many parts of the world, e.g., European countries, Japan, and the USA. The benefits from replacing the conventional internal combustion vehicles by the PHEVs are the subjects of many current research and mass-media because the transport sector is one of the largest and fastest growing contributors to energy demand, urban air pollution, and greenhouse gases (GHGs) [1].The possibility to reduce the dependency on oil consumption by the transportation sector and the possibility to reduce harmful environmental emissions, e.g., CO2, SOx, and NOx by ways of improved conversion efficiency through PHEVs are the key socio-economical and environmental benefits. Given the said benefits, critics have warned that the vehicles could put too much pressure on already strained power grids. The concern is that plug-ins may not appear to be a good way to reduce gasoline consumption, because if they become popular, and millions of car owners recharged their cars at three in the afternoon on a hot day, it would crash the grid. Specially, uncontrolled charging can lead to grid problem on the local scale [2]. Main part of the master thesis deals with the central question: "are the existing power system infrastructures and power system engineers ready to "electrically fuel" the new fleets of PHEV in the foreseeable future?". It is hard to say anything as to whether our power system will be able to take on the increased load from PHEVs without having to be upgraded/modified. PHEVs will be a load when it charges current from the grid, but an interesting and attractive feature of PHEV from the grid operation point of view is that it can also serve as energy storage to provide additional reserve power in contingency situation [3]. PHEVs are claimed to be able to support the power system in several ways such as peak demand generation acting as spinning reserves and regulations [4], [5]. The organization of thesis master thesis is as follow: the next section will provide a comprehensive study of effects of PHEVs on the distribution network. The study will be done on an IEEE 13-Nodes test system and also on a real distribution network in the Gothenburg city using Power World [6] as a simulator. Second part will deal with effect of charging vehicles on the transmission system and investigation will be done on two sample network i.e. Nordic 32-Bus system and also 10-Bus test system. Last part of this master thesis will briefly deal with maximizing the DGs penetration in the distribution network.

Chapter 2

2. Effects of PHEVs on the Distribution Networks

2.1. PHEVs in the Power Systems: A Brief Review

As highlighted in the previous section, PHEVs have the potentials to contribute to reduce the environmental emissions from the transportation sector. However, it will likely pose new challenges in the power system, especially in the power distribution system where the vehicles are directly connected to. This section will highlight those challenges and effects.

Fig. 1 shows the effects of PHEVs on the power systems, and categorizes the problems at different levels, i.e., at system level, distribution system level, and transmission system level. The key question being asked today is how the power system sees the increase in its total loads when high level of PHEVs will be used in the near future. This is largely dependent on the charging habits which will be practiced by the users of PHEVs. As shown in Fig. 1, even though the PHEVs are connected in low voltage distribution system, they also have large effects on the generation system and transmission system levels.

If the vehicle users are free to charge their cars anytime they want (uncontrolled charging), one can easily say that they will plug in at peak loads. In this case, PHEV increases the system peak loads which require additional generation (and transmission) capacity. A new dimension of peak load capacity for the power system might be required if the charging of PHEV is left uncontrolled. On the other hand, if controlled charging is used, which means that the utility controls charging between, for example, 10:00 pm and 07:00 am. In this case the system load profile will be improved in a way similar to the effect of "valley filling" demand-side management measure, meaning that the system utilization can be improved.

PHEVs would result in the changes in the system load shapes which in turn would result in changes in power generation mixes, changes in electricity prices as well as the CO2 emission level from power production. PHEVs are connected to the power systems at low voltage power distribution system level, i.e., at the end-user sides. Potential problems with distribution system include the overloading of distribution feeders when many PHEVs charge at the same time and at the same area. Overloading of feeders are normally associated also with the large voltage drop over the feeders which makes the voltage at end-users lower than minimum acceptable voltage. This will lead to necessity to upgrade substations earlier than expected because of charging, but there could also be the need to change or modify the existing protection systems. Normally, in distribution system, the power flow is uni-directional from medium voltage (MV) grid to low voltage (LV) grid. However, when PHEVs functions as the energy storage and inject the current into the grid, which is known as vehicle-to-grid (V2G), bidirectional power flow would take place within a certain area. Therefore, setting of relays in the LV and MV level may have to be changed because they might trip under normal working conditions when power should be provided from the LV to the MV level. Depending on the design of charging system, either it is one-phase charging or three-phase charging, the load unbalance might occur with the one-phase charging if the distributions of PHEVs between the phases are unequal. A more comprehensive review of the effects of PHEVs on the power systems can be found in [7].

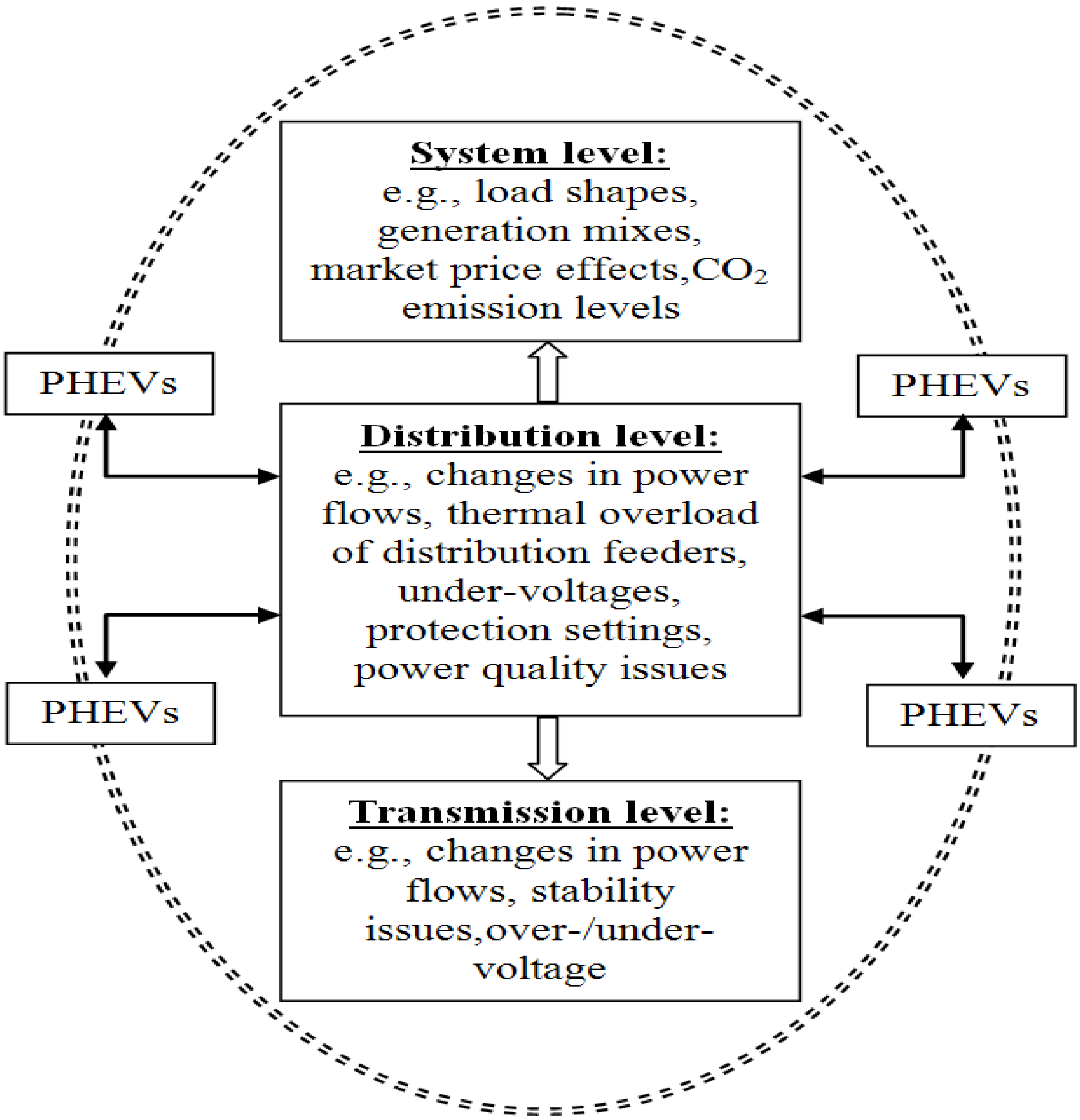

Figure 1: Overview of possible effects of PHEVs on power systems

The above mentioned problems, however, are dependent on the characteristics of the grid in question, number of PHEVs in the areas, types of charging, time of charging, and so on. More specific research would have to be done in order to answer specific questions related to each grid. The next section will provide a specific analysis of the effects of PHEVs on the IEEE Test Distribution System and a real distribution network in the Gothenburg. The effects will be focused on the overloading of the distribution feeders and the voltage problems at the customers position.

2.2. Effect analysis of PHEVs on the IEEE 13 –Node test distribution systems

For better investigation of the effects of PHEVs on the distribution network, charging of the vehicles has been simulated on the modified IEEE 13-Node test system with specific load profile. Both quick and normal charging has been considered at this part.

2.2.1. Description of IEEE 13 –Node test distribution systems

Fig. 2 shows the single line diagram of the IEEE 13-Node Test Feeder [8]. This test system includes

- 13 buses with voltages of 115KV, 4.16KV and 0.48 KV.
- 9 loads
- 2 transformers.
- 2 capacitors at bus 611 and 675.

Bus number 693 has been added just for connecting transformer to the line. 9 other loads have been added to the test system for simulating the PHEVs.

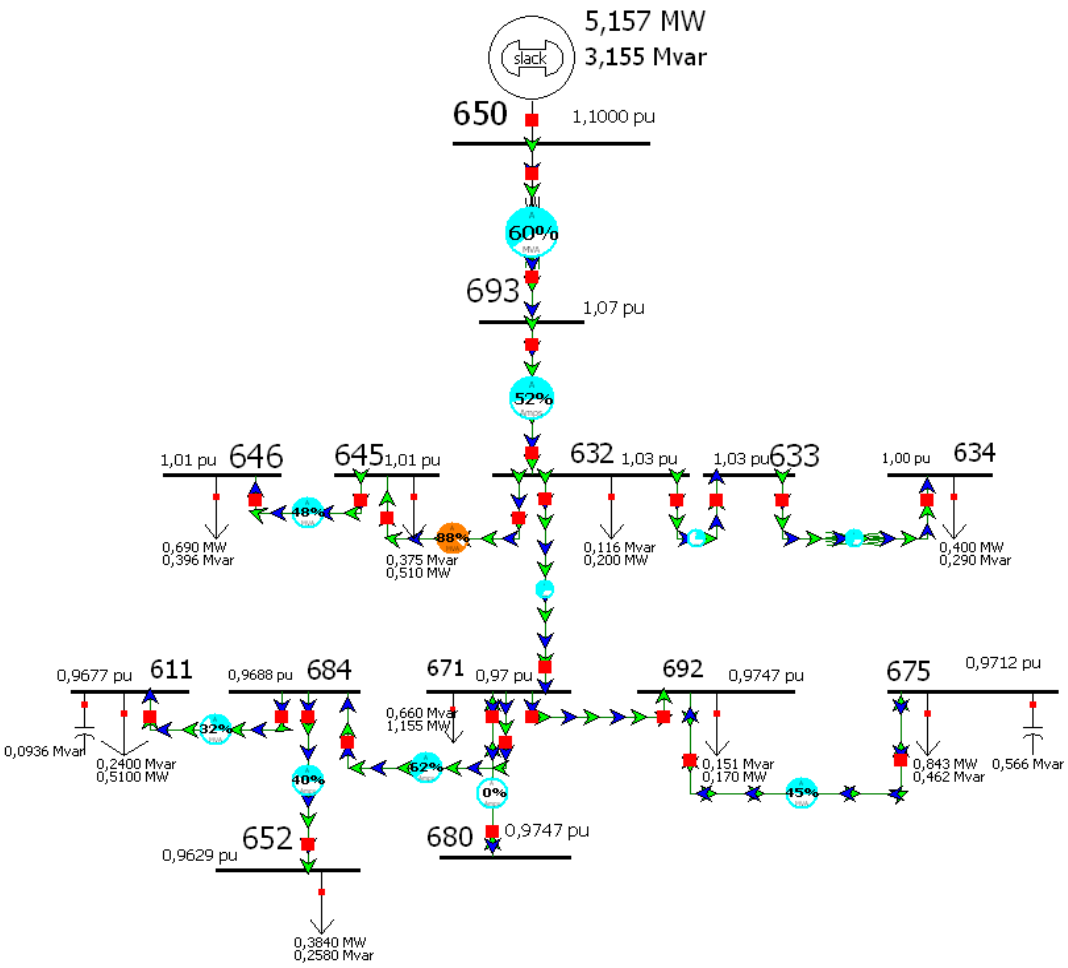

Figure 2: IEEE 13-Node test system without PHEVs.

The system is appropriately modified to simulate distribution supply system for a small residential area. The data has been modified in order to use three-phase power flow analysis software Power World. Table 1 shows the lines resistances and reactances. The Z_{base} for the 4.16 kV network is 0.173Ω and for 115 kV is 132.25 Ω.

Table 1: Lines impedances

Node A	Node B	Total Resistance in ohm	Total reactance in ohm	Total R in PU	Total X in PU
632	645	0.13	0.13	0.73	0.74
632	633	0.01	0.04	0.09	0.23
633	634	0.00	0.00	0.00	0.00
645	646	0.08	0.08	0.44	0.44
650	632	0.13	0.38	0.76	2.22
684	652	0.20	0.08	1.17	0.45
632	671	0.13	0.38	0.76	2.22
671	684	0.07	0.08	0.43	0.44
671	680	0.07	0.19	0.38	1.11
671	692	0.00	0.00	0.00	0.00
684	611	0.02	0.06	0.11	0.33
692	675	0.08	0.05	0.44	0.28

For having a load profile for all 24 hours of a typical day, the load of the different busses of the IEEE 13 busses network have been multiplied by a series of 24 numbers each between 0 and 1, corresponding to hours of a typical day. This series of 24 numbers has been obtained by dividing each hour load by the maximum load of a typical load profile according to [9] . Figure 3 shows how this load profile looks like for a typical day. The power flow analysis for this system is done using the Power World Simulator. In this network, the maximum load is 4.82 MW at 6:00 PM and minimum load is 3.02 MW at 3:00 AM. It is assumed that this network supplies a residential area. According to [10] and [11], each 25 kVA distribution feeder can approximately serve 4 houses and it can be assumed that every 4 houses will own 2 PHEVs. From this assumption, the number of PHEVs at each bus will be calculated as in (1):

$$(1).\ \boldsymbol{N_{PHEV}} = \frac{\mathbf{Smax}}{\mathbf{25}} \times \mathbf{2}$$

Where:
N_{PHEV}: Estimated number of PHEVs at each bus
S_{max}: Maximum supplied kVA at each bus

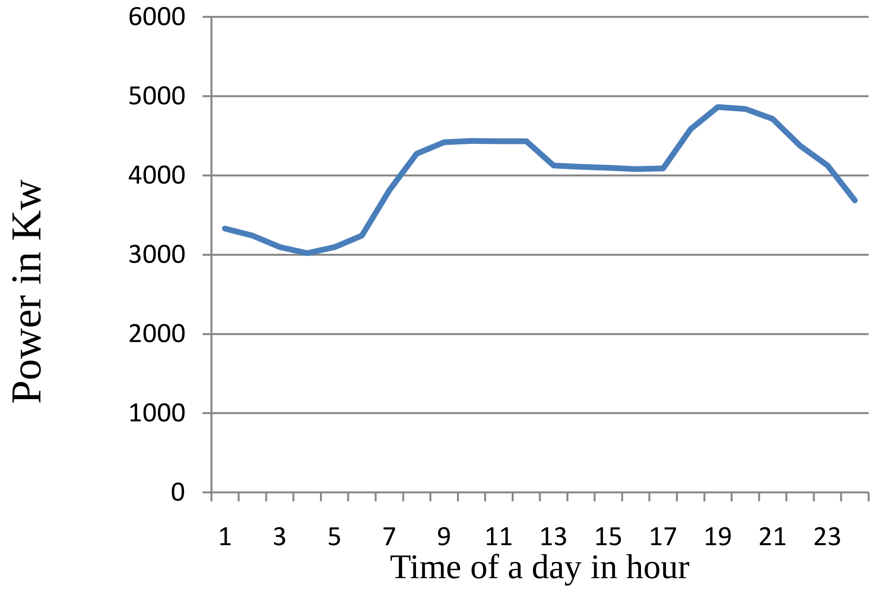

Figure3: Test system Load profile of a typical day.

The PHEV for this investigation is Chevy Volt. Chevy Volt is equipped with a Lithium Ion Battery [12]. In principle there are two methods of charging: normal charging and quick charging.

A Chevy Volt usually uses 50-60% of the battery to travel 40 miles in all electric modes. Assuming that each PHEV commutes a round trip of 40 miles 5 days a week then it will require a full recharge of around 10 KWh on each day [5]. Based on the calculation in the [11] the lithium Ion battery of a Chevy volts draws 1.45 KW in 6 to 6.5 hours in normal charging and also absorbs about 5.8 KW in around 1.7 hour for quick charging after a round trip of 40 miles. The efficiency of 87% is assumed for the whole charging process [10].

The following four different cases have been considered in this study:

- Business as usual (BAU): System at peak load without PHEVs.
- Normal charging, peak load: BAU with PHEVs normal charging.
- Quick charging, peak load: BAU with PHEVs quick charging.
- Quick charging, min load: System at min load with PHEVs quick charging.

Figure 4 indicates how the simulation file looks like. The upward loads simulate the PHEVs which are connected to grid.

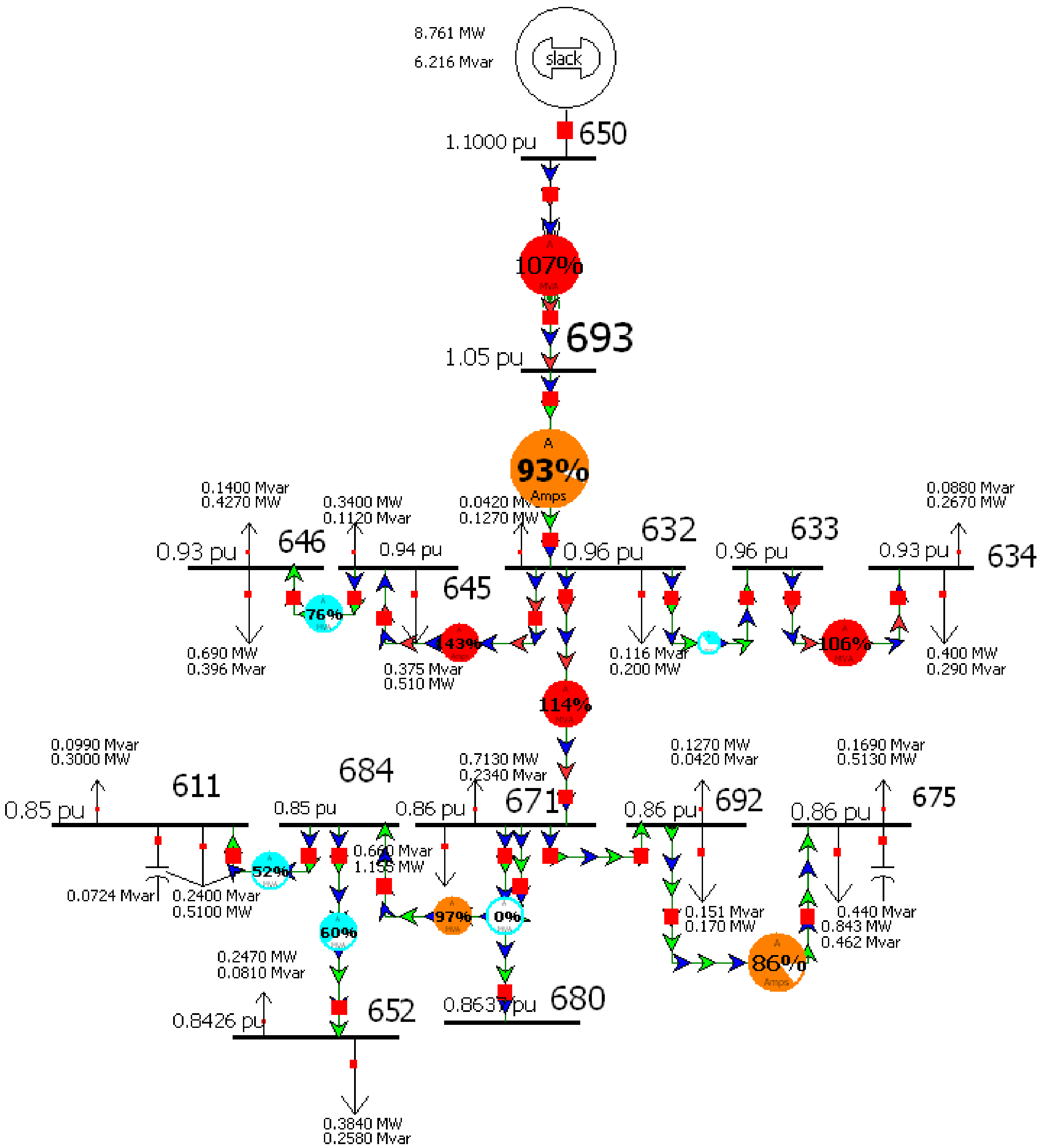

Figure 4: IEEE 13-node distribution test system with quick charging at peak load.

2.2.2. Case Study Results and Discussions

To analyze the simulation results, voltage, line loading and total losses in four different scenarios are compared. Tables 2 shows the bus voltages of four different scenarios described above. In the BAU case, i.e. test system without any PHEVs charging, all the bus voltages are within the acceptable limits of ±10% of nominal voltage. In the normal charging case, there were no violations in voltages at all the buses. However, in the quick charging at peak load scenarios, there are 50% of buses with voltage below the minimum acceptable level (shown with underlined numbers in Table 2). It is because that quick charging draws much higher current/power than the normal charging. The voltages at different buses in the case of quick charging at max load are also shown in Fig. 4 above. If quick charging can be controlled and done during the min load period, there were no problem of voltage violations in the system as shown in Table 2.

Table 2: Buses voltages in per unit for different scenarios

BUS #	BAU	Normal Charging, Peak Load	Quick Charging,Peak Load	Quick Charging Min Load
611	0.97	0.95	**0.85**	0.96
632	1.03	1.01	0.96	1.02
633	1.03	1.01	0.96	1.02
634	1.00	0.99	0.93	1.00
645	1.01	1.00	0.94	1.00
646	1.01	0.99	0.93	1.00
650	1.10	1.10	1.10	1.10
652	0.96	0.94	**0.84**	0.95
671	0.97	0.95	**0.86**	0.97
675	0.97	0.95	**0.86**	0.96
680	0.97	0.95	**0.86**	0.97
684	0.97	0.95	**0.85**	0.96
692	0.97	0.95	**0.86**	0.97
693	1.07	1.07	1.05	1.07

Figure 5 indicates voltage of different busses in the two scenarios of quick charging at peak load and BAU which is a comparison between the worst case and BAU.

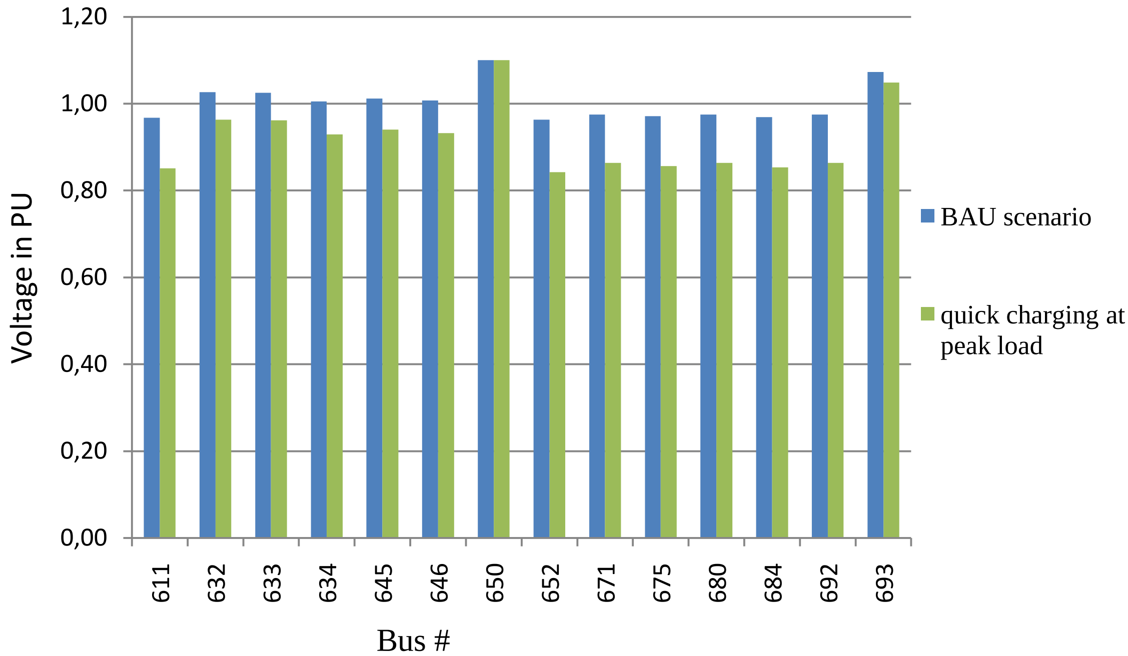

Figure 5: Bus voltages in BAU and quick charging at peak load

Table 3 shows the line loadings in percentage of rated line capacity. In the BAU and normal charging scenarios, the line loadings are within the maximum limits. When PHEVs are charged with quick charging during peak load period, there are four lines (i.e., lines 632-645, 632-671, 633-634, and 650-693) overloaded as can be seen with the red circles in Fig. 4 and they are underlined and bold in the table 3, meaning that the network is under the stress condition. With quick charging but under the minimum load condition, the stress condition for the line overloading is reduced with only one line overloading (i.e., line 632-645).

Table 3: Loading of lines as percentage of rated power

From Bus	To Bus	BAU	normal charging, peak load	quick charging, peak load	quick charging, min load
684	611	32.20	37.10	51.80	39.00
632	633	20.70	23.60	32.60	25.00
632	645	87.50	99.80	**137.80**	**106.00**
632	671	66.20	75.90	**113.70**	80.90
693	632	56.20	64.90	97.50	68.80
633	634	67.20	76.60	**105.80**	81.20
645	646	48.40	55.20	75.70	58.60
650	693	60.50	70.10	**107.40**	74.20
684	652	38.80	44.10	60.40	45.70
671	680	0.00	0.00	0.00	0.00
671	684	60.00	69.00	96.60	72.30
671	692	0.00	0.00	0.00	0.00
675	692	45.60	52.20	73.90	57.50

The other important observation that must be taken into account is the loss analysis in the different scenarios. It is expected to have increase in the line losses when their loading is increased. Fig. 6 shows total system active power losses for different scenarios. System loss increases dramatically when PHEVs have been connected for quick charging at peak load as compared to the BAU scenario. Total system losses at normal charging at peak load and quick charging at minimum load are found to be the same.

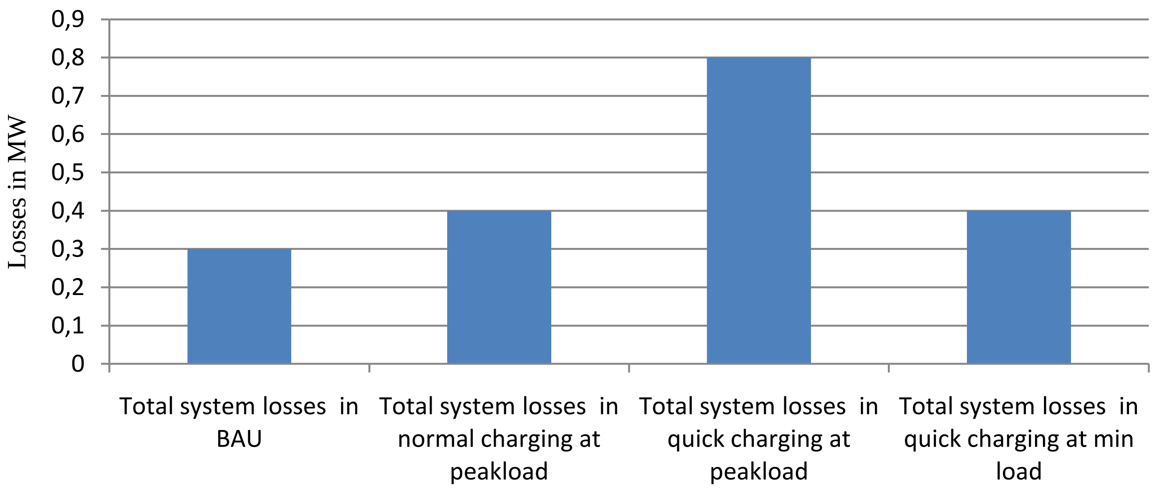

Figure 6: Total system active power losses

2.3. Effect of PHEVs on the Gothenburg Distribution Network

To analyze the effects of PHEVs charging on a real network, this effect has been tested on a part of Gothenburg distribution network. This part of Gothenburg distribution network includes voltage level of 10 and 0.4 kV. There are different areas in this city, some of them are residential, some others commercial and others are industrial. There are many areas which are combination of residential, commercial and industrial areas. The load profile of these areas is totally different. To have a precise investigation, in this master thesis, both 10 kV and 400 V network have been simulated and analyzed for commercial and residential area.

2.3.1. Description of Gothenburg Residential Distribution network (400 V)

In this part, one residential area has been selected to investigate the effect of PHEVs charging on a real distribution network. The selected area is substation RS1 in the Gothenburg. This substation includes two transformers of 10 kV/0.4 kV with rating of 500 kVA. This substation serves for around 144 household customers and is supplied by busbar RBB1 in one 130 to 10 kV Substation. Every hour load profile of line RF1 in year 2008   which is the supplier feeder for number of residential substations including RS1 is available. For this residential area, a typical day in the winter: 10 January 2008 has been selected. . This day is one of the peak days in year 2008. Figure 7shows load profile of this day for line RF1. As it is shown in this figure, peak hour is at 19 PM. It is the time that most of people have backed home and is reasonable to be the peak hour in a residential area.

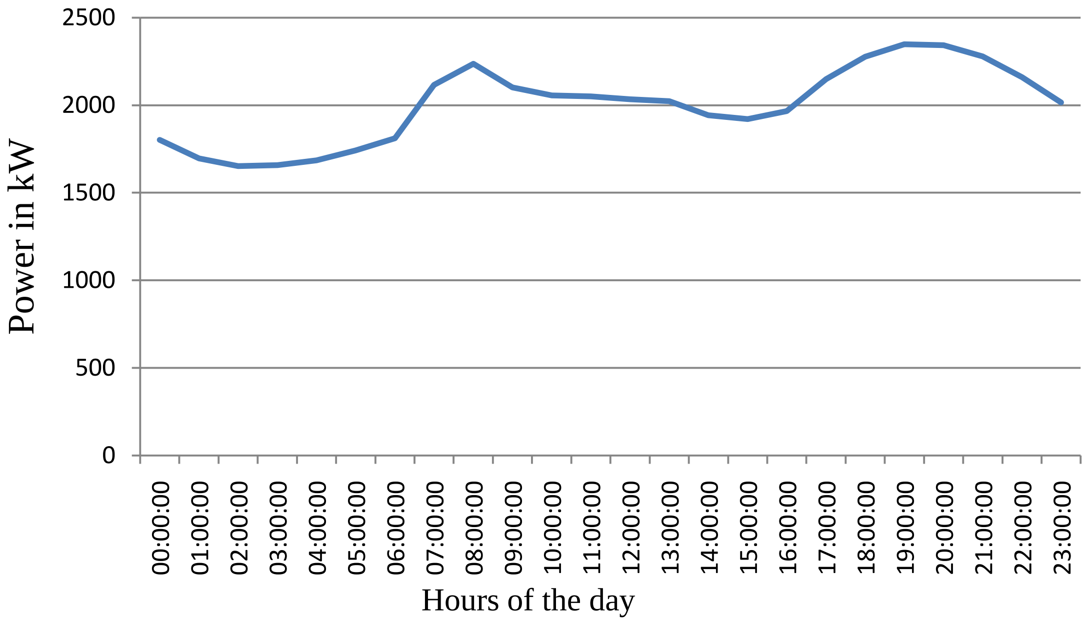

Figure 7: Load profile of a day in the winter for line RF1

10 kV network of this residential area has been designed in a way that in case of one feeder failure, affected loads will be supplied from other feeders by changing some circuit breakers status; therefore there will be no load interruption. This specific configuration increases the reliability of the system. Figure 8 shows how this 10 kV network looks like. To distribute line RF1 loads between all the substations, it has been assumed that contribution of each substation in power consumption is proportional to its maximum current. The maximum

current of all the transformers at each substation are available. In the substations with more than one transformer, maximum current is summation of all the transformers at that substation. The load of substations supplied by the line RF1 in normal condition is calculated as in (2.1).

$P_i = P_{lineRF1} \times a_i$ (2.1)

Where:

P_i: substation (i) load on 10 January 2008 at 19 PM

$P_{lineRF1}$: total line RF1 power consumption on 10 January 2008 at 19 PM

a_i: distribution coefficient of each substation and is calculated as in (2.2).

$a_i = \frac{I_i}{\sum_i I_i}$ and $\sum_i a_i = 1$ (2.2)

Where:

I_i: Each substation maximum current calculated as in (2.3)

$I_i = \sum_j C_j$ (2.3)

Where

C_j: Maximum current of transformer j at substation i

Substation RS1 load has been distributed between two transformer proportional to their maximum current. To calculate each bus load in substation RS1, this substation total load: P_{RS1} calculated in (2.1), has been distributed between different busses proportionally to their average annually energy consumption. Annual energy consumption of all the customers was provided by Göteborg Energy and therefore power of each bus at substation RS1 is calculated as in (2.4):

$P_j = P_{RS1} \times b_j$ (2.4)

Where:

P_j: Power of bus j in substation RS1 on day 10 January 2008 at 19PM

b_j: distribution coefficient of bus j in substation RS1 and calculated as in (2.5):

$b_j = \frac{AAEC_j}{\sum_j AAEC_j}$ and $\sum_j b_j = 1$ (2.5)

Where:

$AAEC_j$: Average Annual Energy Consumption of bus j at substation RS1 and is calculated as in (2.6):

$AAEC_j = \frac{AEC_j}{24*365}$ (2.6):

Where:

AEC_j: Annual Energy Consumption of customer j and is provided by the Göteborg Energy.

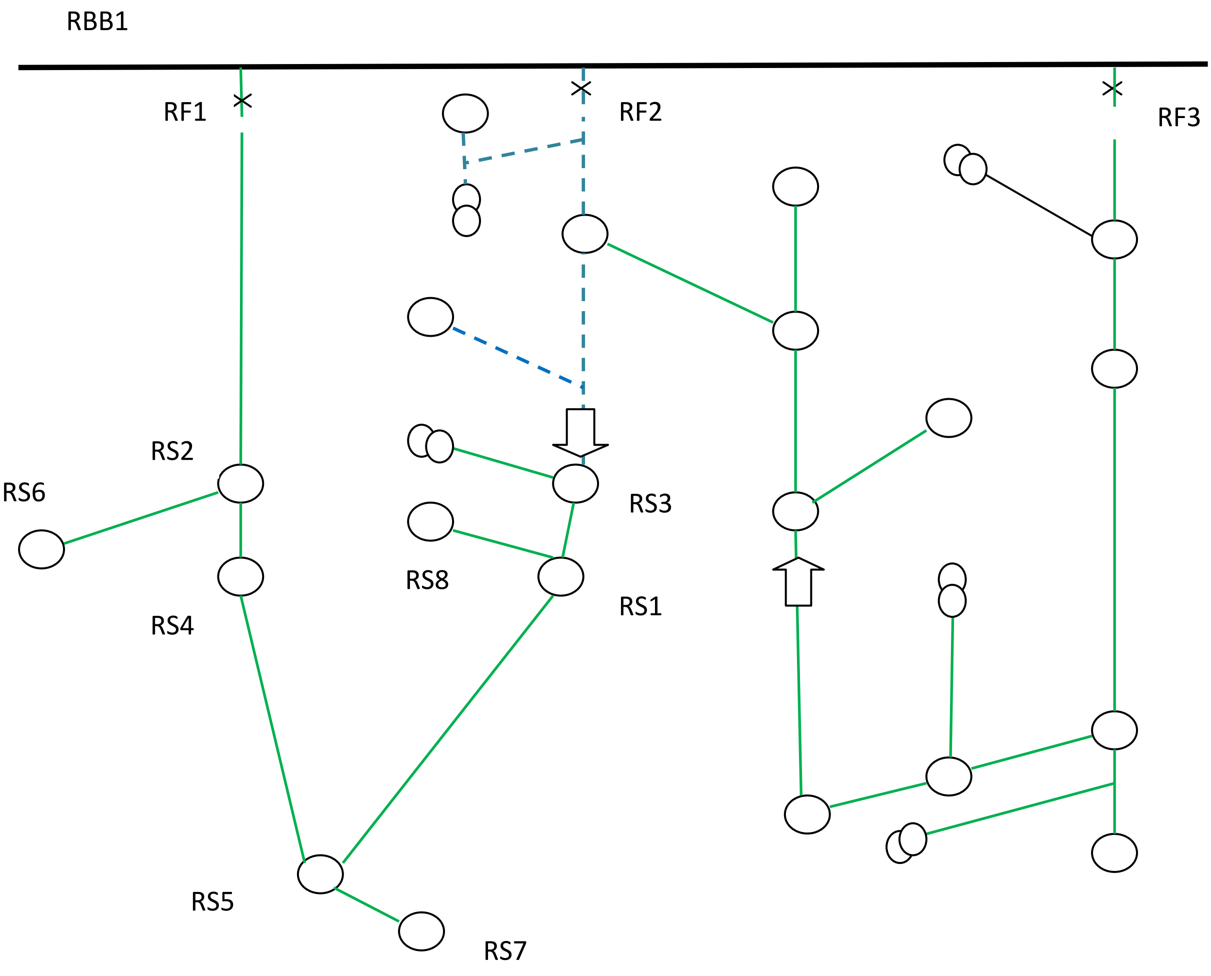

Figure 8: 10 kV residential network in Gothenburg

For residential area, power factor of each load has been considered to be 0.95 lag and then the reactive power at each bus will be as in (2.7):

$Q_j = P_j \times TAN\ (ACOS\ (0.95))$ (2.7)

144 PHEVs has been assumed for the residential area supplied by substation RS1 according to [13] .These vehicles have been distributed proportionally to buses load. That's because the probability of plugging PHEVs in different buses can be proportional to the buses load, in other word the probability of plugging a vehicle at bus with higher load is more than the probability of plugging a vehicle to the buss with lower load. Therefore the number of vehicles at each buss can be calculated as in (2.8):

$N_j=144\times Pro_j$ (2.8):

Where:

N_j: probable number of vehicles at bus j in substation RS1

Proj: probability of having a PHEV at bus j in the substation RS1 connected for charging which is calculated as in (2.9).

$$Pro_j=\frac{P_j}{\sum_j P_j} \quad (2.9)$$

Where:

P_j: Power of bus j at substation RS1 on day 10 January 2008 at 19 PM

Figure 9 shows the number of vehicles at each bus at substation RS1 only for transformer 2.

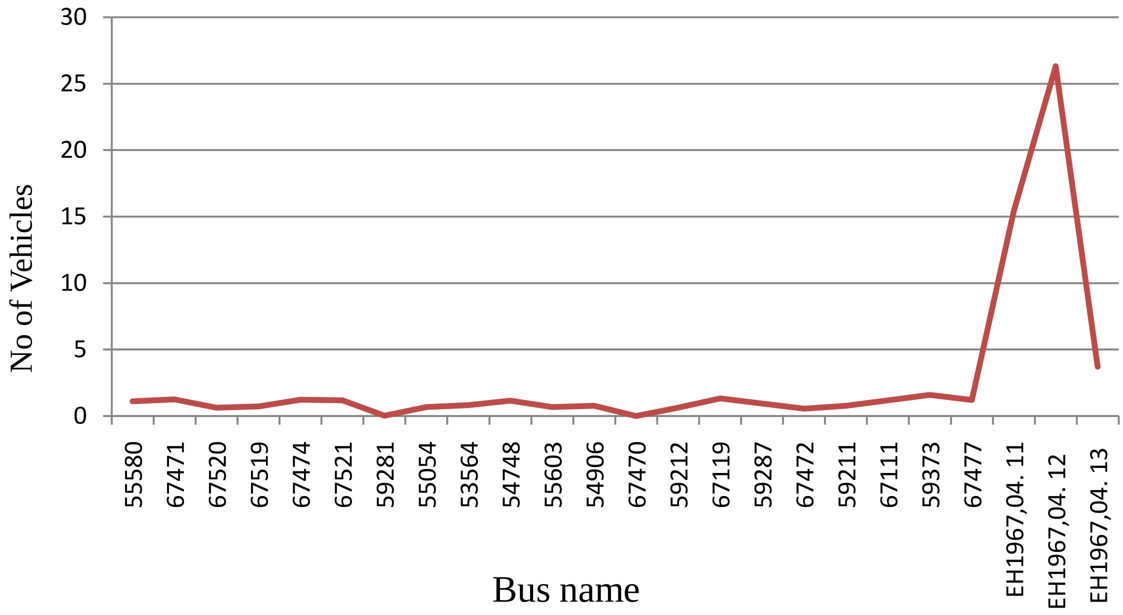

Figure 9: Calculated probable number of vehicles at substation RS1 only for transformer 2

It is supposed that vehicles are charged via a plug of 16 A, therefore the power drawn by the vehicle will be 16A×230V≈3.6 kW and also battery and total charging equipment have a power factor of 0.95. Therefore required power at each bus for charging the vehicles will be as in (2.10)

$P_{PHEVs(j)}= N_j\times 3.6$ kW (2.10)

$Q_{PHEVs(j)} = P_{PHEVs(j)} \times TAN(ACOS(0.95))$

Where:

$P_{PHEVs(j)}$: required power for charging the vehicles at bus (j)

$Q_{PHEVs(j)}$: required reactive power for charging the vehicles at bus (j)

2.3.1.1. Case Study Results and Discussions

Figure 10 shows single line diagram of residential network connected to transformer 2 at substation RS1 in the Gothenburg. Vertical loads are regular loads of the area and horizontal loads are simulating connected plug-in vehicles.

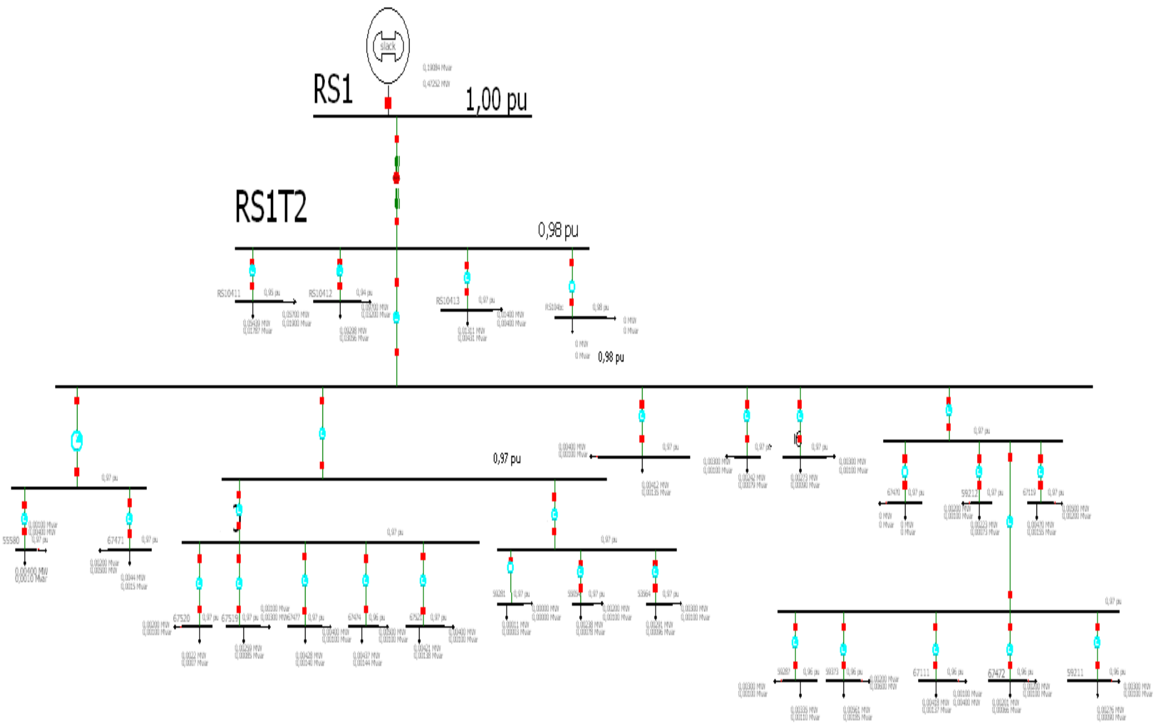

Figure 10: residential 400 V network connected to transformer 2 at substation RS1 while busbar RBB1 voltage is set at 1pu.

To avoid voltage drop at end users, in the distribution network, usually voltage of the busbar which supplies outgoing feeders is set to a voltage higher than 1 pu. These substations are usually equipped with coordinated voltage regulator that controls the main busbar voltage and apply desired voltage to substation busbar via an on load tap changer. Small 10 kV to 0.4 kV transformers are not equipped with tap changer therefore this regulation must be done in the higher voltage level in our case the main 10 kV busbar i.e. RBB1. Voltages of all the substations supplied by the line RF1 are strongly dependent to the voltage setting at busbar RBB1. If the voltage at RBB1 busbar set to 1 pu, RS1 voltage in the BAU and charging at peak load scenarios would be 0.9750 pu and 0.9485 pu respectively and if it set to 1.07 pu which is the real case the voltage of RS1 in the BAU and charging at peak load would be 1.0464 and 1.0215 respectively. This voltage calculation will be shown in details in chapter 3.

To show advantages of this voltage regulation, investigation of residential network has been done for two cases:

- RBB1 busbar voltage is set to 1 pu.
- RBB1 busbar voltage is set to 1.07 pu.

For each of above situation two following scenarios have been considered.

- BAU: System at peak load i.e. 19 PM on day 10 January 2008 without any PHEVs
- Simultaneous charging of all PHEVs at peak load

Table 4: Buses voltages in per unit while RBB1 busbar voltage is 1pu.

Bus name	BAU	Charging at peak load
RS1	0.98	0.95
RS1T2	0.97	0.93
12657	0.96	0.92
13507	0.96	0.92
13677	0.96	0.92
13687	0.96	0.91
15387	0.96	0.92
15397	0.96	0.92
15407	0.96	0.92
13567	0.96	0.92
1547487	0.96	0.92
1549067	0.96	0.92
1054	0.96	0.92
1580	0.96	0.92
1603	0.96	0.92
1111	0.96	0.91
1212	0.96	0.92
8181	0.96	0.92
8787	0.96	0.91
7373	0.96	0.91
6767	0.96	0.91
1671197	0.96	0.91
470470	0.96	0.92
471471	0.96	0.92
472472	0.96	0.91
474474	0.96	0.91
477477	0.96	0.92
519519	0.96	0.92
520520	0.96	0.92
521521	0.96	0.91
RS10411	0.95	**0.90**
RS10412	0.95	**0.89**
RS10413	0.96	0.92
RS104bc	0.97	0.93

As it is seen In the table 4 when all the PHEVs in this area start charging simultaneously and busbar RBB1 voltage is set to 1 pu, there is voltage drop at all of the busses comparing with BAU scenario. The voltage of bus RS10411 and RS10412 go below the acceptable range of ±10%. These out of range voltages are show in bold and underlined font in table 4.

Table 5: Loading of lines as percentage of rated power while voltage at RBB1 busbar is 1 pu

From bus	To bus	BAU	Charging at peak load
RS1	RS1T2	48.7	**<u>102.3</u>**
RS1T2	15387	20.9	42.6
RS1T2	RS10411	17.5	36.5
RS1T2	RS10412	30.1	62.8
RS1T2	RS10413	4.2	8.6
RS1T2	RS104bc	0	0
15387	12657	7.8	16.2
12657	1580	7.2	14.5
12657	471471	8.2	17.7
ELN539	13507	9.4	19
13507	474474	8.1	17.1
13507	477477	7.9	15.2
13507	519519	4.8	10.4
13507	520520	4.1	8
13507	521521	7.8	15.1
13677	13687	9.5	19.2
15387	13677	13.3	27.1
13677	1212	4.1	8
13677	1671197	8.7	18.3
13677	470470	0	0
13687	1111	5.1	10.7
13687	8787	6.2	11.8
13687	7373	10.4	21.6
13687	6767	7.7	15.1
13687	472472	3.7	7.6
15387	ELN539	7.3	14.7
15387	1547487	7.6	14.9
15387	1549067	5	10.6
15387	1603	4.5	10
ELN539	15407	1.7	3.3
15407	53564	5.4	11
15407	1054	4.4	8.3
15407	8181	0.2	0.2

Table 5 shows different lines percentage loading while busbar RBB1 voltage is set to 1 pu. This table indicates that all the lines loading increase in charging at peak load scenario comparing to BAU. In the BAU scenario there is no overloaded line, however, line from bus RS1 to RS1T2 is overloaded in charging at peak load scenario.

Table 6: Buses voltages in per unit for different scenarios while RBB1 voltage is 1.07pu

Bus name	BAU	Charging at peak load
RS1	1.05	1.02
RS1T2	1.04	1.00
12657	1.04	1.00
13507	1.03	0.99
13677	1.03	0.99
13687	1.03	0.99
15387	1.04	1.00
ELN539	1.03	1.00
15407	1.03	1.00
53564	1.03	0.99
1547487	1.03	0.99
1549067	1.03	1.00
1054	1.03	0.99
1580	1.03	0.99
1603	1.04	1.00
1111	1.03	0.99
1212	1.03	0.99
8181	1.03	1.00
8787	1.03	0.99
7373	1.03	0.98
6767	1.03	0.98
1671197	1.03	0.99
470470	1.03	0.99
471471	1.03	0.99
472472	1.03	0.99
474474	1.03	0.99
477477	1.03	0.99
519519	1.03	0.99
520520	1.03	0.99
521521	1.03	0.99
RS10411	1.03	0.98
RS10412	1.02	0.96
RS10413	1.03	0.99
RS104bc	1.04	1.00

Table 6 and 7 shows different busses voltage and line loading in the BAU and charging at peak load scenario while the RBB1 busbar voltage is set to 1.07 pu.

Table 7: Loading of lines as percentage of rated power while RBB1 busbar voltage is 1.07 pu

From bus	To bus	BAU	Charging at peak load
RS1	RS1T2	48.7	**<u>102</u>**
RS1T2	15387	20.8	42.2
RS1T2	RS10411	17.4	36
RS1T2	RS10412	29.8	62.1
RS1T2	RS10413	4.2	8.6
RS1T2	RS104bc	0	0
15387	12657	7.7	16.1
12657	1580	7.2	14.4
12657	471471	8.2	17.6
ELN539	13507	9.4	18.8
13507	474474	8	17
13507	477477	7.9	15.1
13507	519519	4.8	10.3
13507	520520	4.1	8
13507	521521	7.8	15
13677	13687	9.4	19
15387	13677	13.2	26.8
13677	1212	4.1	8
13677	1671197	8.7	18.1
13677	470470	0	0
13687	1111	5.1	10.6
13687	8787	6.2	11.7
13687	7373	10.3	21.4
13687	6767	7.7	14.9
13687	472472	3.7	7.6
15387	ELN539	7.3	14.6
15387	1547487	7.6	14.8
15387	1549067	5	10.6
15387	1603	4.4	10
ELN539	15407	1.7	3.3
15407	53564	5.4	10.9
15407	1054	4.4	8.2
15407	8181	0.2	0.2

As it is seen in the tables 6, after setting the busbar RBB1 voltage to 1.07 pu, there is no under voltage at any buses nor in BAU neither in charging at peak load scenario. Line loading percentage for all the lines in this situation is shown in the table 7. There is no overloading line in the BAU scenario however line from RS1 to RS1T2 is overloaded in the charging at peak load scenario.

2.3.2. Description of Gothenburg Commercial Distribution network (400 V)

In this part, one commercial area has been selected to investigate the effect of PHEVs charging on a real distribution network. Selected area is substation CS1 in the Gothenburg. This substation includes two transformers of 10 kV/ 0.4 kV with rating of 750 and 1250 kVA. This substation serves for around 115 commercial customers and is one substation of 10 kV network supplied by busbar CBB1 and CBB2 in one 130 to 10 kV Substation. This 10 kV network has been made up of 4 lines named CF1, CF2, CF3, and CF4. Every hour load profile of all these four lines in year 2008 is available. For this commercial area, a typical day in the winter: 14 February 2008 has been selected. This day is one of the peak days in this year. Figure 11shows this 10 kV network load profile i.e. summation of line CF1, CF2, CF3, and CF4 power on 14 February 2008. As it is shown in this figure, peak hour is at 12 PM.

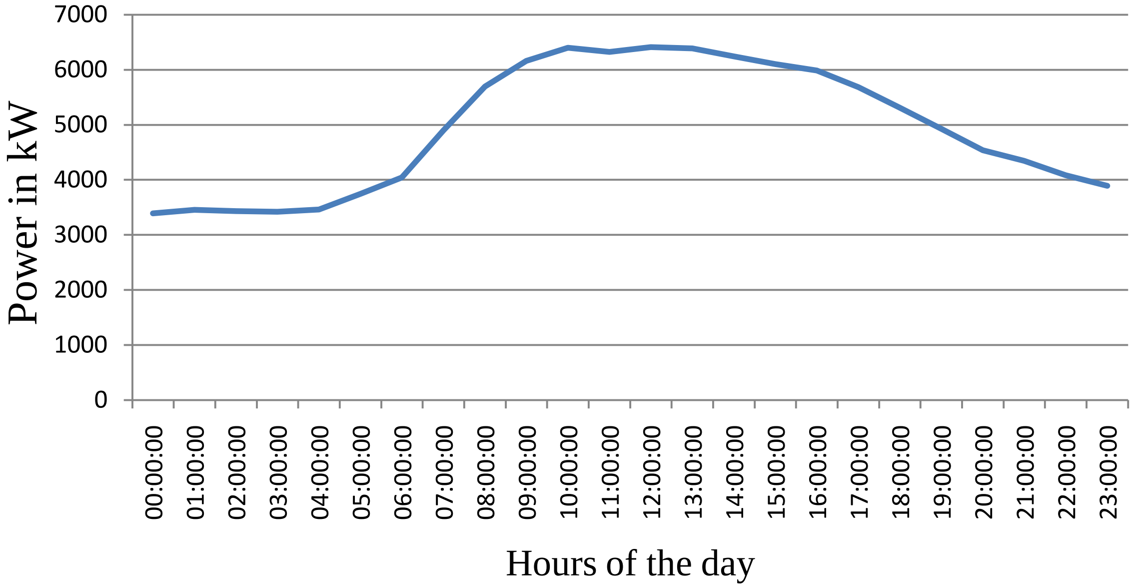

Figure 11: load profile of the 10 kV network supplying a commercial area in the Gothenburg on 14 February 2008.

This commercial area 10 kV network is designed in a way that in case of one feeder failure , affected load, is fed from other feeders by changing some circuit breakers status. Figure 12 shows how this 10 kV network looks like. To distribute this commercial 10 kV network load between all substations, it has been assumed that contribution of each substation in load consumption is proportional to its maximum transformer current. The maximum current of all the transformers are available. In substations with more than one transformer, maximum current is summation of all the transformers at that substation. Each substation load is calculated according to (2.11):

$$P_i=P_{10kV\ network}\times a_i \qquad (2.11)$$

Where:

P_i: load of substation (i) at peak load on day 14 February 2008.

$P_{10kVring}$: Total power of 10 kV commercial network i.e. summation of lines CF1, CF2, CF3, and CF4 loads at peak load on day 14 February 2008.

a_i: each substation distribution coefficient and is calculated as in (2.12):

$a_i = \frac{I_i}{\sum_i I_i}$ and $\sum_i a_i = 1$ (2.12)

Where:

I_i: Maximum current of each substation calculated as in (2.13)

$I_i = \sum_j C_j$ (2.13)

Where

C_j: Maximum current of transformer j in substation i

Load at substation CS1 has been distributed between two transformers proportionally to their maximum current. For calculation each bus load in substation CS1, total load of this substation: P_{CS1} calculated by (2.11), has been distributed between different busses proportionally to their average annually energy consumption. The annual energy consumption of all the customers was provided by Göteborg Energy and therefore power of each bus at substation CS1 is calculated as in (2.14):

$P_j = P_{CS1} \times b_j$ (2.14)

Where:

P_j: bus j Power in substation CS1 at peak load on day 14 February 2008.

b_j: bus j distribution coefficient in substation CS1 and calculated as in (2.15):

$b_j = \frac{AAEC_j}{\sum_j AAEC_j}$ and $\sum_j b_j = 1$ (2.15)

Where:

$AAEC_j$ is Average Annual Energy Consumption of bus j in substation CS1 and is calculated as in (2.16)

$AAEC_j = \frac{AEC_j}{24*365}$ (2.16)

Where:

AEC_j: Annual Energy Consumption of customer j and is provided by the Göteborg Energy.

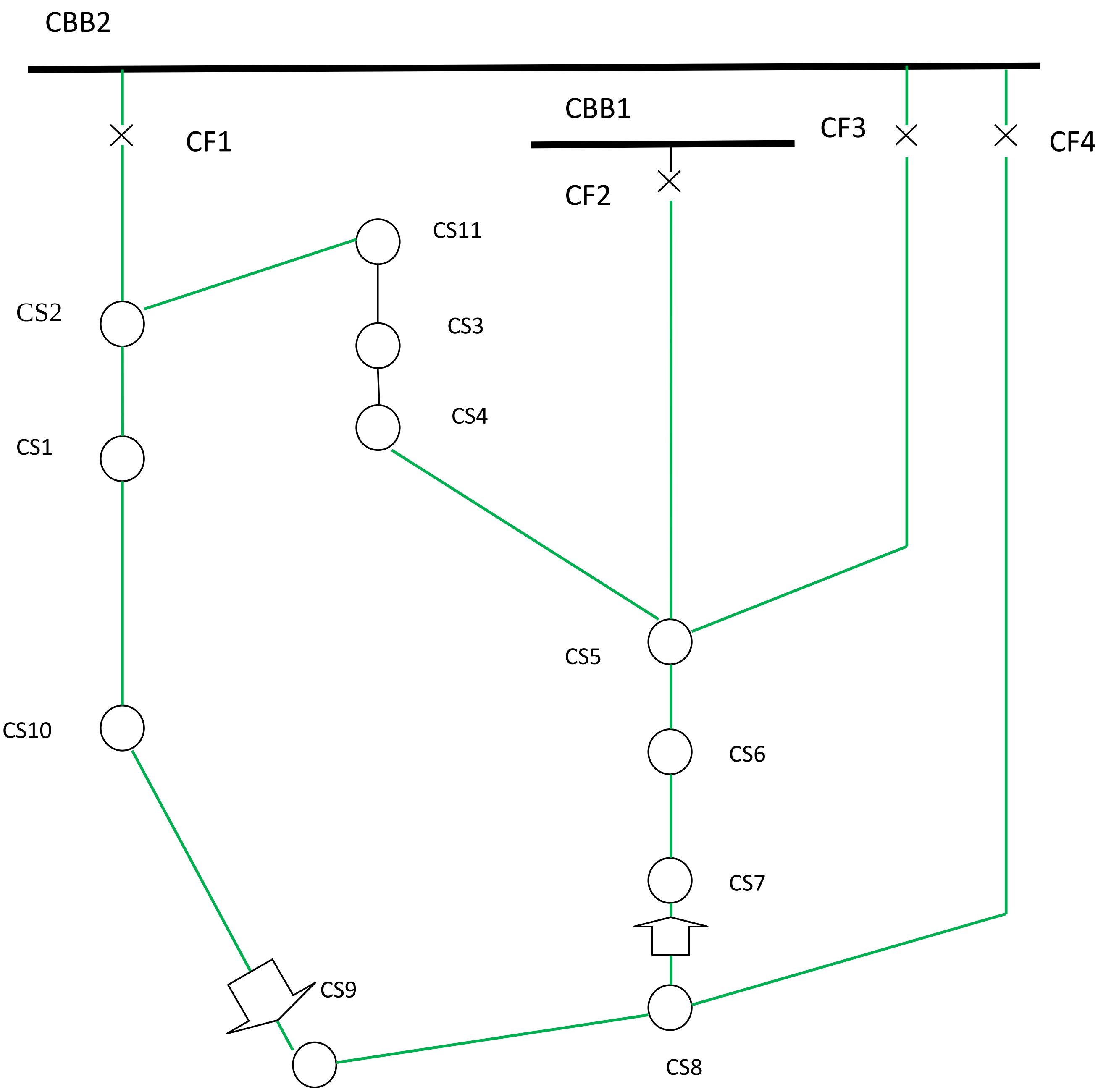

Figure 12: 10 kV network of a commercial area in the Gothenburg

For this commercial area, power factor of each load has been considered to be 0.95 lag and then the reactive power at each bus will be as in (2.17):

$$Q_j = P_j \times \text{TAN}\ (\text{ACOS}\ (0.95)) \quad (7)$$

It is assumed there are 148 vehicles at commercial area at peak load and demand for charging. This number of PHEVs has been obtained according to the day time number of vehicles at this commercial area [13]. The probability of plugging PHEVs in different busses can be proportional to buses load, in other word probability of plugging a vehicle at bus with higher load is more than the probability of plugging a vehicle to the buss with lower load. Therefore the probable number of vehicles at each buss can be calculated as in (2.18):

Nj=148×Pro_j (2.18)

Where:

N_j: probable number of vehicles at bus j

Proj: probability of having a PHEV at bus j connected for charging which is calculated as in (2.19):

$$Pro_j = \frac{P_j}{\sum_j P_j} \qquad (2.19)$$

Where:

P_j: bus j power in substation CS1 at peak load on day 14 February 2008.

Figure 13 shows number of vehicles at each bus at substation CS1.

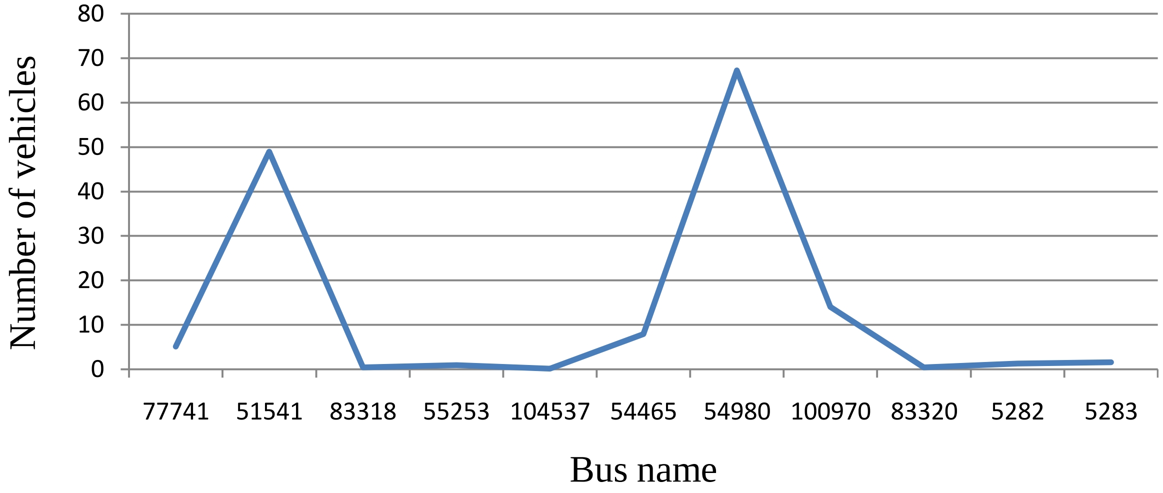

Figure 13: Number of vehicles at each bus in substation CS1.

Charging facility in the commercial area is like residential area i.e. a 16 A and 230 V plug with total charging equipment power factor of 0.95 therefore:

$P_{PHEVs(j)} = N_j \times 3.6$ kW (2.20)

$Q_{PHEVs(j)} = P_{PHEVs(j)} \times$ TAN(ACOS(0.95))

Where:

$P_{PHEVs(j)}$: required power for charging vehicles at bus (j)

$Q_{PHEVs(j)}$: required reactive power for charging vehicles at bus (j)

2.3.2.1. Case Study Results and Discussions

In this part, simulation results for mentioned commercial area are presented and analyzed in details. Figure 14 and 15 show single line diagram of two transformers and their outgoing feeders at substation CS1 in the Gothenburg. Vertical loads are the regular loads of the commercial area and horizontal loads are simulating plugged in vehicles.

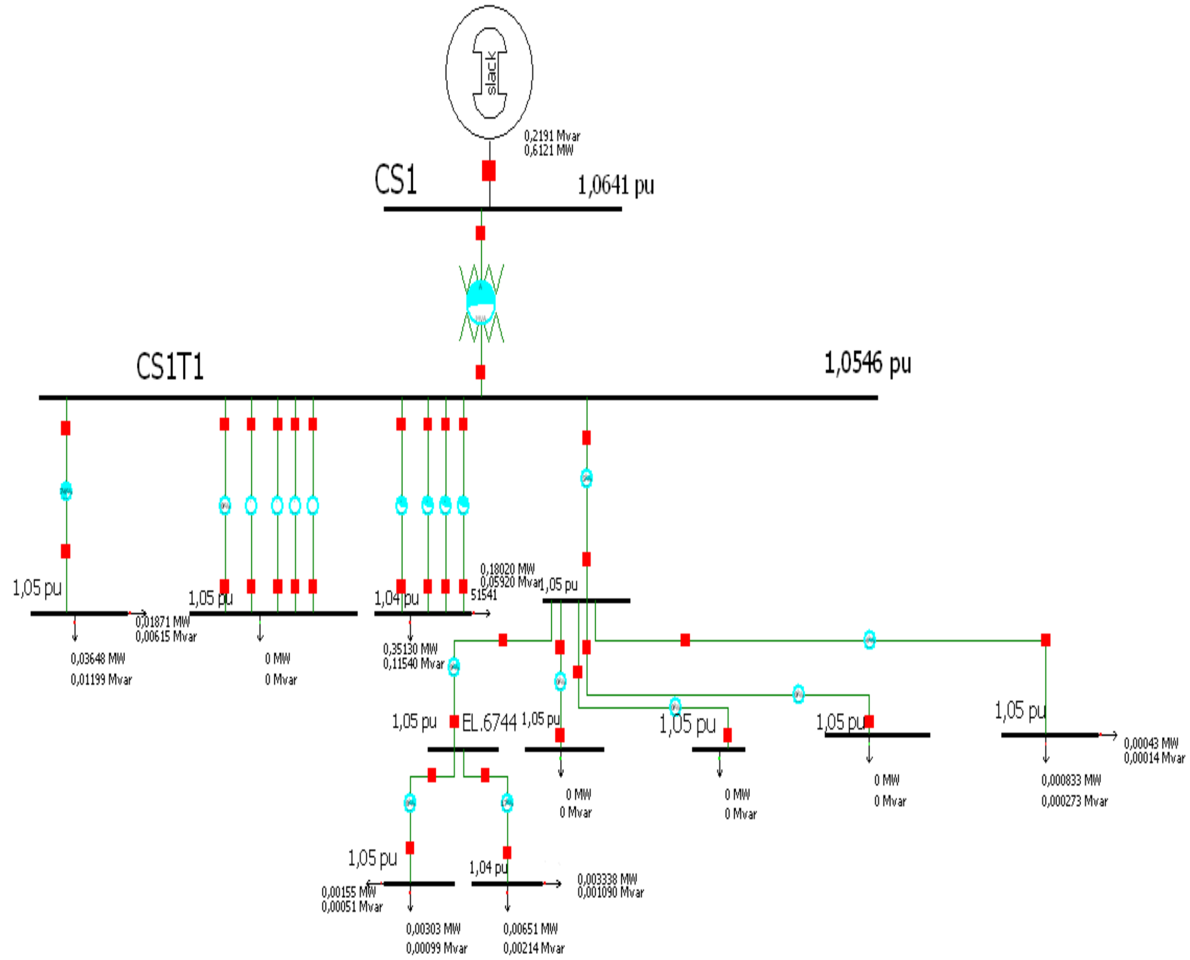

Figure 14: Single line diagram of commercial 400 V network connected to transformer 1at substation CS1.

Substation CS1 voltage with and without PHEVs in the 10 kV network is 1.0641 and 1.0643 respectively. Calculation of these voltages has been explained in chapter 3 in details.

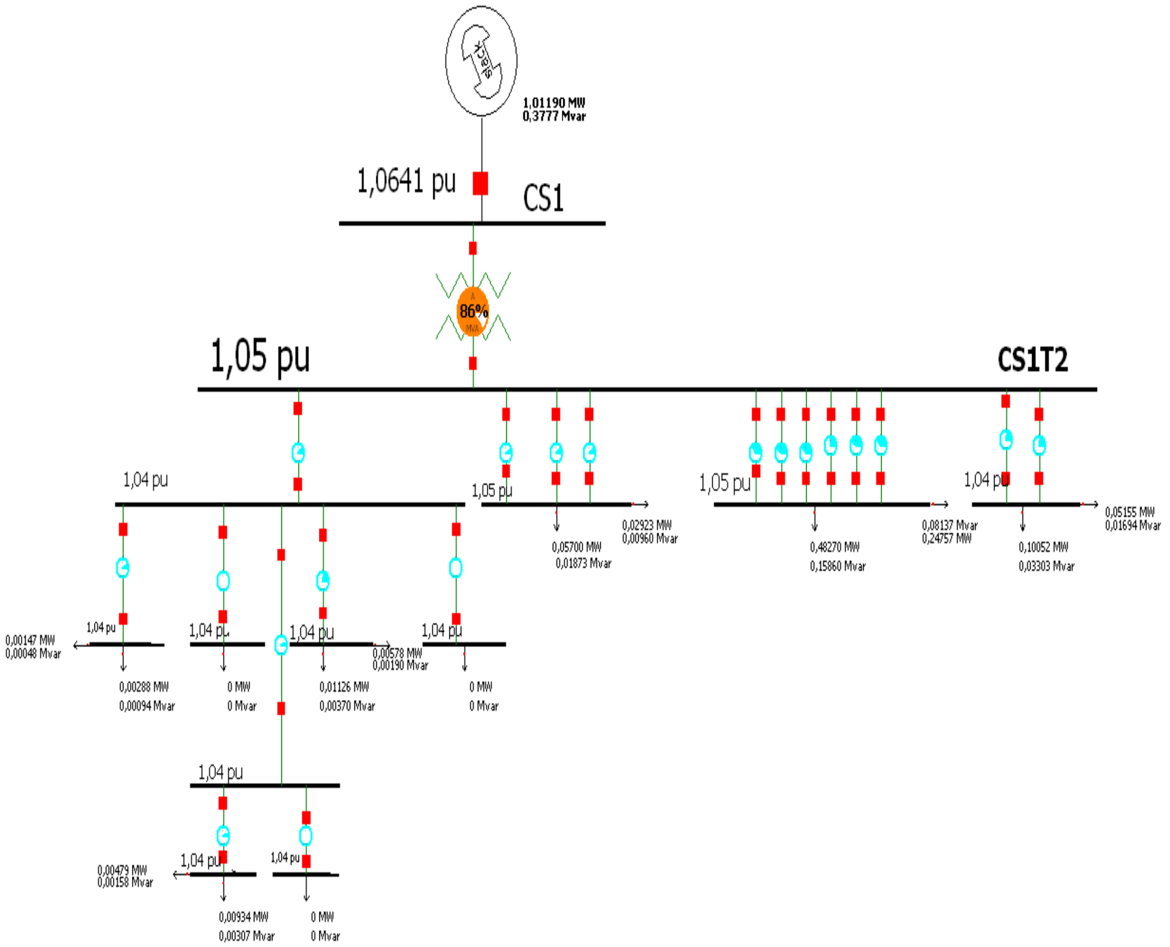

Figure 15: Single line diagram of commercial 400 V network connected to transformer 2 at substation CS1.

Table 7 and 8, shows bus voltages and line loading for two different cases:

- BAU: System at peak load i.e. on day 14 February 2008 at 12 PM without any PHEVs
- Simultaneous charging of all PHEVs at peak load

As it is observed in the table 7, there is no considerable voltage drop when PHEVs start to charge simultaneously. That's mainly because of large cross section of cables in this area. The voltage difference in the BAU and charging at peak load is quite negligible.

Table 8 shows loading of the lines in two different cases. Line loading increases in charging at peak load scenario but there is no over loaded line yet.

Table 8: Buses voltages in per unit for different scenarios in commercial area

Bus #	BAU	Charging at peak load
CS1	1.06	1.06
318	1.05	1.05
53	1.05	1.04
CS1T1	1.06	1.05
64	1.05	1.05
37	1.06	1.05
51	1.05	1.04
59	1.06	1.05
71	1.06	1.05
79	1.06	1.05
75	1.06	1.05
76	1.06	1.05
107	1.06	1.05
CS10417	1.05	1.05
820	1.05	1.05
017	1.05	1.05
806	1.05	1.05
530	1.05	1.05
007	1.05	1.05
008	1.05	1.05
009	1.05	1.05
005	1.05	1.05
80	1.05	1.05
1000	1.05	1.04
5460	1.05	1.05
CS1T2	1.06	1.06

Table 9: Line loading as percentage of rated power in the commercial area

From bus	To bus	BAU	charging at peak load
CS1	CS1T1	34.10	52.00
CS1T1	51	28.00	42.40
CS1T1	51	28.10	42.70
CS1T1	51	27.60	41.80
CS1T1	59	0.00	0.00
CS1T1	71	51.70	78.10
CS1T1	51	28.10	42.70
CS1T1	37	3.30	5.00
CS1T1	59	0.00	0.00
CS1T1	59	0.00	0.00
CS1T1	59	0.00	0.00
59	CS1T1	0.00	0.00
64	53	12.10	18.30
64	318	5.60	8.40
37	64	6.10	9.30
37	107	2.50	3.80
37	76	0.00	0.00
37	75	0.00	0.00
37	79	0.00	0.00
CS10417	80	28.80	43.40
CS10417	005	9.60	9.60
CS10417	80	26.50	39.90
CS10417	80	24.60	37.00
CS10417	80	17.90	27.00
CS10417	005	8.60	8.60
CS10417	005	9.20	9.20
CS10417	1000	16.00	24.00
CS10417	80	28.80	43.40
CS10417	1000	16.00	24.00
CS10417	5460	11.30	11.40
CS10417	80	26.50	39.90
CS1T2	CS10417	60.10	86.40
5460	820	8.00	8.00
5460	007	0.00	0.00
5460	530	15.30	15.30
5460	806	0.00	0.00
017	008	4.20	4.30
017	5460	4.20	4.30
017	009	0.00	0.00

2.4. Comments on the Protection

PHEVS in the Gothenburg are supposed to be charged via a 220 V 16 ampere single phase plug. Many of the customers both in the residential and commercial area are using fuse of 20 Ampere for their main feeders. It means in a case that customers are charging their vehicles cannot use more than 4 amperes corresponding to 4*220=0.88 kW. It can be risky for the customer especially when it is taken to account that one simple hair dryer has power of around 1 kW. Maybe the fuses replacement will be inevitable for using the PHEVs. The other solution can be using three phases plug, then current of each phase will decrease to one third and it will be safe in terms of the fusing. The protection scheme of the distribution networks is usually designed for a unidirectional power flow and in a case that vehicles inject power to the grid; this protection system might be required to be verified.

Chapter 3

3. Effects of PHEVs on the Gothenburg 10 kV Network

Effect of PHEVs charging have been investigated on two 400 V distribution network with residential and commercial characteristic so far. The more important case is accumulated effect of some similar distribution network when reaches to higher voltage level network for example 10 kV. In this part of Master thesis, effect of charging PHEVs on a network made up of number of 10 to 0.4 kV substations will be investigated both for residential and commercial area. To have an estimation of maximum number of vehicle that can be connected to grid for charging simultaneously, one iterative method has been used with considering reliability issues.

3.1. Description of Sample 10 kV Commercial Network in Gothenburg

This sample network is a 10 kV network located in the Gothenburg city. It has been made up of four 10 kV feeders i.e. CF1, CF2, CF3, CF4 supplied from CBB1 and CBB2 10 kV busbar. Figure 12 shows how this 10 kV commercial network looks like. It is called a commercial distribution network, because most of the customers in this area are business offices. The power consumption of all the outgoing feeders separately and also the aggregation of these four feeders load consumption is available through the data from Göteborg Energy. For this study worst case i.e. maximum load of the 10 kV network in normal operation i.e. no feeders outage in the year 2008 which is 7.632 MW has been considered .To have a fair load distribution, total loads have been distributed between substations proportionally to the maximum current drawn by each substation in year 2008. Maximum current of each transformer are available via the data obtained from Göteborg Energy. According to equation (2.11) in chapter 2:

$P_i = P_{10kV\ network} \times a_i$

Where:

P_i: load of substation (i) at peak load.

$P_{10kVring}$: total power of 10 kV commercial network i.e. the summation of lines CF1, CF2, CF3, and CF4 loads at peak load in the year 2008 which is 7.632 MW.

a_i: distribution coefficient of each substation and is calculated as below

$$a_i = \frac{I_i}{\sum_i I_i} \quad \text{and} \quad \sum_i a_i = 1$$

Where:

I_i: Maximum current of each substation and calculated as below

$$I_i = \sum_j C_j$$

Where

C_j: Maximum current of transformer j at substation i

Having calculated each substation load, then probable power required for charging vehicles at each substation must be calculated. It is assumed that probable number of vehicles at each substation is proportional to that substation load.

$$N_{CS1} = N_{total} \times Pro_{CS1} \qquad (2.21)$$

Where:

Pro_{CS1}: probability of having a vehicles charging at substation CS1 which is calculated as in (2.22):

$$Pro_i = \frac{P_i}{\sum_i P_i} \qquad (2.22)$$

Where:

P_i: load of each substation in 10 kV network

Proi: probability of having a vehicle charging at substation i in the 10 kV network.

So the probable total number of PHEVs at 10 kV network will be

$$N_{total} = \frac{N_{CS1}}{\frac{P_{CS1}}{\sum_i P_i}} \cong 894 \qquad (2.23)$$

And probable number of vehicle at each substation will be:

$$N_i = N_{total} \times Pro_i \qquad (2.24)$$

Required power for charging the PHEVs at each substation will be:

$$P_{PHEVi} = N_i \times 3.6\ kW = \frac{N_{CS1}}{P_{CS1}} \times \frac{\sum_i P_i}{\sum_i P_i} \times P_i \times 3.6 = N_{CS1} \times 3.6 \times \frac{P_i}{P_{CS1}}$$

And finally

$$P_{PHEVi} = \frac{P_{PHEVCS1}}{P_{CS1}} \times P_i = 0.51284 \times P_i \qquad (2.25)$$

Where:

P_{PHEVi}: probable active power required for charging the vehicles at substation i

Figure 16 shows single line diagram of the 10 kV network of the commercial area in the Gothenburg drawn in the Power World. In this simulation buss bar CBB2 and CBB1in figure 12 has been merged to one infinite bus, indicating with CBB2 in the figure 16. As it is observed there are over loaded lines in this network, meaning that this network cannot handle charging of 894 vehicles simultaneously at peak load of the 10 kV commercial networks.

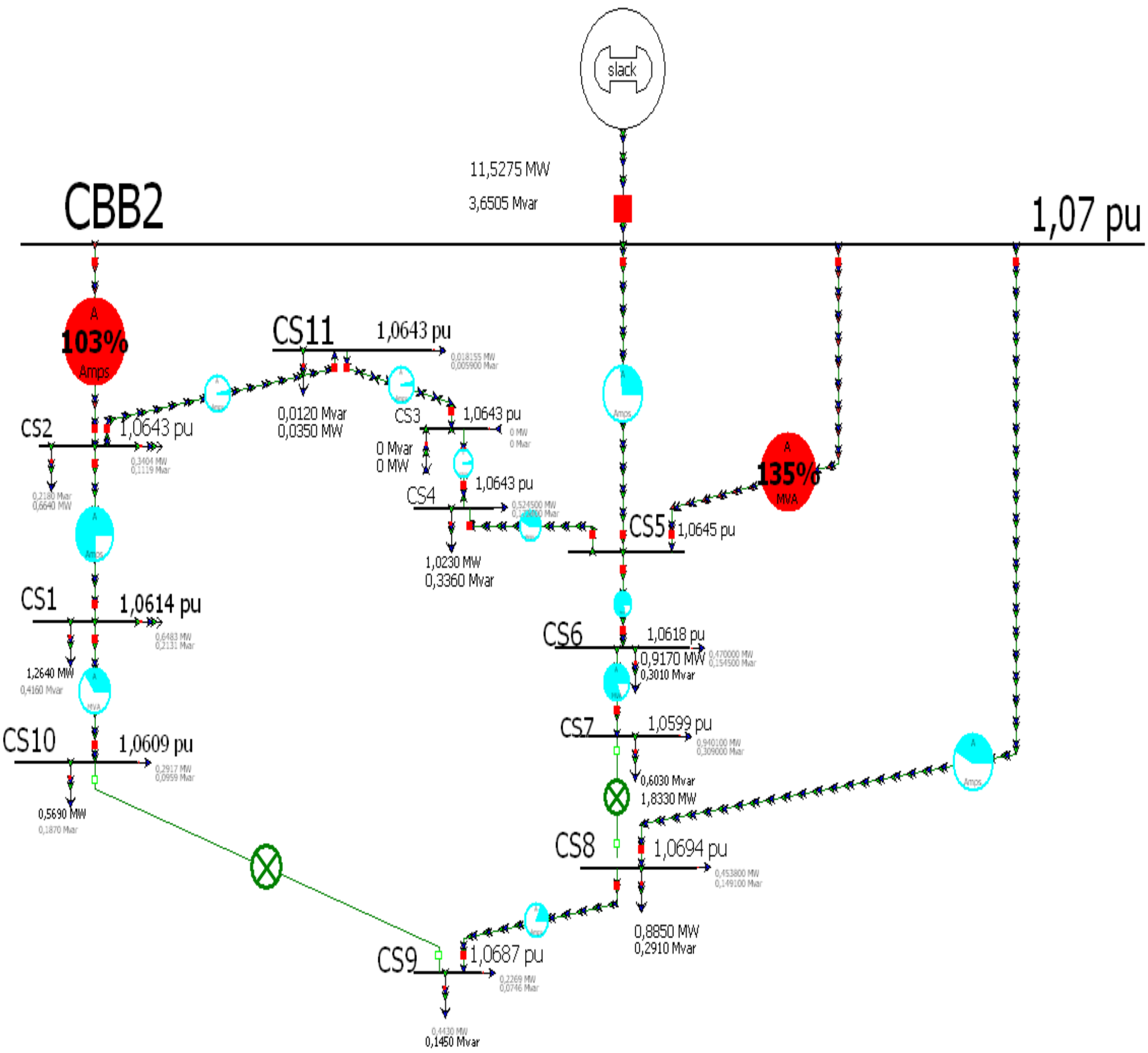

Figure 16: single line diagram of 10 kV network of the commercial area in Gothenburg.

3.1.1. Case study Results and Discussions

Here, two scenarios have been considered as below:

- BAU: System at peak load without any PHEVs
- Simultaneous charging of all PHEVs at peak load

Table 10 shows all the buses voltages in two different scenarios. Buses voltages are more or less same in both scenario and there is no considerable voltage drop when the vehicles start charging .This is mainly due to network configuration. Table 10 shows lines percentage loading with and without charging vehicles at peak load. Without PHEVs there is no overloaded line at peak load but after vehicles start to charge, line loading increase dramatically and there are two overloaded lines, indicated in the table with bold and underlined format, one from bus CBB2 to CS2 with 109.9% loading and other one from CS5 to CBB2 with 135.8% loading, meaning that system is under stress condition.

Table 10: Buses voltages in per unit for different scenarios

Bus Name	**BAU**	**Charging at peak load**
CBB2	1.07	1.07
CS10	1.06	1.06
CS3	1.07	1.06
CS9	1.07	1.07
CS1	1.06	1.06
CS4	1.07	1.06
CS7	1.06	1.06
CS8	1.07	1.07
CS2	1.07	1.06
CS11	1.07	1.06
CS5	1.07	1.06
CS6	1.06	1.06

Table 11: Loading of lines as percentage of rated power

From Name	**To Name**	**BAU**	**Charging at peak load**
CS8	CBB2	29.80	45.60
CBB2	CS2	73.30	**<u>109.90</u>**
CBB2	CS5	19.10	28.40
CS5	CBB2	90.60	**<u>135.80</u>**
CS10	CS9	0.00	0.00
CS1	CS10	23.60	35.50
CS3	CS4	1.50	2.20
CS3	CS11	1.50	2.20
CS9	CS8	12.80	19.30
CS2	CS1	53.00	80.00
CS5	CS4	29.70	44.70
CS7	CS8	0.00	0.00
CS6	CS7	53.10	80.00
CS11	CS2	1.60	2.50
CS5	CS6	52.30	78.90

3.2. Description of Sample 10 kV Residential Network in Gothenburg

This sample network is a 10 kV residential network located in the Gothenburg city. It has been made up of three 10 kV feeders i.e. RF1, RF2, and RF3 supplied from RBB1 10 kV busbar. Figure 8 shows how this 10 kV residential network is. It is called a residential distribution network, because most of the customers in this area are residential houses. The power consumption of all the outgoing feeders separately and also the aggregation of these three feeders load consumption is available through the data from Göteborg Energy. In normal situation, circuit breaker at substation RS2 is open, so line RF1 supplies all the substation starting from RS3 and ending at RS2 therefore investigation of residential 10 kV network is limited to one radial configuration starting from RS3 and ending at RS2 as it is shown in the figure 18. Maximum loading of this 10 kV network i.e. maximum summation of these three feeders in the year 2008 is 7.874 MW and contribution of line RF1 is 2.815 MW at this peak load.

Similar to commercial area, to have a fair load distribution, total loads have been distributed proportionally to the maximum current drawn by each substation in year 2008.

$P_i = P_{LineRF1} \times a_i$ (2.26)

Where:

P_i: load of substation (i) at peak load.

$P_{LineRF1}$: total power of line RF1 at peak loads i.e. 2.815 MW.

a_i: distribution coefficient of each substation supplied by the line RF1 and is calculated as below:

$a_i = \frac{I_i}{\sum_i I_i}$ and $\sum_i a_i = 1$

Where:

I_i: Maximum current of each substation and calculated as below

$I_i = \sum_j C_j$

Where

C_j: Maximum current of transformer j at substation i

Like the commercial area, having calculated each substation load, then probable power required for charging vehicles at each substation must be calculated. Here it is assumed that probable number of vehicles at each substation is proportional to that substation load.

$N_{RS1} = N_{total} \times Pro_{RS1}$ (2.27)

Where:

Pro_{RS1}: probability of having a vehicles charging at substation RS1 which is calculated as in (2.27):

$Pro_i = \frac{P_i}{\sum_i P_i}$ (2.27)

Where:

P_i: load of each substation supplied by line RF1

Proi: probability of having a vehicle charging at substation i supplied by line RF1.

So the probable total number of PHEVs at this residential area at peak load will be:

$$N_{total}=\frac{N_{RS1}}{\frac{P_{RS1}}{\sum_i P_i}} \cong 680 \qquad (2.28)$$

Probable number of vehicle at each substation will be:

$$N_i=N_{tota}\times Pro_i$$

Probable required power for charging the PHEVs at each substation will be:

$$P_{PHEVi}= N_i\times 3.6\ kW=\frac{N_{RS1}}{P_{RS1}} \times \frac{\sum_i P_i}{\sum_i P_i}\times P_i \times 3.6 = N_{RS1} \times 3.6 \times \frac{P_i}{P_{RS1}}$$

And finally

$$P_{PHEVi} = \frac{P_{PHEVRS1}}{P_{RS1}}\times P_i \cong 1\times P_i$$

Where:

P_{PHEVi}: the probable active power required for charging the vehicles at substation i

Figure 17 shows single line diagram of the 10 kV residential network in the Gothenburg drawn in the Power World. As it is observed, there are over loaded lines in this network, meaning that this network cannot handle charging of 680 vehicles simultaneously at peak load of the 10 kV residential network.

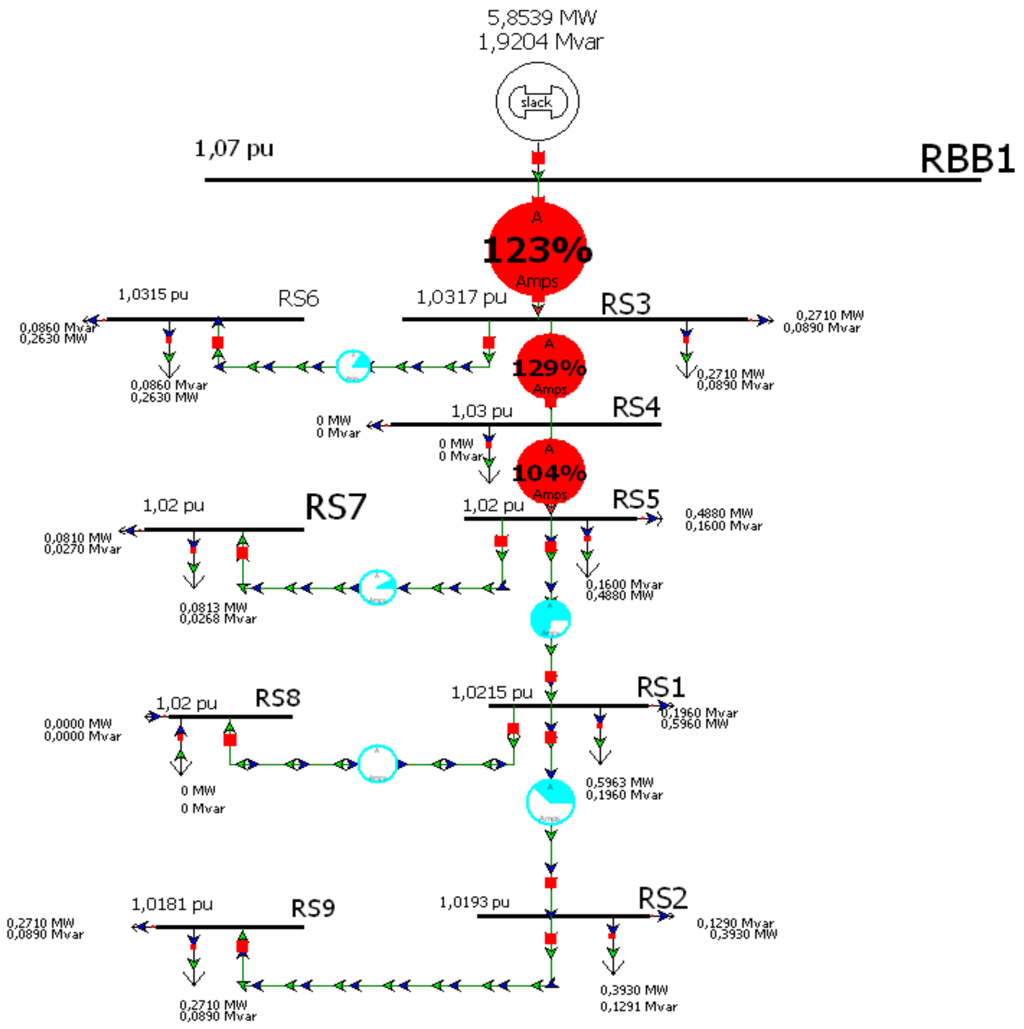

Figure 17: single line diagram of the 10 kV residential network in the Gothenburg

3.2.1. Case study Results and Discussions

To see effect of charging PHEVs on a real 10 kV residential network, two scenarios like commercial area have been considered as below:

- BAU: System at peak load without any PHEVs
- Simultaneous charging of all PHEVs at peak load

Table 12 and 13 indicates the result of this case study. As it is seen in the table 12 when vehicles start charging simultaneously, there is a voltage drop at buses but all the buses voltages are in the acceptable range in both scenarios. Table 13 indicates line loading as percentage of their nominal rating. In the BAU scenario there is no overloaded line but in the charging at peak load scenario there are three overloaded lines i.e. line form bus RBB1 to RS3, line from bus RS3 to RS4 and line from bus RS4 to RS5, indicating that network is under stress condition.

Table 12: Buses voltages in per unit for different scenarios

Bus #	BAU	Charging at peak load
RBB1	1.07	1.07
RS3	1.05	1.03
RS4	1.05	1.03
RS5	1.05	1.02
RS6	1.05	1.03
RS7	1.05	1.02
RS1	1.05	1.02
RS2	1.05	1.02
RS8	1.05	1.02
RS9	1.04	1.02

Table 13: line loading as percentage of rated power

From bus	To bus	BAU	Charging at peak load
RBB1	RS3	64.10	**131.80**
RS3	RS4	66.10	**133.00**
RS3	RS6	7.60	15.20
RS4	RS5	53.00	**106.40**
RS5	RS7	4.10	8.20
RS5	RS1	36.50	73.10
RS1	RS2	19.20	38.50
RS1	RS8	0.00	0.00
RS2	RS9	0.00	0.00

3.3. Calculation maximum number of vehicles that can be charged without any violation

For the distribution companies (Discos) it is very important to know the maximum number of the vehicles that can be charged at any time in the distribution network. This number is strongly dependent to the way that vehicles have been distributed in the distribution network i.e. with different distribution of charging vehicles; different maximum possible vehicle charging is obtained. In this part of the master thesis maximum possible charging is obtained for both commercial and residential 10 kV network in one area in Gothenburg while the most possible distribution has been considered. Most possible distribution here, is proportional to load, in other word, it is assumed that the places with more load are more probable to be used for charging the vehicles. This seems to be a quite fair assumption because in the residential and commercial area, places with higher load level include more people and consequently more vehicle owners and finally more vehicles demanding for recharge. In the part 3.1 and 3.2 it was seen that commercial and residential 10 kV network in the Gothenburg were not able to charge 894 and 680 vehicle respectively at their peak load because there were some overloaded lines.

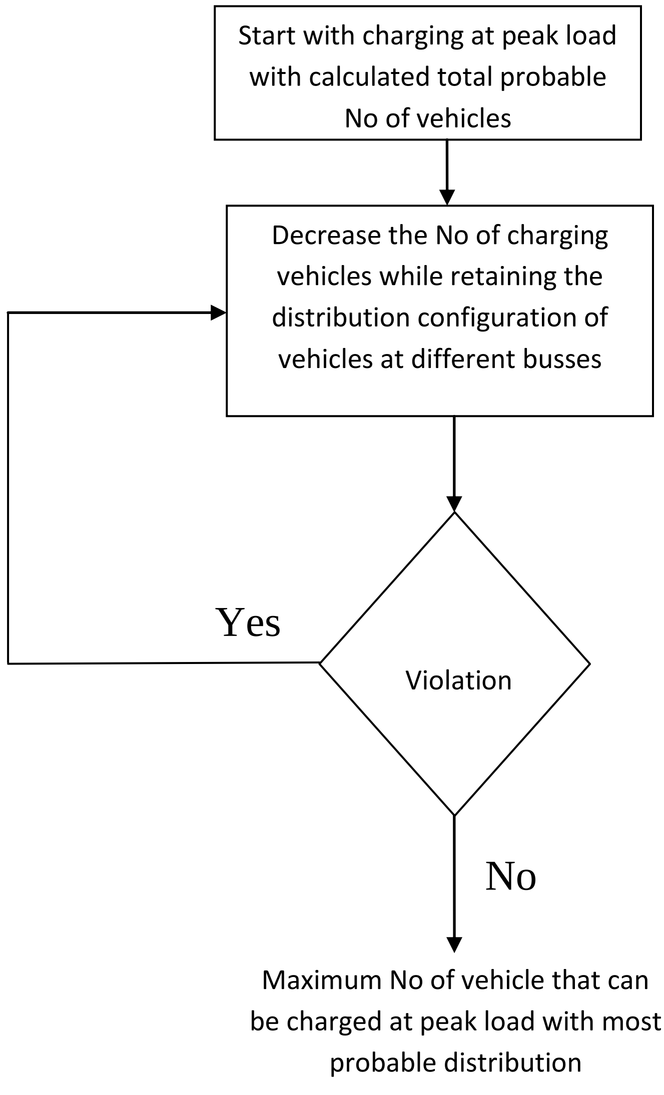

Figure 18: flow chart for calculation maximum possible charging

Figure 18 shows the procedure that has been used for calculation maximum possible vehicle charging. Based on the procedure illustrated in the figure 18, table14 and figure 19 shows the maximum possible vehicle charging for the commercial area at its peak load.

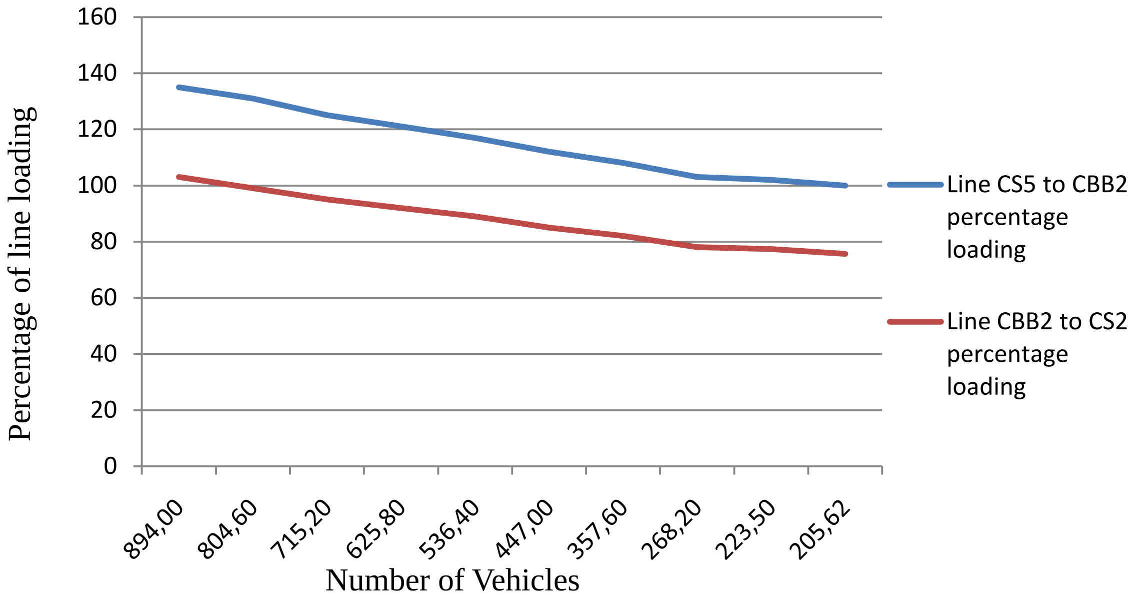

Figure 19: Percentage loading of 2 most loaded line in the commercial area versus different number of charging vehicles

As it is seen in figure 19, two most loaded lines at commercial 10 kV network are line from CS5 to CBB2 and line from CBB2 to CS2. Number of vehicles has been decreases till reaching loading of 100% for line from CS5 to CBB2. In this network, there is no under voltage, even when all the vehicles have been connected for charging simultaneously. Therefore considered violation is overloading of the lines. Figure 19 indicates that number of vehicles charging has been decreased till 205.62 vehicles that correspond to no overloaded lines. Table 14 shows exact number of the quantities in figure 19 in the table format.

Table 14: Percentage loading of 2 most loaded line in the commercial area with different number of charging vesicles'.

Percentage of vehicles	Number of Vehicles	Line CS5 to CBB2 percentage loading	Line CBB2 to CS2 percentage loading
100	894.00	135	103.00
90	804.60	131	99.00
80	715.20	125	95.00
70	625.80	121	92.00
60	536.40	117	89.00
50	447.00	112	85.00
40	357.60	108	82.00
30	268.20	103	78.00
25	223.50	102	77.30
23	205.62	100	75.70

Same procedure has been done for the residential area i.e. number of vehicles has been decreased till there is no violations in the network. In the residential area like the commercial one the violation means line over loading and under voltage is not the case in this network.

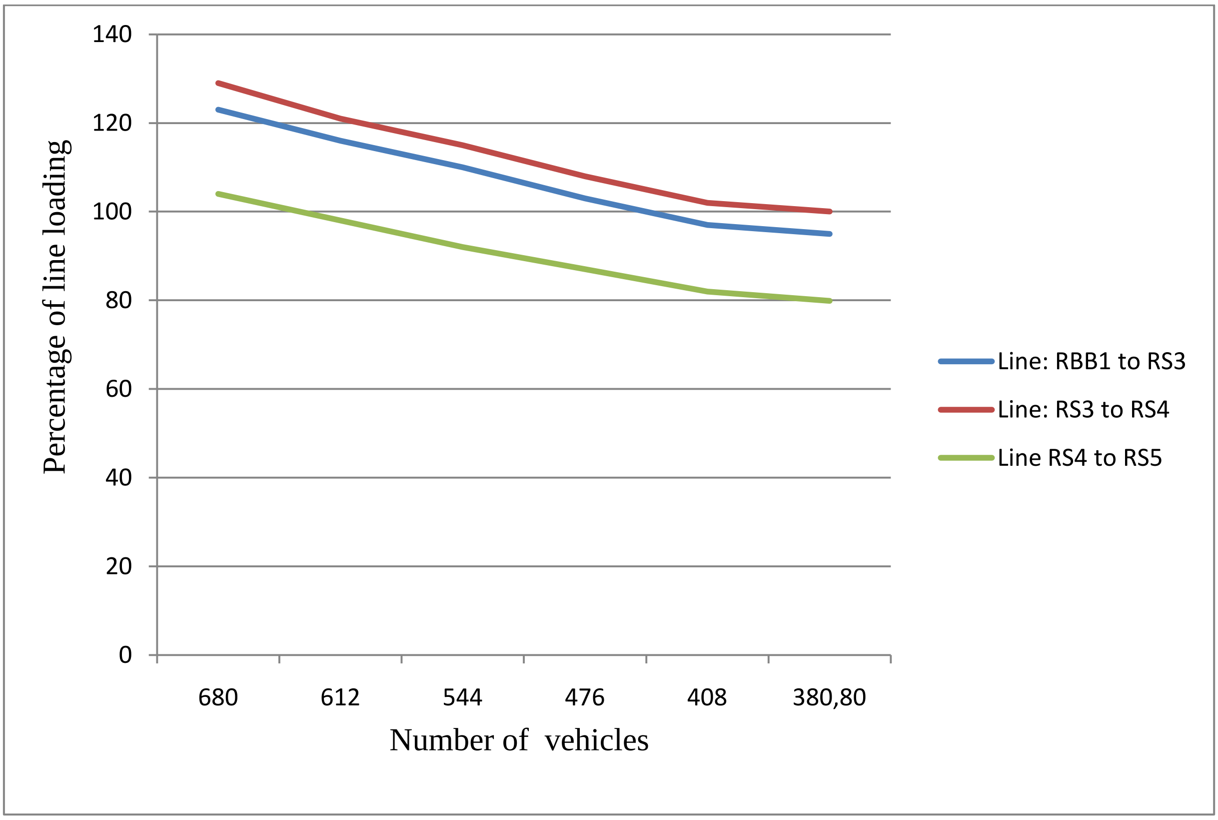

Figure 20: Percentage loading of 3 most loaded line in the residential area versus different number of charging vehicles

Figure 20 shows percentage of three most loaded lines in the residential network. As it is seen number of vehicles has decreased to 380 till there is no line with loading percentage of more than 100%. Table 15 shows the same data in more details.

Table 15: Percentage loading of 3 most loaded line in the residential area with different number of charging vehicles**.**

Percentage of vehicles	Number of Vehicles	Line RBB1 to RS3 percentage loading	Line RS3 to RS4 percentage loading	Line RS4 to RS5 percentage loading
100	680	123	129	104.00
90	612	116	121	98.00
80	544	110	115	92.00
70	476	103	108	87.00
60	408	97	102	82.00
56	380,80	95	100	79.90

3.4. Reliability Issues

Finding maximum number of vehicles that can be charged in the distribution network without any over loading does not necessarily mean this number of vehicles can be charged in the network without any problem. In other word system must be capable to meet the loads requirement without any violation both in the normal condition and fault condition. For example during the time that vehicles are charging, if a fault happens, there must be at least one path for loads supply without any over loading. This safe path can be obtained by changing different circuit breakers status in the network. Figure 21 shows flow chart for the procedure that can be used for the maximum number of vehicles that can be charged simultaneously without any over loading and in a reliable manner in terms of feeder failure.

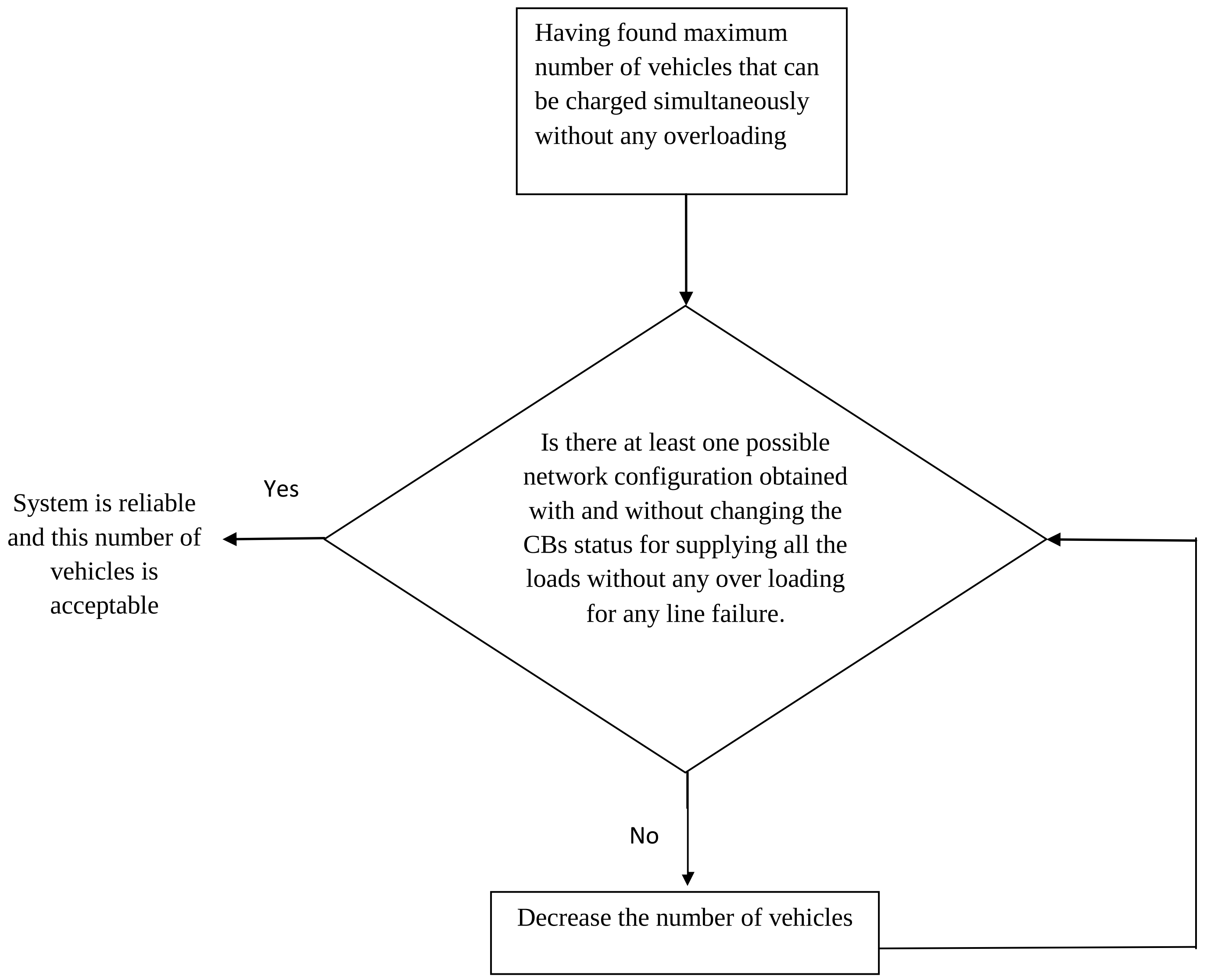

Figure 21: flow chart for checking the system reliability

3.5. Effect of power electronic devices

In the close future, V2G i.e. voltage to grid will be applicable and vehicle batteries will inject power to grid. The charger of these vehicles are bidirectional, in other word they can flow the power both from grid to vehicles and also from vehicles to grid. These chargers are equipped with controllers that are able to set any power factor for the charger. For example they will be capable to inject pure active or reactive power to grid. This feature will be very useful for mitigation the violation in the distribution network. For example in a case that there is a voltage drop because of charging vehicles, some of the vehicles can inject reactive power to the grid for reactive power compensation and finally mitigate the voltage drop. These chargers are also capable of power factor correction. In fact they can compensate the other loads inductive current by injection of a capacitive current.

Chapter 4

4. Analysis of PHEVs on the Meshed Transmission Networks

4.1. PHEVs in the Transmission Networks: A Brief Review

As it was shown in Fig. 1, even though the PHEVs are connected in low voltage distribution system, they also have large effects on the generation system and transmission system levels. If the vehicle users are free to charge their cars anytime they want (uncontrolled charging), one can easily say that they will plug in at peak loads. In this case, PHEV increases the system peak loads which require additional generation (and transmission) capacity. A new dimension of peak load capacity for the power system might be required if the charging of PHEV is left uncontrolled. On the other hand, if controlled charging is used, which means that the utility controls charging between, for example, 10:00 pm and 07:00 am. In this case the system load profile will be improved in a way similar to the effect of "valley filling" demand-side management measure, meaning that the system utilization can be improved. So the required power for charging the vehicles could affect the generation and transmission capacity by demanding more power than the case without PHEVs. In other hand the interesting feature of the PHEVs from power system point of view is their capability to inject power to grid when they are parked (V2G). V2G presents a mechanism to meet power requirement of the power system, using electric vehicles, when they are parked. The most economic effect of this green feature is the market for ancillary services. The second interesting feature of V2G is spinning reserve. In the areas with deregulated market this advantages of V2G is easier to observe. PHEVs are well suited for ancillary services and spinning reserves because the batteries of the vehicles are quick enough to respond the power demand required by the power systems [3]. To have a good understanding of PHEVs effects on the transmission network, two test transmission networks with specified penetration of PHEVs have been considered in this chapter.

4.2. Effect Analysis of PHEVs on the 10-Bus Test System

First, effects of PHEVs have been considered on a sample meshed transmission network. The system description and analysis of this simulation is as below.

4.2.1. Description of 10-Bus system

10 bus systems is a sample transmission network. This system includes:

- 10 busses of 138 kV.
- 7 loads
- 6 generators
- 7 capacitors

7 other loads have added to the PQ busses of this test system for simulation of the PHEVs. Figure 22 shows how this system looks like. The horizontal loads connected to the busses simulate thePHEVs.

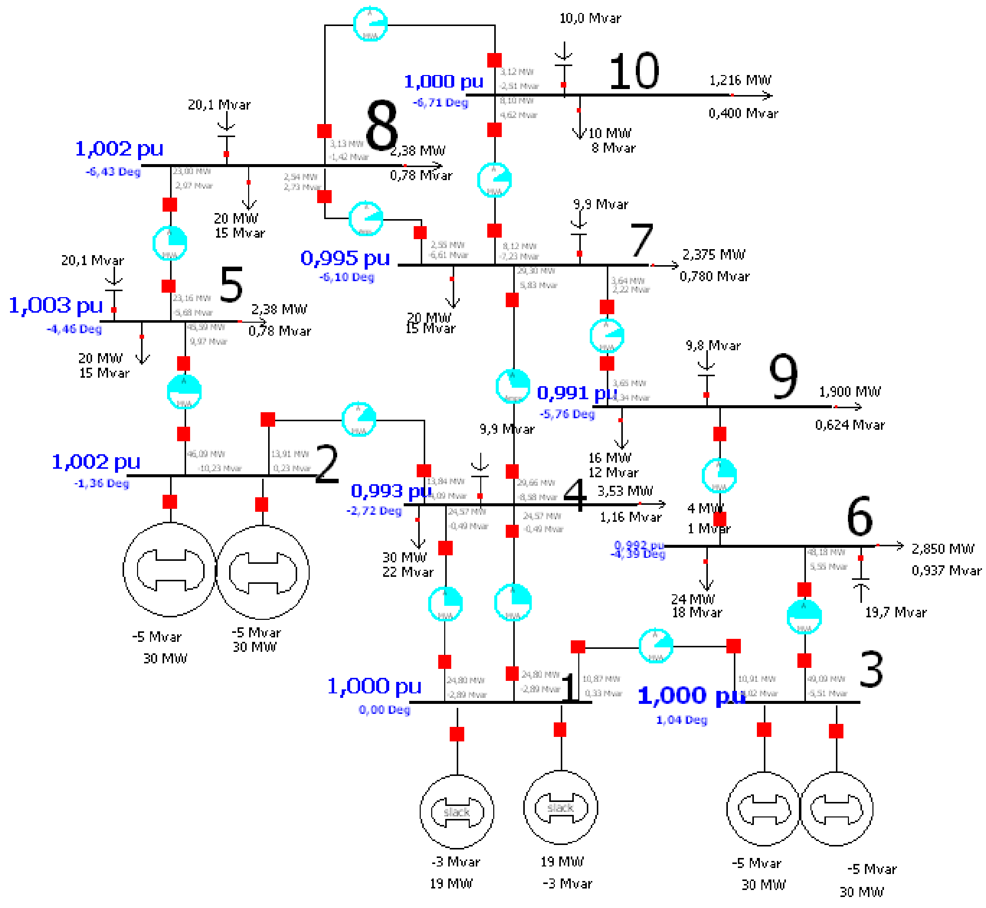

Figure 22: Single line of 10 bus test system

A 10 percent penetration of PHEVs i.e. 10 percent of test system total load has been introduced to this system. Total power factor of the battery and charging equipments has been assumed to be 0.95 while regular load of the network have different power factor. Required power for charging vehicles at each bus has been calculated as in (4.1):

$$P_{PHEVi} = \sqrt{{P_i}^2 + {Q_i}^2} \times 0.1 \times 0.95$$

$$Q_{PHEVi} = P_{PHEVi} \times TAN(ACOS(0.95)) \qquad (4.1)$$

Where:

P_{PHEVi}: Required active power for charging vehicles at bus i

Q_{PHEVi}: Required reactive power for charging vehicles at bus i

P_i: Demanded active power at bus i

Q_i: Demanded reactive power at bus i

4.2.2. Case study results and discussions

The results of this simulation indicate that introducing a 10 percent penetration of PHEVs in to the test system will lead to voltage decrees in all the busses. Figure 23, the diagram of buses voltage for both cases i.e. with and without PHEVs, shows the voltage drop after PHEVs have been connected to the grid for recharging. As it is shown in this picture except the buss 1, which is slack buss, all other busses voltage have decreased but important result is that all buses voltage are still in the range and there is no out of range bus voltage.

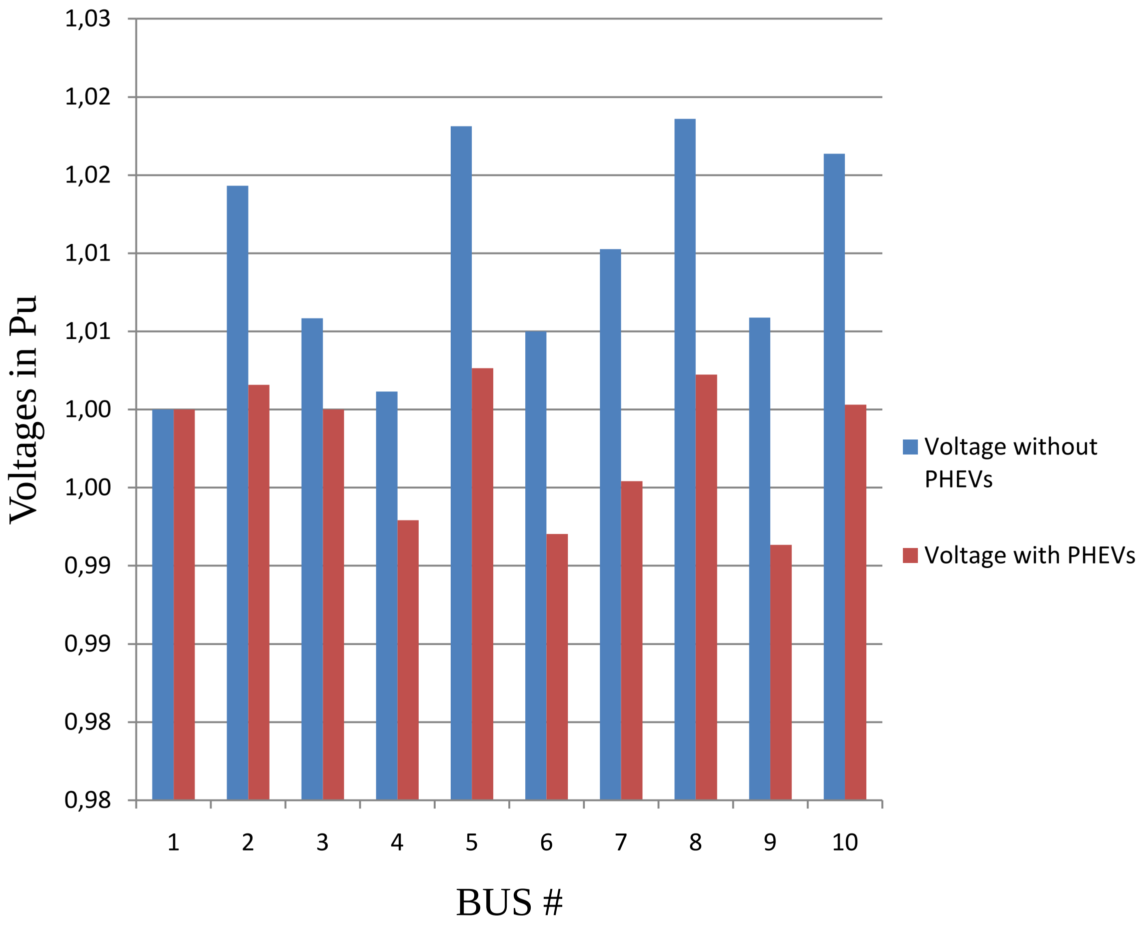

Figure 23: Different busses voltage with and without PHEVs

4.3. Effects of PHEVs on the 32-Bus Nordic system

While it is found the problems with low voltage distribution network mainly related to overloading of distribution feeders, in the transmission level it was seen an interesting phenomena caused by PHEVs on the 32-Bus Nordic system. The results have shown that with 10% penetration level of PHEVs in this system, voltage levels at many buses have increased. This is quite interesting since this is not normally the case for the radial system. It cannot be concluded for all the system but for this particular Nordic 32-bus system, the power flows in the South have changed significantly in the case with PHEVs as compared to the base case without PHEVs.

Nordic 32-bus system is a meshed transmission network with 3 voltage levels. The single-line diagram of this system is shown in Fig. 9. The detailed information about the system can be found in [14]. The test system information and assumptions that are considered for this case are as below.

4.3.1. Description of Nordic 32-Bus system

Nordic 32-Bus system is a simulated Nordic transmission system. This network has got three different voltage levels. Most of the generators have been located in the north part of the network and most of the loads have been located in the south part. The power is transmitted from the north part to the south part via the long transmission lines. Nordic 32-Bus system includes:

- 19 buses with 400 kV voltage, 2 busses of 220 kV and 20 busses of 130 kV.
- 20 generators.
- 22 loads.
- 11 switched shunts.
- 61 transmission lines.

22 other loads have been added to the system to simulate the PHEVs. Figure 24 shows an overview of this network. In this figure the 400 kV busses and transmission lines have been shown in black and 220 kV and 130 kV lines and busses are in gray. Again a power factor of 0.95 has been considered for whole charging system i.e. battery and charging equipments. Required power for charging PHEVs has been considered as a percentage of the present load. P and Q required for charging at each bus is calculated according to equation (4.1).In the figure 25 required powers for charging PHEVs have been shown with horizontal loads.

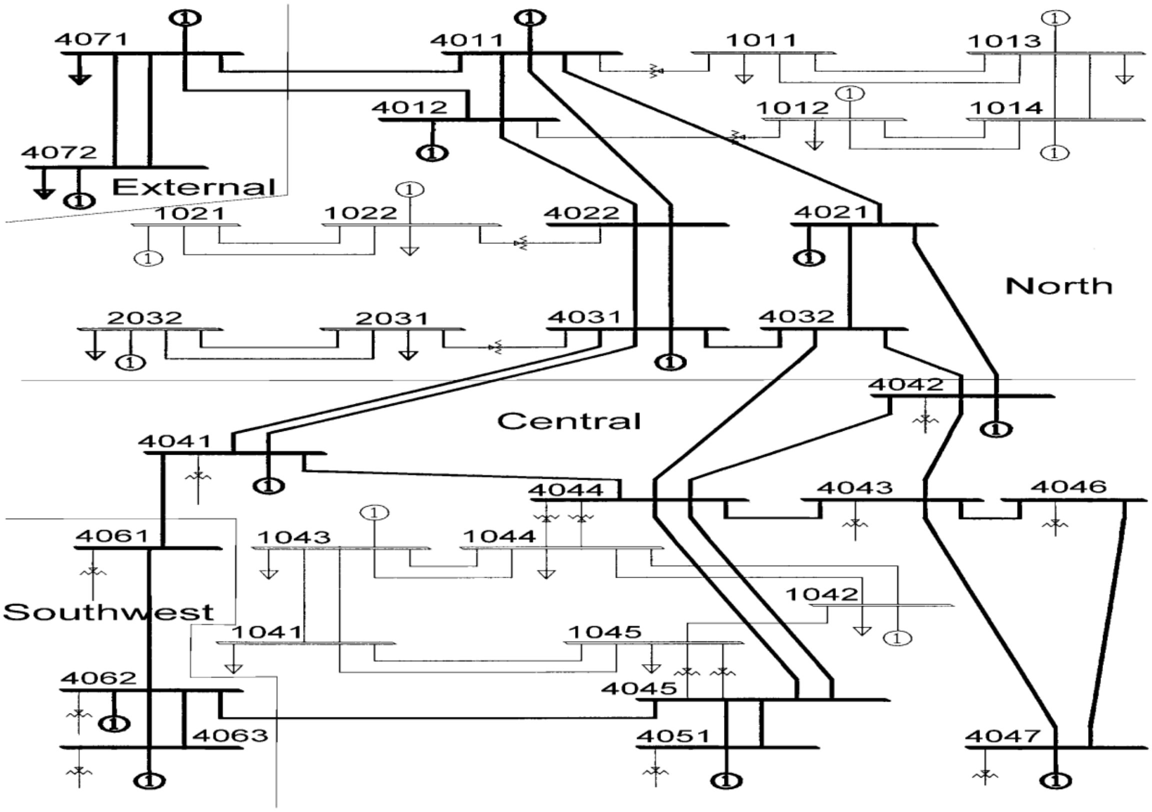

Figure 24: Nordic 32-Bus system overview

4.3.2. Case study results and description

To analyze effect of the PHEVs on the network, the following 3 cases have been considered:

- Business as usual (BAU): The system without PHEVs
- 10% penetration: The BAU with 10% load as PHEVs at each bus with load.
- 10% penetration V2G: The BAU with 10% load as V2G at each bus with load.

For simulation the V2G effect of the PHEVs on the transmission network, loads with minus sign have been considered.

Introducing the penetration of 10 percent will dramatically change the voltage profile of the transmission network. As shown in Table 16, figure 25 and 26, when adding PHEVs penetration of 10% to the system, there would be 26 buses in the system with voltages level over the maximum allowable limit. This is quite interesting since it is normally expected that the voltage is decreased when the load is increased. However, this can always be true with the radial system like in the distribution network. In the meshed network like the Nordic 32-bus system, when PHEVs loads are added, the power flows over the system have changed quite significantly, especially the reactive power flow. This makes the voltages magnitudes in southern part of the system increased. In this simulation study, the increase in PHEVs load can be managed by existing generators for both active and reactive power.

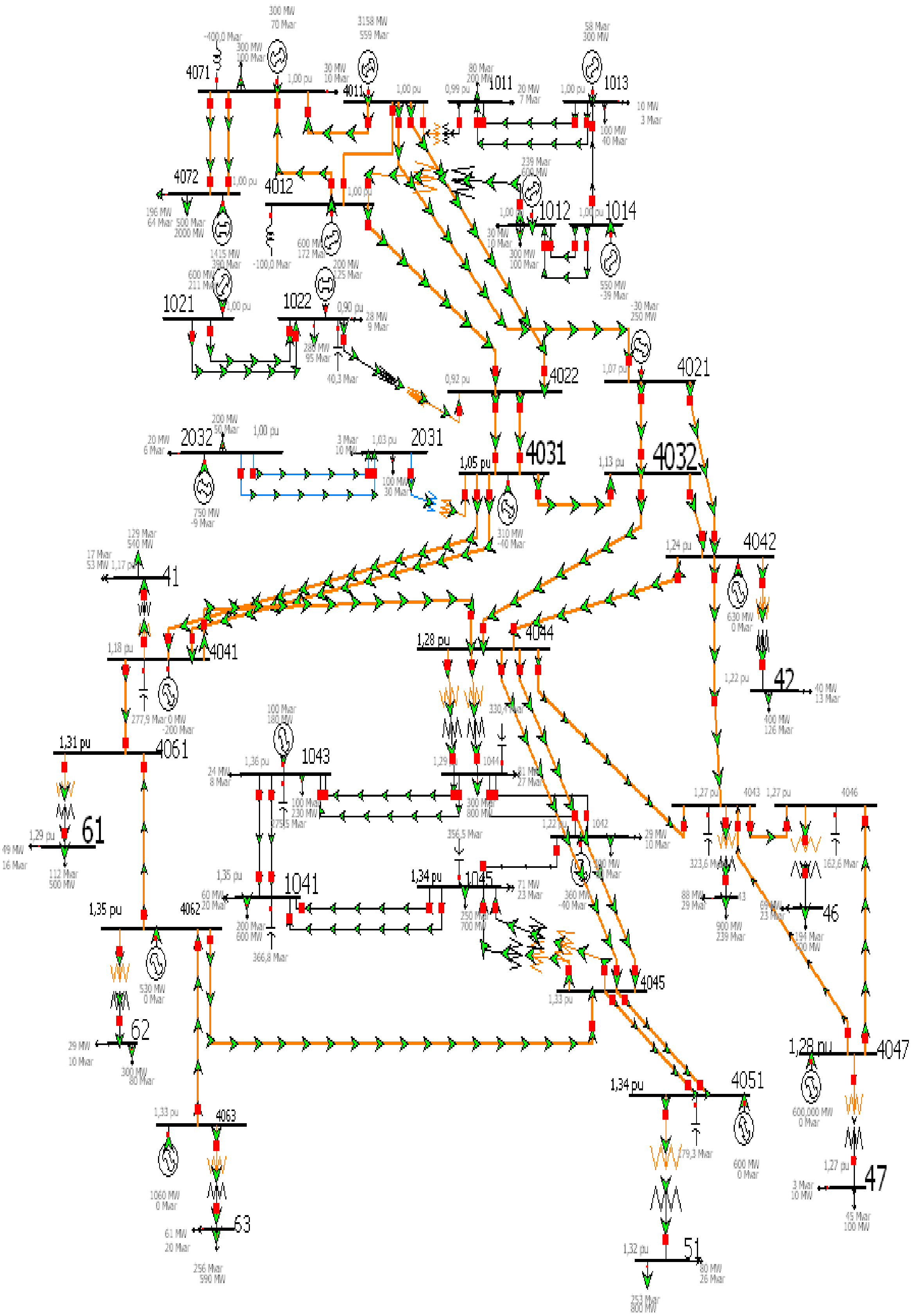

Figure 25: Nordic 32-Bus system with 10% penetration of PHEVs

Figure 26 shows a comparison between the voltage profile of the tests system before and after introduction a penetration of PHEVs in to the transmission network.

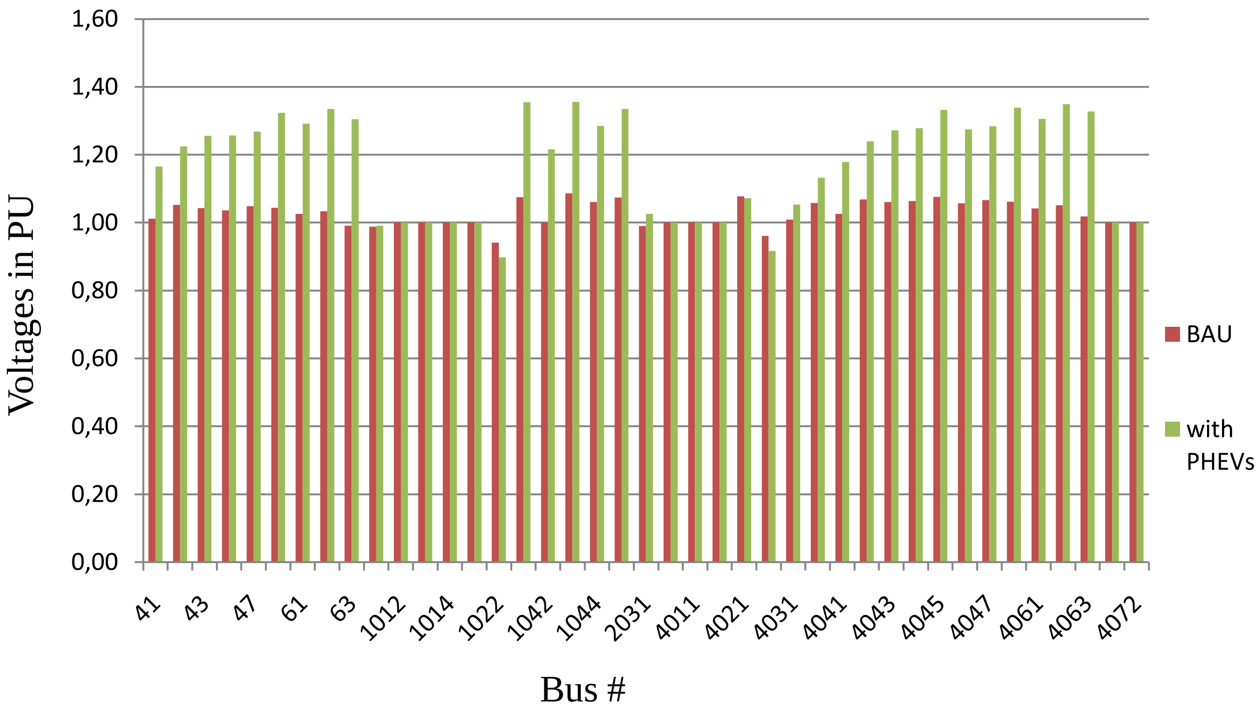

Figure 26: Voltage profile of the system before and after introduction of 10% penetration of the PHEVs

As it is seen in the figure 26, after adding PHEVs into the test system, almost all the network voltages increase, meaning that power flow especially reactive power flow in the system has changed dramatically.

Table 16: system specifications in three scenarios

	No of over voltage busses	No of under voltage busses	No of violations in N-1 contingency analysis	Active power losses	Total active power generation
without PHEVs	0	0	307 violations and 9 unsolvable contingencies	606.8 Mw	11679.8
with 10% penetration of PHEVS	26	1	1257 violations and 16 unsolvable contingencies	964.6Mw	12544.9
with 10% penetration of V2G	1	6	587 violations and 15 unsolvable contingencies	491.5Mw	10254.3

Buss No 1041 is one of those buses which will have over voltage when there is a 10% penetration of PHEVs .At this buss, it is possible to add 189.73 kVA load with PF of 0.95 lag for simulating battery recharging while other busses are not serving PHEVs without reaching the overvoltage limit. This amount of power is equivalent to normal charging of 124 PHEVs simultaneously. This critical amount of load has been obtained by iterative method i.e. keep increasing the load at this bus till bus voltage exceed the limit as it is illustrated in figure 27.

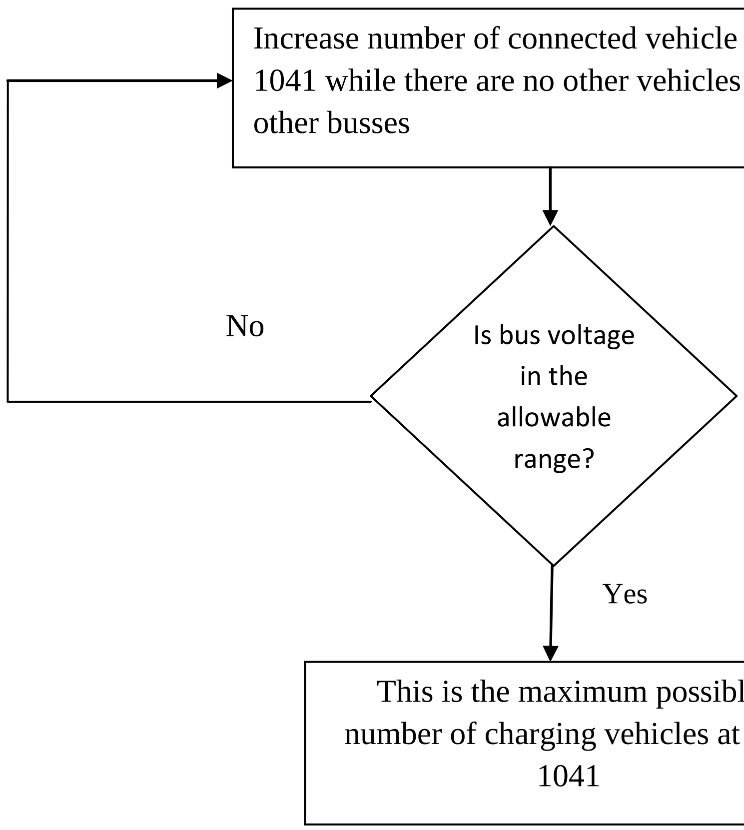

Figure 27: Iterative method for calculation maximum possible charging at one bus

Another important result from this study is that number of violations (mainly in bus voltages) in N-1 contingency analysis of the system increases dramatically with 10% penetration of PHEVs, indicating that power system security must be properly studied with mass introduction of PHEVs. With V2G, the number of violations is reduced as compared to the 10% penetration of PHEVs case. The number of violations in the 10% penetration of V2G is not less than the BAU scenario. It can be concluded that when there is a V2G penetration, the number of existing elements in the networks has increased and consequently the number of violations has increased. Table 16 also shows a comparison between the losses in three scenarios. As it is observed, the minimum losses are for the case with V2G penetration, which emphasizes the superior feature and economical benefits of V2G.

Chapter 5

5. Maximizing penetration of DGs in the distribution network

5.1. Over voltage effect of the DGs in the networks and introduction of the existing solutions

European governments are working toward an ambitious target of considerably increasing the amount of the renewable energy in order to reduce the adverse environmental impacts of traditional sources of energy [15] and [16].The superior feature of using green energy sources encourage the governments all around the world to keep on investment on the renewable energy sources. This new tendency toward green energy sources has arisen many challenges regarding embedded generation. The connection of DGs, their protection and also their operation in the different load levels are new challenges that have been posed to the power system operators. These challenges usually limit the penetration level of DGs to the existing network. For example in a rural network, voltage rise effect is a factor that limits the penetration of the wind turbine or DGs in general. To overcome the voltage rise effect, power system operators prefer to connect the wind turbines to the high voltage side to minimize the effect of voltage rise but the economical viability of the wind turbine is very sensitive to connection costs i.e. the higher the voltage the higher the costs and therefore the developers of the wind turbines prefer to connect at lower voltage [15]. At time being, there are three ways for mitigation voltage rise effect in the networks equipped with DGs.

- Power curtailment, which means decrees the power output of the distributed generator when it is lightly loaded.
- Absorbing reactive power at DGs bus can mitigate the voltage rise effect. So using of reactive power control facilities like STATCOM at connecting point is recommended.
- Using of co-ordinated voltage control strategy for example by OLTC (On load tap changer) is another existing solution for voltage rise effect.

5.2. Over voltage effect of DGs on the modified IEEE 13 –Node test distribution systems

To study the voltage rise effects in the networks equipped with DGs, one sample network including three distributed generators has been tested and possible solution for mitigation of over voltage has been simulated. The test network is IEEE13-Node test distribution system. It has been modified to fit in our simulation. The single phase loads has changed to three phase loads to make the Power World simulation possible. Figure 28 shows how this test system looks like.

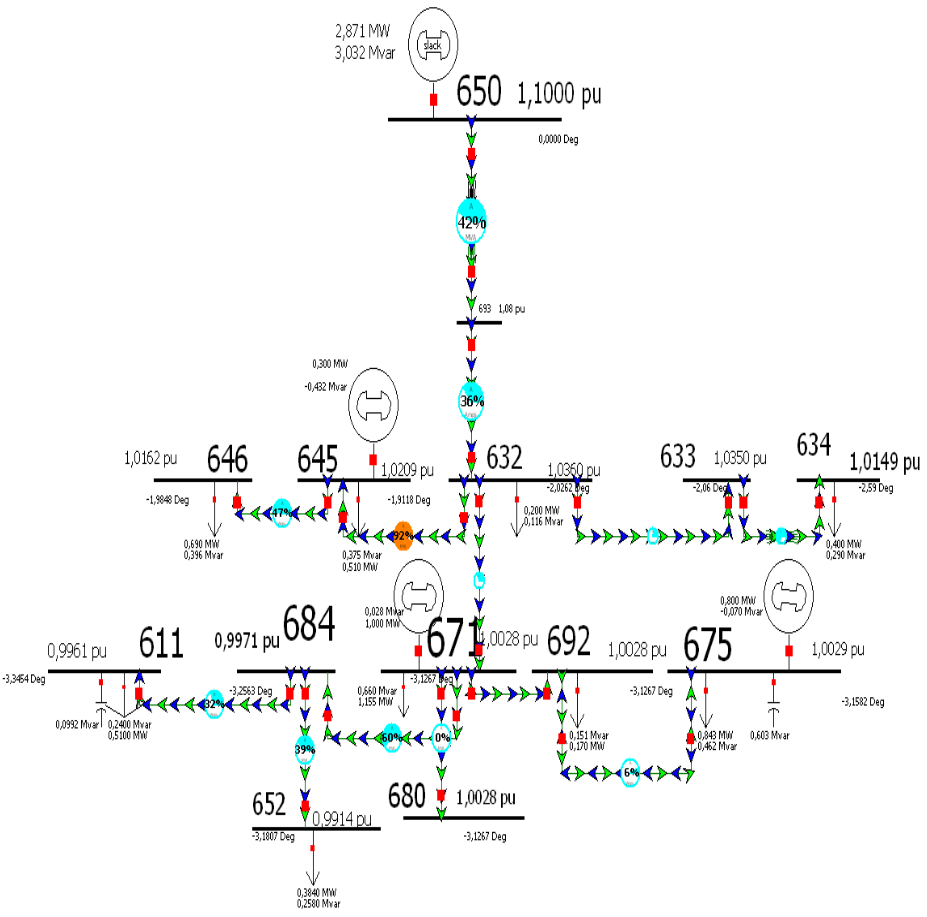

Figure 28: Over view of the IEEE 13- Node test system with some modification.

5.2.1. Description of modified IEEE 13 –Node test distribution systems.

System which has been used for this study is IEEE 13-Node test system. It has been modified to fit in our investigation. The impedance of all three phases in the cables and over headlines are equal. The imbalanced loads have changed to balanced loads to be able to simulate the network with Power World. Three generators have been added to this system at busses 645,671 and 675. These generators show the DGs in the distribution network. The line ambacities have been set according to [8].

These systems include:

- 13 busses with voltages of 115KV, 4.16KV and 0.48 KV.
- 9 loads
- 2 transformers.
- 2 capacitors at bus 611 and 675.
- 3 distributed generators and one slack generator

Bus number 693 has been added just for connecting transformer to the line.

In this network, by disconnecting bus 645 load while the DGs generation remain constant for simulating the lightly load, there will be voltage increase in many of the network buses but still all of the buses voltage are in the acceptable range. If the penetration of the DGs increase by disconnecting the other load like load at bus 675, then considerable voltage increase will be observed in the networks and the voltage of the busses 633, 632, 645 as it is seen in the table 18 will be out of acceptable range. It shows that lightly loaded network with high penetration of DGs will lead to over voltage in busses.

Table 17: DG Penetration percentage

	Normal condition	Disconnecting 645	Disconnecting 645 and 671
DGs Penetration	42,85%	47,72%	60%

Table 17 shows DGs penetration in different scenarios and table 18 shows the different bus voltage at different scenarios. Power curtailment is one of the solutions to mitigate voltage rise. In our case for example by 100% power curtailment of generator 675 and 50% power curtailment of the generator 671 the voltage of bus 645 will back to acceptable range i.e. 1.04 pu.

Table 18: Bus voltage in different scenarios

Bus #	PU volt: normal condition	PU volt: discon 645	Pu Volt: discon 645 and 671
611	0,994	1,004	1,038
632	1,035	1,045	**1,060**
633	1,034	1,044	**1,059**
634	1,014	1,024	1,039
645	1,020	1,037	**1,052**
646	1,015	1,032	1,047
652	0,989	1,000	1,033
671	1,001	1,011	1,044
675	1,001	1,011	1,049
680	1,001	1,011	1,044
684	0,995	1,005	1,039
692	1,001	1,011	1,044

5.2.2. Further work for Maximizing DGs penetration in the modified IEEE 13 –Node test distribution systems with GAMs

Non linear programming with GAMS [17], [18] and [19] can be used to maximize the DGs penetration to existing distribution network. In a lightly loaded distribution network that has been simulated by disconnecting some loads in this study, optimization with GAMS determines the minimum required power curtailment and also the optimal way of distribution this minimum power curtailment between DGs to mitigate the voltage rise effect. The variables and parameters for this optimization will be:

i subscript for all of the buses

j subscript for all of the buses

k subscript for the DG buses

P_i generation power at bus i

$Pdem_i$ demand power at each bus

Q_i generation power at bus i

$Qdem_i$ demand power at bus i

V_i voltage amplitude at bus i

$Delta_i$ voltage angle at bus i

$Pcur_i$ curtailed power at bus i which is set to zero for non DG busses and has been limited between zero and maximum power of DG at DG busses.

$Genphi_i$ DGs generation angle i.e. ARCTAN (Q/P) for DGs buses and is zero for all the other buses.

$Y_{(i,j)}$ admittance amplitude between bus i and j

$Theta_{(i,j)}$ admittance angle between bus i and j

Penet summation of DGs generation minus summation of DGs curtailment

Objective function is maximizing Penet=$\sum_k P_k - \sum_k Pcur_k$ (5.1)

Constraint 1 for all the buses will be active power flow equation:

$$P_i = Pdem_i + Pcur_i + \sum_j V_i \times V_j \times Y_{(i,j)} \times COS\left(Theta_{(i,j)} + Delta_{(j)} - Delta_{(i)}\right) \quad (5.2)$$

And constraint 2 for all the buses will be reactive power flow equation:

$$Q_i = Qdem_i + \left(Pcur_i \times TANG(Genphi_i)\right) - \sum_j V_i \times V_j \times Y_{(i,j)} \times Sin\left(Theta_{(i,j)} + Delta_{(j)} - Delta_{(i)}\right) \quad (5.3)$$

Total program text is available in the Appendix A.

Chapter 6

6. Conclusions

6.1. Conclusions

This master thesis summarizes possible key effects of introduction of PHEVs in the power system. Results from the studies on the IEEE 13-Node test system, show that problems with low voltage distribution networks with PHEVs are mainly related to overloading of distribution feeders, and under voltages in end-users locations, in the case of quick charging during peak load period. If normal charging is to be used, the system would be able to support the PHEVs without overloading and under voltage problems.

Study on the real distribution network in the Gothenburg indicates that if charging of vehicles, with most probable distribution which is proportional to loads, left uncontrolled overloading of lines at peak load in the 10 kV network will happen and it implies requirement for smart charging strategy. Study results show that if there is suitable voltage controller in the 10 kV network i.e. main supplier busbar in the 10 kV network has voltage higher than1 pu, the voltage drop in the 400 V network will be negligible both for the commercial and residential area. Fuse rating of the main feeders for the customers in the residential and commercial area must be revised if one phase plug is used for charging the vehicles. Introduced procedure for calculation maximum possible charging in one area can be useful to give an over view of distribution network capacity for charging vehicles in the secure manner to the system operators.

In the transmission level, effects of vehicles charging on the network are strongly dependent to the network topology. While in the 10-Bus test system, voltage drop was the result of PHEVS penetration, an interesting phenomenon with regard to the bus voltage level is observed for the Nordic 32-bus system. That is when PHEVs equally distributed in the system; the voltage in the system might increase, showing the need for voltage regulation measures. However, this could not be concluded for every system since this is system-dependent. Another problem with meshed transmission networks is typically that the level of security could be affected when more PHEVs are plugged into the network.

In the last chapter, study results show the necessity of mitigating measurers regarding with the voltage rise effect in the distribution networks equipped with Distributed Generators. It was also proposed to use the Nonlinear programming with GAMS for maximizing DGs penetration in the lightly loaded situation.

6.2. Future research directions

The following topics which are relevant to the current work are proposed for the further work.

- Since most of the quantities related to effects of PHEVs on the power systems topic are probabilistic quantities, so one comprehensive statistic research about the people driving behavior in the under research area is required.
- Many of the research relates to PHEVs effects on the power system, have concluded that one smart charging strategy is required, therefore in each area many research and investigation are required to find an optimal charging strategy
- A dynamic model of all kind of the electric vehicles is required to investigate the effect of these vehicles on the power systems stability in the transient states.
- Protective scheme of the distribution systems with mass introduction of PHEVs must be revised and especially in the case that these vehicles are capable of power injection to grid this revision will be more necessary.
- Precise model of the DGs in the GAMS will improve the optimal penetration of the DGs in the existing distribution networks.

7. Appendix A

Text of the optimization program with GAMS.

```
********************************************************************************
set i buses/611,632,633,634,645,646,650,652,671,675,680,684,692,693/ ;
alias (i,j);
set k(i) DGs/645,671,675/;
set f(i) non DG Busses /611,632,633,634,646,650,652,680,684,692,693/
    load(i) Load buses /611,632,633,634,645,646,652,671,675,680,684,692,693/
    Head1   Generator data headings / PMin, PMax, QMin, QMax, A, B, C, D, E, F/
    Head2   Line data table headings / Re, Xe, Ch /
    Head3   Demand data table headings / PDem, QDem /;
Scalar Base base KVA  /100000 /;
scalar phi           /3.141592654 /;
************************** DATA SECTION ****************************************
TABLE Generation(i,Head1)  generator data
       PMin    PMax   QMin     QMax      A     B     C
*       KW      KW     KVAR     KVAR
*645     0      230     0       75.593    1.0   8.50   5
650      0      3100   -1000     3100      3.4   25.50  9
*671     0      1000   -100      328.66    3.4   25.50  9
*675     0      750    -100      846.5     3.4   25.50  9
*611     0      0       0        100
;
*****------- Convert generator data to per unit quantities ----------*******
Parameter PMx(i), PMn(i), QMx(i), QMn(i), Ac(i), Bc(i), Cc(i),SMaxpu;
PMx(i) = Generation(i,"PMax")/Base;
PMn(i) = Generation(i,"PMin")/Base;
QMx(i) = Generation(i,"QMax")/Base;
QMn(i) = Generation(i,"QMin")/Base;
Ac(i)  = Generation(i,"A")*Base*Base;
Bc(i)  = Generation(i,"B")*Base;
```

```
Cc(i)  = Generation(i,"C");
**SMaxpu=Maxflow/Base;
*******************************************************************
Table Demand(i,Head3)        Real and reactive power demand at bus i
            PDem       QDem
*           (KW)     (KVAr)
611          510        240
632          200        116
634          400        290
645          510        375
646          690        396
652          384        258
671          1155        660
675          843        462
692          170        151
680            0          0
684            0          0
633            0          0
650            0          0
693            0          0
;
***** convert demand data to pu****************************************
 Parameter Pdempu(i), Qdempu(i);
 Pdempu(i)=Demand(i,"PDem")/Base;
 Qdempu(i)=Demand(i,"QDem")/Base;
 Qdempu("611")=Qdempu("611")-0.001;
 Qdempu("675")=Qdempu("675")-0.00602;
*******************************************************************
Table LineData(i,j,Head2)
```

```
                 Re        Xe        Ch
*               (p.u.)    (p.u.)   (p.u.)
632.645     0.7261     0.7358     0
632.633     0.0863     0.2313     0
633.634     2.2              4          0
645.646     0.4357      0.4415    0
650.693     0.1              0.8        0
693.632     0.37            1.1        0
684.652     1.173      0.4478      0
632.671     0.7570      2.2240    0
671.684     0.4326     0.4447     0
671.680     0.3785     1.1120     0
671.692        0               0          0
684.611     0.1135     0.3336     0
692.675     0.4360     0.2798     0
;
*---FORMATION OF THE Y-BUS MATRIX -----------------------------------
Parameter Z(i,j), GG(i,j), BB(i,j), YCL(i);
Parameter G(i,j), B(i,j), Y(i,j), ZI(i,j), Theta(i,j);
LineData(j,i,"Re")$(LineData(i,j,"Re") gt 0.00) = LineData(i,j,"Re");
LineData(j,i,"Xe")$(LineData(i,j,"Xe") gt 0.00) = LineData(i,j,"Xe");
LineData(j,i,"Ch")$(LineData(i,j,"Ch") gt 0.00) = LineData(i,j,"Ch");
Z(i,j) = (LineData(i,j,"Re"))**2 + (LineData(i,j,"Xe"))**2 ;
GG(i,j)$(Z(i,j) ne 0.00) = LineData(i,j,"Re")/z(i,j) ;
BB(i,j)$(Z(i,j) ne 0.00) = -LineData(i,j,"Xe")/Z(i,j);
BB(j,i)$(Z(i,j) ne 0.00) = -LineData(i,j,"Xe")/Z(i,j);
YCL(i) = sum(j, LineData(i,j,"Ch"));
B(i,i) = sum(j, BB(i,j)) + YCL(i);
G(i,i) = sum(j, GG(i,j));
G(i,j)$(ord(i) ne ord(j)) = -GG(i,j);
B(i,j)$(ord(i) ne ord(j)) = -BB(i,j);
```

```
Y(i,j) = sqrt(G(i,j)*G(i,j) + B(i,j)*B(i,j));
ZI(i,j)$(G(i,j) ne 0.00)  = abs(B(i,j))/abs(G(i,j)) ;
Theta(i,j) = arctan(ZI(i,j));
Theta(i,j)$((B(i,j) eq 0) and (G(i,j) gt 0)) = 0.0 ;
Theta(i,j)$((B(i,j) eq 0) and (G(i,j) lt 0))   = -0.5*phi ;
Theta(i,j)$((B(i,j) gt 0) and (G(i,j) gt 0))   = Theta(i,j) ;
Theta(i,j)$((B(i,j) lt 0) and (G(i,j) gt 0))   = 2*phi - Theta(i,j) ;
Theta(i,j)$((B(i,j) gt 0) and (G(i,j) lt 0))   = phi - Theta(i,j);
Theta(i,j)$((B(i,j) lt 0) and (G(i,j) lt 0))   = phi + Theta(i,j);
Theta(i,j)$((B(i,j) gt 0) and (G(i,j) eq 0))   = 0.5*phi;
Theta(i,j)$((B(i,j) lt 0) and (G(i,j) eq 0))   = -0.5*phi;
Theta(i,j)$((B(i,j) eq 0) and (G(i,j) eq 0))   = 0.0 ;
*******************  Variable Declaration *****************************
positive variable V(i) the bus voltage amplitude;
free variable Delta(i) the bus voltage phase;
free variable P(i) the   bus active power generation;
free variable Q(i) the  bus reactive power generation;
free variable Pcur(i) the curtailed active power of the DGs;
free variable loss the total loss;
integer variable T position of the tap changer of the DG at bus # 650;
free variable S(i,j) the amplitude of apparent power between the buss i and j;
free variable Penet penetration of the DGs;
********** *************Initialization of variables*************************************
V.l(i)=1;
V.fx("650")=1.1;
Delta.l(i)=0;
Delta.fx("650")=0;
P.up(i)=PMx(i);
P.lo(i)=PMn(i);
Q.up(i)=QMx(i);
Q.lo(i)=QMn(i);
```

```
P.fx("645")=0.003;
P.fx("671")=0.01;
P.fx("675")=0.008;
Q.fx("645")=-0.00432;
Q.fx("671")=0.00028;
Q.fx("675")=-0.0007;
********************DGs Power factor definition***************************************
Parameter genphi(i) the angle of the generators ;
genphi("611")=0;
genphi("632")=0;
genphi("634")=0;
genphi("646")=0;
genphi("650")=0;
genphi("652")=0;
genphi("680")=0;
genphi("684")=0;
genphi("692")=0;
genphi("693")=0;
genphi("633")=0;
genphi("645")=arctan(Q.l("645")/P.l("645"));
genphi("671")=arctan(Q.l("671")/P.l("671"));
genphi("675")=arctan(Q.l("675")/P.l("675"));
Pcur.up("675")=P.l("675");
Pcur.lo("675")=0;
Pcur.up("671")=P.l("671");
Pcur.lo("671")=0;
Pcur.up("645")=P.l("645");
Pcur.lo("645")=0;
*Pcur.fx("645")=0;
*Pcur.fx("671")=0;
*Pcur.fx("675")=0;
```

```
Pcur.fx("611")=0;

Pcur.fx("632")=0;

Pcur.fx("633")=0;

Pcur.fx("634")=0;

Pcur.fx("646")=0;

Pcur.fx("650")=0;

Pcur.fx("652")=0;

Pcur.fx("680")=0;

Pcur.fx("684")=0;

Pcur.fx("692")=0;

Pcur.fx("693")=0;

*****************************Assignment of the Bounds**************************

V.lo(load)=0.95;

V.up(load)=1.05;

***************** ****definition of equations******************************************

Equation

obj

*LOSSES

const1(i)

const2(i);

obj..

Penet=e=sum(k,P(k))-sum(k,Pcur(k));

*LOSSES..

*Loss =e= 0.5*SUM( (i,j) , (-1)*G(i,j)*( V(i)*V(i) + V(j)*V(j) - ( 2*V(i)*V(j)*cos( Delta(j)-Delta(i) ) )  )
);

const1(i)..

P(i)=e=Pdempu(i)+Pcur(i)+sum(j,V(i)*V(j)*Y(i,j)*cos(Theta(i,j)+Delta(j)-Delta(i)));

const2(i)..

Q(i)=e=Qdempu(i)+(Pcur(i)*(sin(genphi(i))/cos(genphi(i))))-
sum(j,V(i)*V(j)*Y(i,j)*sin(Theta(i,j)+Delta(j)-Delta(i)));

model OPF/all/;

SOLVE OPF  using NLP maximizing Penet;
```

```
DISPLAY P.l ;
DISPLAY Q.l ;
Display Penet.l;
DISPLAY v.l;
Display Pcur.l;
Display Delta.l;
Display P.lo;
Display P.up;
```

8. Appendix B

EFFECTS OF PHEVs IN POWER DISTRIBUTION SYSTEMS: REVIEWS AND ANALYSES

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ABSTRACT

This paper deals with the analysis of the impacts of plug-in hybrid electric vehicles (PHEVs) on the power system, with focus on the low voltage power distribution system. First a review of the technical challenges in the power system due to the mass introduction of PHEVs in the transporation sector is given. Then the paper shows on an analysis of the overloading effects of PHEVs on the distribution system with normal charging and quick charging of PHEVs for an IEEE 13-node distribution test system using power flow analysis. The results of the study show that introduction of PHEVs in the transportation sector will lead to overloading of distribution system and cause voltage problems at the end-users. The paper also analyzes the effects of PHEVs in the transmission system, using the Nordic 32-bus test system. The study results showed that the overloading problem is not prominent. However, one interesting and important result is that PHEVs may lead to overvoltages in some buses in the transmission system which requires the voltage control measures. PHEVs would also lead to increased number of network violations in the contingency analysis.

Introduction

High penetration of plug-in hybrid electric vehicles (PHEVs) in the transportation sector will likely be envisioned by the transportation authority as well as energy authority in many parts of the world, e.g., European countries, Japan, and the USA. The benefits from replacing the conventional internal combustion vehicles by the PHEVs are the subjects of many current research and mass-media because the transport sector is one of the largest and fastest growing contributors to energy demand, urban air pollution, and greenhouse gases (GHGs) [1]. The possibility to reduce the dependency on oil consumption by the transportation sector and the possibility to reduce harmful environmental emissions, e.g., CO_2, SO_x, and NO_x by ways of improved conversion efficiency through PHEVs are the key socio-economical and environmental benefits. Given the said benefits, critics have warned that the vehicles could put too much pressure on already strained power grids. The concern is that plug-ins may not appear to be a good way to reduce gasoline consumption, because if they become popular, and millions of car owners recharged their cars at three in the afternoon on a hot day, it would crash the grid. Specially, uncontrolled charging can lead to grid problem on the local scale [2].

The organization of the paper is as follows: The next section will provide a brief overview and discussions on the effects of PHEVs on the power system with focus on the low voltage power distribution system. The power flow analysis in the IEEE test distribution system when assuming certain levels of PHEVs penetration levels is presented in the following section. The effects on PHEVs on the meshed transmission network are shown in the following section. The grid support effects of PHEVs are also analyzed through the contingency analysis of the transmission system. Finally, conclusions and remarks are made in the last section.

PHEVs in the power DISTRIBUtion sytem: A brief review

As highlighted in the previous section, PHEVs have the potentials to contribute to reduce the environmental emissions from the transportation sector. However, it will likely pose new challenges in the power system, especially in the power distribution system where the vehicles are directly connected to. This section will highlight those challenges and effects. Other detailed information about the current technology and charging requirement of PHEVs will be presented in the next Section.

Fig. 1 shows the effects of PHEVs on the power systems, and categorizes the problems at different levels, i.e., at system level, distribution system level, and transmission system level. The key question being asked today is how the power system sees the increase in its total loads when high level of PHEVs will be used in the near future. This is largely dependent on the charging habits which will be practiced by the users of PHEVs. As shown in Fig. 1, even though the PHEVs are connected in low voltage distribution system, they also have large effects on the generation system and transmission system levels.

If the vehicle users are free to charge their cars anytime they want (uncontrolled charging), one can easily say that they will plug in at the end of the day, which corresponds with peak loads. In this case, PHEV increases the system peak loads which require additional generation (and transmission) capacity. A new dimension of peak load capacity for the power system might be required if the charging of PHEV is left uncontrolled. On the other hand, if controlled charging is used, which means that the utility controls charging between, for example, 10:00 pm and 07:00 am. In this case the system load profile will be improved in a way similar to the effect of “valley filling” demand-side management measure, meaning that the system utilization can be improved.

PHEVs would result in the changes in the system load shapes which in turn would result in changes in power generation mixes, changes in electricity prices as well as the CO_2 emission level from power production.

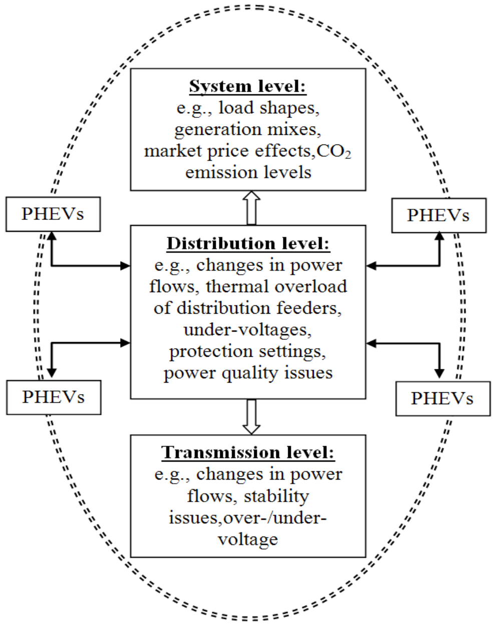

Fig. 1: Overview of possible effects of PHEVs on power systems

PHEVs are connected to the power systems at low voltage power distribution system level, *i.e.*, at the end-user sides. Potential problems with distribution system include the overloading of distribution feeders when many PHEVs charge at the same time and at the same area. Overloading of feeders are normally associated also with the large voltage drop over the feeders which makes the voltage at end-users lower than minimum acceptable voltage. This will lead to necessity to upgrade substations earlier than expected because of charging, but there could also be the need to change or modify the existing protection systems. Normally, in distribution system, the power flow is normally uni-directional from medium voltage (MV) grid to low voltage (LV) grid. However, when PHEVs functions as the energy storage and inject the current into the grid, which is known as vehicle-to-grid (V2G) [3], bidirectional power flow would take place within a certain area. Therefore, setting of relays in the LV and MV level may have to be changed because they might trip under normal working conditions when power should be provided from the LV to the MV level. Depending on the design of charging system, either it is one-phase charging or three-phase charging, the load unbalance might occur with the one-phase charging if the distributions of PHEVs between the phases are unequal. A more comprehensive review of the effects of PHEVs on the power systems can be found in [4].

The above mentioned problems, however, are dependent on the characteristics of the grid in question, number of PHEVs in the areas, types of charging, time of charging, and so on. More specific research would have to be done in order to answer specific questions related to each grid. The next section will provide a specific analysis of the effects of PHEVs on the IEEE Test Distribution System. The effects will be focused on the overloadings of the distribution feeders and the voltage problems at the customers' positions.

Analysis of PHEVs in the distribution system

Description of the IEEE 13-Node Test Distribution System

Fig. 1 shows the single line diagram of the IEEE 13-node distribution test system [5].

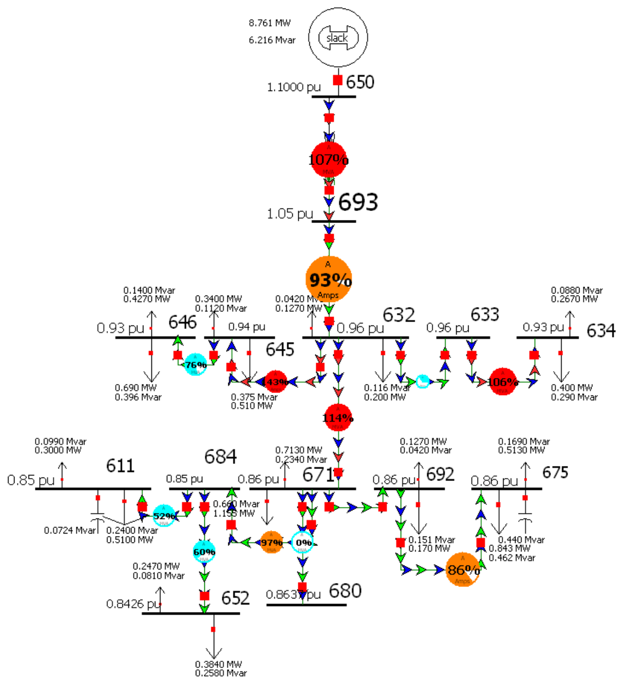

Fig. 2: IEEE 13-node distribution test system

The system is appropriately modified to represent the power distribution system for a small residential area. The power flow analysis for this system is done using the PowerWorld Simulator [6]. To model PHEVs, 9 loads have been added to the system, showing with the up arrows in Fig. 2. In this network, the maximum load is 4.82 MW at 6:00 PM and minimum load is 3.02 MW at 3:00 AM. It is assumed that this network for the residential area. According to [7] and [8], each 25 kVA distribution feeder can approximately serve 4 houses and it can be assumed that every 4 houses will own 2 PHEVs. From this assumption, the number of PHEVs at each bus will be calculated as in (1):

$$N_{PHEV} = \frac{S_{max}}{25} \times 2 \qquad (1)$$

where,

N_{PHEV}: Estimated number of PHEVs at each bus

S_{max}: Maximum supplied kVA at each bus

Chevy Volt is taken as the model of PHEVs used in this study. Chevy Volt is equipped with a Lithium-Ion battery [8]-[9]. In principle, there are two methods of charging: *normal charging* and *quick charging*. According to [8], the Lithium-Ion battery of a Chevy Volt car draws 1.45 kW in 6 to 6.5 hours for normal charging and draws 5.8 kW in 1.7 hours for quick charging. The efficiency of 87% is assumed for the whole charging process [7]. The following four different cases have been considered in this study:

1. *Business as usual (BAU):* System at peak load without PHEVs.
2. *Normal charging, peak load:* BAU with PHEVs normal charging
3. *Quick charging, peak load:* BAU with PHEVs quick charging
4. *Quick charging, min load:* System at min load with PHEVs quick charging

Case study results and discussions

Tables 1 shows the bus voltages of four different scenarios described above. In the BAU case, all the bus voltages are within the acceptable limits of ±10% of nominal voltage. In the normal charging case, there were no violations in voltages at all the buses. However, in the quick charging at peak load scenarios, there are 50% of buses with voltage below the minimum acceptable level (shown with underlined numbers in Table 1). It is because that quick charging draws much higher current/power than the normal charging. The voltages at different buses in the case of quick charging at max load are also shown in Fig. 2 above. If quick charging can be controlled and done during the min load period, there were no problem of voltage violations in the system as shown in Table 1.

Table 1: Buses voltages in per unit for different scenarios

Bus #	BAU	Normal charging, peak load	Quick charging, peak load	Quick charging, min load
611	0.97	0.95	**0.85**	0.96
632	1.03	1.01	0.96	1.02
633	1.03	1.01	0.96	1.02
634	1.00	0.99	0.93	1.00
645	1.01	1.00	0.94	1.00
646	1.01	0.99	0.93	1.00
650	1.10	1.10	1.10	1.10
652	0.96	0.94	**0.84**	0.95
671	0.97	0.95	**0.86**	0.97
675	0.97	0.95	**0.86**	0.96
680	0.97	0.95	**0.86**	0.97
684	0.97	0.95	**0.85**	0.96
692	0.97	0.95	**0.86**	0.97
693	1.07	1.07	1.05	1.07

Table 2 shows the line loadings in percentage of rated line capacity. In the BAU and normal charging scenarios, the line loadings are within the maximum limits.

Table 2: Loading of lines as percentage of rated power

From bus	To bus	BAU	Normal charging, peak load	Quick charging, peak load	Quick charging, min load
684	611	32.20	37.10	51.80	39.00
632	633	20.70	23.60	32.60	25.00
632	645	87.50	99.80	**137.80**	**106.00**
632	671	66.20	75.90	**113.70**	80.90
693	632	56.20	64.90	97.50	68.80
633	634	67.20	76.60	**105.80**	81.20
645	646	48.40	55.20	75.70	58.60
650	693	60.50	70.10	**107.40**	74.20
684	652	38.80	44.10	60.40	45.70
671	680	0.00	0.00	0.00	0.00
671	684	60.00	69.00	96.60	72.30
671	692	0.00	0.00	0.00	0.00
675	692	45.60	52.20	73.90	57.50

When PHEVs are charged with quick charging during peak load period, there are four lines (i.e., lines *632-645*, *632-671*, *633-634, and 650-693*) overloaded as can be seen with the red circles in Fig. 2, meaning that the network is under the stress condition. With quick charging but under the min load condition, the stress condition for the line overloading is reduced with only one line overloading (i.e., line *632-645*).

Fig. 3 shows total system active power losses for different scenarios. System loss increases dramatically when PHEVs have been connected for quick charging at peak load as compared to the BAU scenario. Total system losses at normal charging at peak load and quick charging at minimum load are found to be the same.

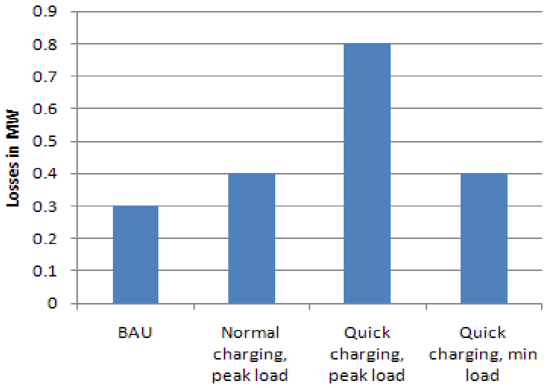

Fig. 3: Total system active power losses

As shown in Fig. 1 and discussed in previous section, PHEVs are connected directly in the distribution network but they will have potential effects in the meshed transmission network. The following section will present the power flow analysis for the effects of PHEVs on the Nordic 32-bus test system.

Analysis of PHEVs in the meshed Transmission network

The Description of Nordic 32-Bus System

Nordic 32-bus system is used in this study to represent different scenarios with PHEVs. The single-line diagram of this system is shown in Fig. 4. The detailed information about the system can be found in [10]. In this study, 22 loads have been added to the network to represent PHEVs load. The PHEVs penetration has been considered as percent of total load of each bus with load connected in the system. Batteries have been modelled with negative loads when they are injecting power into the grid (i.e, in V2G mode). To analyse the effect of the PHEVs on the network, the following 3 cases have been considered:

1. *Business as usual (BAU):* The system without PHEVs
2. *10% penetration:* The BAU with 10% load as PHEVs at each bus with load.
3. *10% penetration V2G:* The BAU with 10% load as V2G at each bus with load.

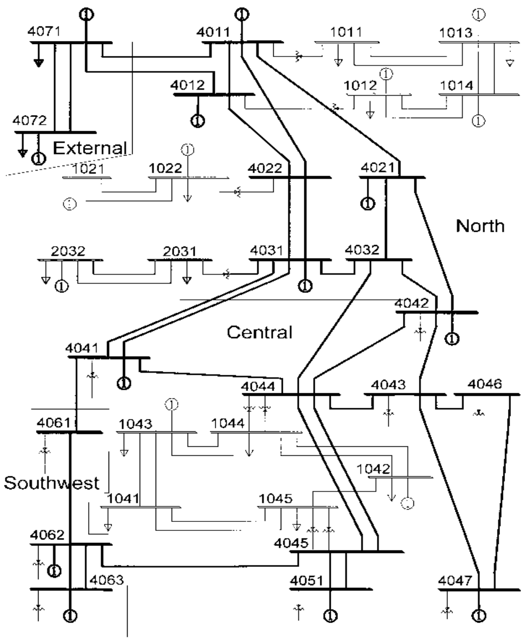

Fig. 4: Single line diagram of Nordic 32-bus system

Case study results and discussions

Introducing the penetration of 10 percent will dramatically change the voltage profile of the transmission network. As shown in Table 3, when adding PHEVs penetration of 10% to the system, there would be 26 buses in the system with voltages level over the maximum allowable limit. This is quite interesting since it is normally expected that the voltage is decreased when the load is increased. However, this can always be true with the radial system like in the distribution network. In the meshed network like the Nordic 32-bus system, when PHEVs loads are added, the power flows over the system have changed quite significantly, especially the reactive power flow. This makes the voltages magnitudes in southern part of the system increased. In this simulation study, the increase in PHEVs load can be managed by existing generators for both active and reactive power.

Table 3: Case study results for 3 cases

	No of over voltage buses	No of under voltage buses	No of violations in N-1 contingency analysis
BAU	0	0	307 violations and 9 unsolvable contingencies
10% penetration of PHEVs	26	1	1257 violations and 16 unsolvable contingencies
with 10% penetration of V2G	1	6	587 violations and 15 unsolvable contingencies

Another important result from this study is that the number of violations (mainly in bus voltages) in N-1 contingency analysis of the system increases dramatically with 10% penetration of PHEVs, indicating that power system security must be properly studied with mass introduction of PHEVs. With V2G, the number of violations is reduced as compared to the 10% peneration of PHEVs case.

conclusion

This paper summarizes possible key effects of introduction of PHEVs in the power system. Results from the studies show that problems with low voltage distribution networks with PHEVs are mainly related to overloadings of distribution feeders, and under voltages in end-users' locations in the case of quick charging during peak load period. If normal charging is to be used, the system would be able to support the PHEVs without overloading and under voltage problems. In the transmission level, an interesting phenomena with regard to the bus voltage level is observed for the Nordic 32-bus system. That is when PHEVs equally distributed in the system, the voltage in the system might increase, showing the need for voltage regulation measures. However, this could not be concluded for every system since this is system-dependent. An other problem with meshed transmission networks is typically that the level of security could be affected when more PHEVs are plugged into the network.

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