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TRABAJO FIN DE GRADO

CASE STUDY OF REACTIVE POWER MANAGEMENT VIA ELECTRIC VEHICLES IN DISTRIBUTION GRIDS

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Director: Subhonmesh Bose

Madrid

Junio de 2020

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

CASE STUDY OF REACTIVE POWER MANAGEMENT VIA ELECTRIC
VEHICLES IN DISTRIBUTION GRIDS

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EXECUTIVE SUMMARY OF THE PROJECT

CASE STUDY OF REACTIVE POWER MANAGEMENT VIA ELECTRIC VEHICLES IN DISTRIBUTION GRIDS

Author: Veuthey Mordini, Gonzalo.
Supervisor: Bose, Subhonmesh.
Collaborating Entity: University of Illinois at Urbana-Champaign

1. Introduction

In the last few decades, humankind has been concerned with finding a feasible way of coping with the expected future increase in the demand for electricity, while reducing the emissions of pollutants to the atmosphere. Many governments worldwide are investing in the development of new technologies, and it is believed by experts in the field that a potential solution for these problems is to replace the internal combustion engine automobiles with Electric Vehicles (EVs).

The adoption rate of EVs is increasing and their development and especially the improvement in their batteries could provide a completely new enhancement of the existing power system grid. In an electric power system, the demand and supply of electricity must be met constantly. Therefore, the energy storage in the EVs batteries and the potential connection of thousands of these to the network could actively help with the distribution grid operation while providing Vehicle-to-Grid (V2G) reactive power support.

Some of the operations service benefits include reactive power compensation for power factor correction, voltage regulation, increased efficiency and reduction of installation and maintenance costs. The effectiveness of these services depends on the number of vehicles and on the type of chargers available. It was also demonstrated that the lifetime of the EV batteries, with the required control structure implemented, is not affected when they are providing V2G reactive power operations. Therefore, active power support will not be considered because it affects the EV battery lifetime and only reactive power support services will be implemented throughout the project. In addition, a vehicle can provide reactive power to the grid regardless of the battery state of charge and anytime, even while charging.

2. Case Study of a 22-Bus Distribution Grid

Distribution grids represent the final stage in an electrical transmission network, where electricity is distributed for domestic, industrial and commercial load. They hold a very significant position in the power system since they are the final link between generators and consumers. Power companies are interested in finding the most efficient configuration to minimize energy losses over its transmission in order to reduce costs and enhance the overall performance of the distribution systems.

The distribution network analyzed in the project consists of one generator, 21 fixed loads and 21 branches and represents a typical U.S. residential neighborhood with a total of 82 households and 154 vehicles. Its distribution corresponds to the following figure.

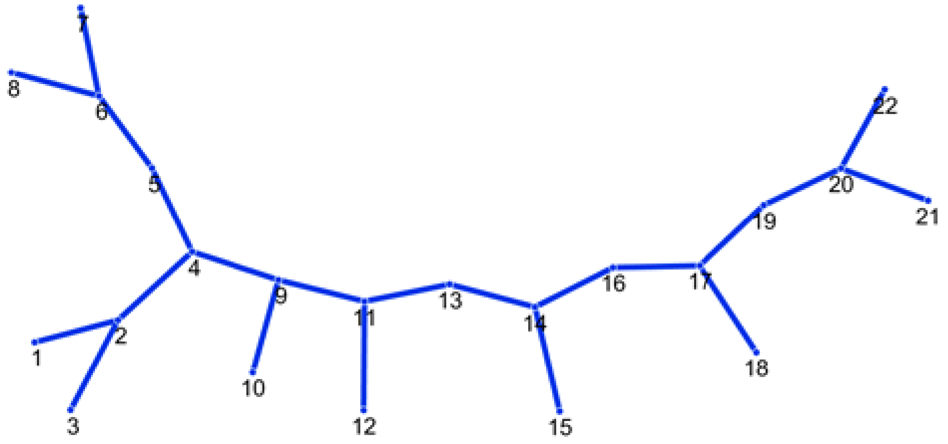

Figure 1: 22-Bus Distribution Grid

Several scenarios have been analyzed with different EV penetration percentages of 10%, 20% and 50%, according to the number of EVs available and their distribution throughout the grid. The guidelines that have been utilized to analyze the different scenarios in the case study are the voltage profiles. Viable voltage levels are essential for maintaining a proper reliable service in the network. Every device connected to the grid was designed to work at a specific voltage including generators and loads. Therefore, the ideal voltage level for all the nodes in the network considered throughout the analysis of the different scenarios is 1 per unit (p.u.).

The following figure represents the voltage profile of the 22-bus distribution network with an EV penetration of 20%.

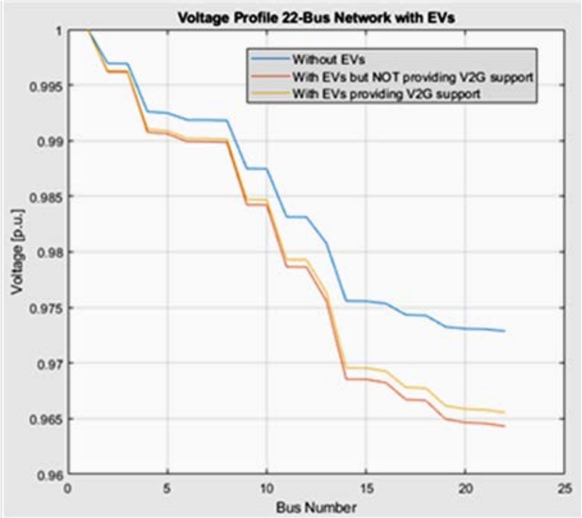

Figure 2: Voltage Profile of the 22-Bus Distribution Network with 20% EVS

The decrease in the voltage profile because of the connection of the EVs is driven by the augmented active power demanded by the charging EVs. This decrease is in part compensated when the EVs are providing V2G reactive power support, compared to when they are not.

Additionally, the project demonstrates that the location of the EVs plays an essential role in the voltage profiles of the distribution network. To analyze this, two different scenarios were examined. The first scenario consisted of the concentration of the EVs close to the feeder node, whereas in the second one, the EVs were mostly concentrated at the end of the line. The tendency of the voltage profile is the same. However, interesting to mention is that injecting reactive power close to the feeder bus to improve the voltage profile is more effective than having it randomly distributed throughout the grid or having it generated at the final nodes of the line.

3. Analysis of Daily Timeframes according to Charging Patterns

An important aspect that has been analyzed for the case study is the daily behavior of the EV users to truly understand the impact they have on the distribution network. As was explained, the increase in the load when the EVs are being charged deteriorates the voltage profiles. However, in a typical day, cars are not actively-driven for long periods of time during which they are parked. Additionally, the fact that they are connected to the network does not necessarily mean that they are being charged. These long parking periods can be considered as an excellent opportunity to provide V2G reactive power regulation services.

The hourly variation of the voltage profiles of all different timeframes on a 24-hour period have been evaluated according to the number of EVs available, their location in the network and their charging patterns. The existing residential load variations over a working day cycle as well as realistic EV driving behavior and residential parking occupancy were considered when analyzing two different charging scenarios. The first charging scenario assessed that the majority of EVs were charged immediately when they arrived home, coinciding with the peak demand periods. In the second scenario, the charging process was delayed for the majority of the EVs to concur with the load valley demand, when the electricity prices are the lowest. The fact that the inclusion of the charging EVs into the network can affect the peak demand and the technical limits of the network such as current or voltage violation in the buses have also been considered in the case study. In order to better understand the impact the EVs can have on the distribution network, each scenario has been analyzed with two different EV penetration cases, a low penetration of 10% and a larger EV penetration of 50%.

The following figure represents a good example of when the EVs could provide reactive power support efficiently, as there is a large number of connected EVs that are not drawing power from the grid, so the voltage profile of the network improves.

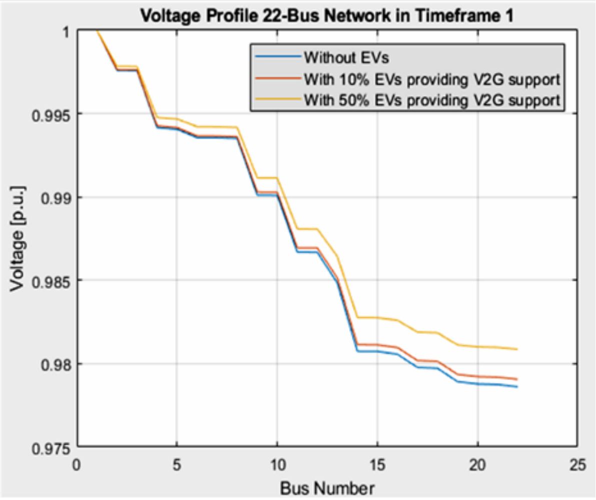

Figure 3: Voltage Profile of the 22-Bus Distribution Network with EVs providing V2G support

4. Economic Analysis

The optimal location and sizing of capacitor banks in the electrical network is a procedure that aims towards reducing power losses and minimizing the sum of costs. However, with the future increase in the number of available EVs, they have the potential of replacing the capacitor banks and therefore reduce costs. The economic analysis of the project studies the feasibility of replacing the existing capacitor banks in the 22-bus distribution grid with the utilization of EVs providing V2G reactive power support. This provides a feasible solution with both technical and economic benefits. The goal is always to minimize the total losses and costs while maintaining acceptable voltage levels throughout the whole network.

In order to compute the economic analysis, the cost of the capacitor banks had to be assessed. There are discrepancies in the literature about their cost as it is a complex issue with many variables involved like the installation costs, the service lifetime of the capacitor banks, the reactive power generation sizes or the number of working cycles. According to [37,38] the installation and maintenance costs and the reactive power generation costs of capacitor banks in distribution grids that was utilized in the project is 3.27 $/kVar. Overall, an average life for the capacitor banks of ten years has been examined.

The efficiency and influence on the distribution grid of the capacitor banks was considered similar to the one transmitted by the EVs. The same charging scenarios were examined, immediate charging and scheduled charging. Three different EV penetration scenarios were analyzed on a daily basis according to the hourly electricity prices of a typical working day in the U.S. The following table shows the results for the actual EV penetration of 4%.

	1st Charging Scenario (Immediately Charging)	**2nd Charging Scenario (Controlled Charging)**
Charging Costs ($)	17.20	11.48
Reactive Power Savings ($)	32.70	32.70
Total Savings ($)	15.50	21.22

Table 1: Daily Savings with a 4% EV penetration

The aim of this section is to demonstrate that with the inclusion of EVs providing reactive power support, not only would the voltage profiles improve, but also it would be economically profitable. To avoid the uncertainty of having enough EVs providing V2G reactive power support in the network to replace the existing capacitor banks, a monetary incentive could be given to the customers for connecting their EVs. That way, both the customer and the grid operators would enjoy the savings produced by the inclusion of EVs and an elevated number of connected EVs would be ensured.

5. Conclusions

This project analyzes the influence of different EV penetrations scenarios on the voltage profiles of a 22-bus distribution network according to the number of EVs available, their location in the network and their charging patterns. The existing residential load variations over a 24 hour cycle as well as realistic EV residential parking occupancy and the network operation limits were considered too. It was demonstrated that the location of the EVs is essential in determining the voltage profile of the distribution network and that injecting reactive power close to the feeder bus is more effective than having it randomly distributed throughout the grid or having it generated at the final nodes of the line.

When connected to the grid, the EVs can provide V2G reactive power support to improve the operation of the distribution network in terms of voltage profile. EVs are considered as flexible loads that can be charged throughout the day. Therefore, a scheduled charging scenario avoids the decrease in the voltage profile and a potential system overloading compared to an immediate charging of the EVs when they arrive home. This coordination of EV charging produces an overall stabilization of the voltage profiles for the 24 hour timeframe and an improvement of the system efficiency which would finally reduce system losses even with a high EV penetration.

It was also shown that, from an economic point of view, the EVs would be a feasible option to replace the existing capacitor banks in the distribution network. The higher the EV penetration, the more reactive power would be introduced into the grid and finally the greater system savings would be made. The data are based on the actual data of energy prices, without the potential future influence of the EVs. Therefore, the values could possibly change in the future, but as long as the data does not change drastically, it has been demonstrated that the connection of EVs to the grid providing reactive power operations could potentially mitigate the high initial investment compared to the traditional gasoline automobiles. This could improve the competitiveness of the EVs and trigger their future penetration into the system.

RESUMEN EJECUTIVO DEL PROYECTO

ESTUDIO SOBRE LA INFLUENCIA DE POTENCIA REACTIVA EN REDES DE DISTRIBUCIÓN MEDIANTE VEHÍCULOS ELÉCTRICOS

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Entidad Colaboradora: University of Illinois at Urbana-Champaign

1. Introducción

Durante la última década, los seres humanos nos hemos visto en la necesidad de encontrar nuevas formas factibles de hacer frente al futuro incremento de la demanda energética a la vez que reducimos las emisiones contaminantes a la atmósfera. Mundialmente, numerosos gobiernos están invirtiendo en el desarrollo de nuevas tecnologías y expertos en el sector aseguran que una posible solución al problema sería sustituir los automóviles de combustión interna por vehículos eléctricos (EVs).

El índice de integración de los EVs en el mercado se ha incrementado considerablemente en los últimos años y su desarrollo, y más específicamente el de sus baterías, podría ofrecer una mejora significativa en la gestión de las redes de distribución. La oferta y demanda de energía en una red eléctrica debe respetarse en todo momento. Por ello, la energía almacenada en sus baterías y la posible conexión de miles de ellos a la red podría influir notablemente en las tareas de gestión del sistema mediante la integración de potencia reactiva.

Algunos de los beneficios del servicio de los EVs incluyen la corrección del factor de potencia mediante inserción de potencia reactiva, el control del perfil de tensiones, la mejora del rendimiento del sistema y la reducción de costes tanto en la instalación como en el mantenimiento. La efectividad de dichos beneficios depende del número de vehículos disponibles y del tipo de cargador. Se ha demostrado que la vida útil de las baterías de los EVs, con la debida estructura de control implementada, no se ve afectada cuando están proporcionando potencia reactiva. Debido a esto, en el proyecto no se considerará la aportación de potencia activa por parte de los EVs y sólo se analizará la transmisión de potencia reactiva. Asimismo, los EVs son capaces de proporcionar potencia reactiva sin importar el nivel de carga de la batería y en cualquier momento, incluso durante la carga.

2. Estudio de una Red de Distribución de 22 Nodos

Las redes de distribución representan la última etapa en una red eléctrica. Es en esta etapa donde la energía se distribuye para su uso doméstico, industrial o comercial. Tienen una importancia significativa puesto que son el último eslabón entre los generadores y los consumidores. Las empresas eléctricas están en constante búsqueda de la configuración más eficiente para minimizar las pérdidas de energía en su transmisión y así reducir costes.

La red de distribución analizada en el proyecto consta de un generador, 21 nudos de carga y 21 ramas conectoras. Representa el típico barrio residencial americano con un total de 82 viviendas y 154 vehículos y su distribución se corresponde a la de la siguiente ilustración.

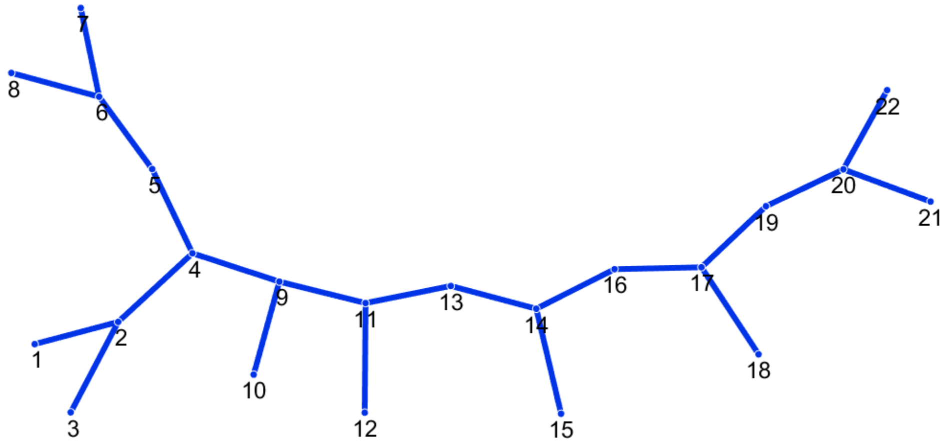

Figura 1: Red de Distribución de 22 Nodos

Varios escenarios han sido analizados según el número de vehículos eléctricos disponibles y su distribución a lo largo de la red con diversos porcentajes de inclusión de 10%, 20% y finalmente 50%. El criterio que se ha utilizado para analizar los diversos escenarios a lo largo del proyecto es el perfil de tensiones de los nudos.

Un perfil de tensiones adecuado en la red es esencial para proporcionar un servicio eficiente al consumidor y todos los aparatos conectados a ella se diseñaron para trabajar a una determinada tensión. Por ello, el valor ideal de tensión en todos los nudos de la red considerado para el análisis de los escenarios es 1 por unidad (p.u).

La siguiente figura representa el perfil de tensiones de la red de distribución de 22 nodos con una penetración del 20% de EVs.

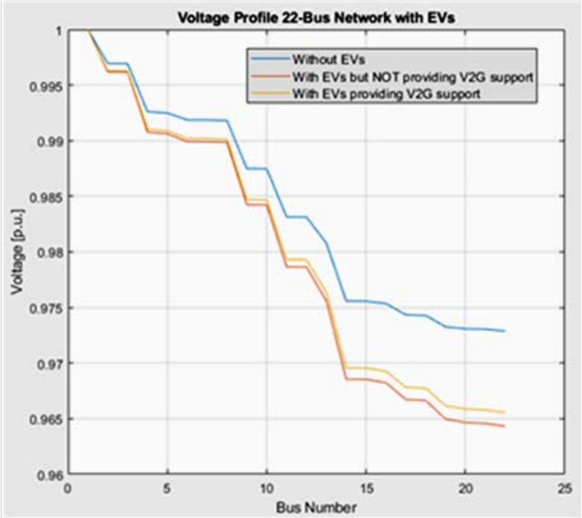

Figura 2: Perfil de Tensiones de la Red de Distribución de 22 Nodos con 20% EVs

El descenso del perfil de tensiones al conectar los vehículos eléctricos se debe al aumento de la demanda de potencia activa debido a la carga de los vehículos. Este descenso en parte se compensa cuando los vehículos están proporcionando soporte de potencia reactiva a la red.

Por otra parte, el estudio demuestra que la ubicación de los vehículos juega un papel fundamental en el perfil de tensiones de la red de distribución. Para ello, dos escenarios han sido analizados. En el primero, la mayoría de los EVs estaban concentrados próximos al nudo generador, mientras que en el segundo escenario se encontraban ubicados al final de la línea. La tendencia del perfil de tensiones es la misma, sin embargo, se comprobó que la inyección de potencia reactiva cerca del nudo generador para mejorar el perfil de tensiones es más eficaz que su generación aleatoria a lo largo de la red o su generación en los nudos finales.

3. Análisis de los Intervalos Diarios de acuerdo a los Patrones de Carga

Un aspecto importante a la hora de llevar a cabo el estudio ha sido analizar la conducta diaria de los usuarios de vehículos eléctricos para poder comprender el impacto que pueden llegar a tener en la red de distribución. Como se ha mencionado, el incremento en la demanda cuando se están cargando produce un deterioro del perfil de tensiones. Sin embargo, en un día de media los coches están aparcados durante largos períodos de tiempo. Asimismo, el hecho de que estén conectados a la red no significa que necesariamente se estén cargando. Estos largos períodos de aparcamiento se consideran una oportunidad excelente para proporcionar servicios de soporte de potencia reactiva.

Se han evaluado las variaciones en los perfiles de tensión de los intervalos a lo largo de un período de 24 horas de acuerdo al número de vehículos disponibles, su ubicación en la red y los patrones de carga. También se han considerado las variaciones de la demanda residencial así como los porcentajes de estacionamiento de vehículos de manera horaria para analizar dos posibles escenarios de carga. El primer escenario evalúa la carga de la mayoría de los vehículos inmediatamente al llegar a casa, que coincide con el período pico de demanda. En el segundo escenario, el proceso de carga se aplazó para la mayoría de vehículos para que coincida con el período de valle de la demanda, cuando los precios son los más bajos. El hecho de que la inclusión de los vehículos eléctricos pueda afectar al pico de demanda y a los límites técnicos de tensión e intensidad en la red también se ha considerado en el análisis. Para visualizar mejor el impacto que los vehículos eléctricos pueden tener en la red de distribución, cada escenario de carga se ha analizado mediante dos casos distintos de porcentajes de vehículos eléctricos, uno bajo de 10% y otro elevado de 50%.

La siguiente figura presenta un buen ejemplo de cuando los EVs pueden proporcionar soporte de potencia reactiva eficientemente. En la figura se muestra un número elevado de vehículos conectados a la red pero que no se están cargando, por lo tanto mejora el perfil de tensiones.

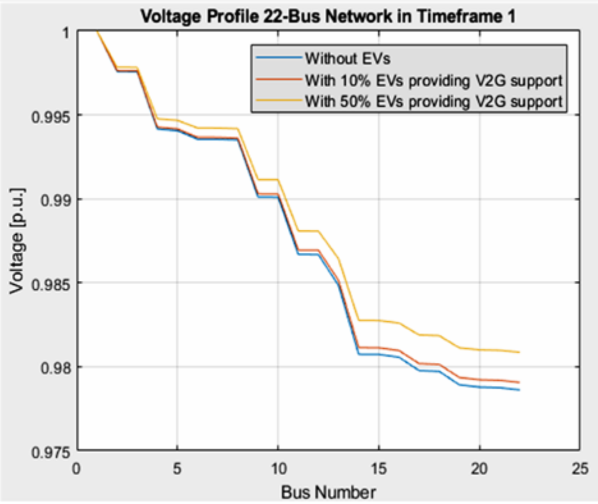

Figura 3: Perfil de Tensiones con EVs Proporcionando Soporte de Potencia Reactiva

4. Análisis Económico

El estudio de la ubicación y magnitud óptima de los bancos de condensadores en las redes eléctricas es un procedimiento complejo cuyo objetivo es reducir las pérdidas y minimizar los costes. Sin embargo, con el potencial aumento del número de EVs disponibles en el futuro, existe la posibilidad de sustituir los bancos de condensadores y reducir los costes. El análisis económico del proyecto estudia la viabilidad de reemplazar los bancos de condensadores en la red de distribución de 22 nodos con EVs proporcionado soporte de potencia reactiva. Esta solución tiene beneficios tanto técnicos como económicos y su objetivo es minimizar las pérdidas manteniendo niveles de tensión aceptables en toda la red.

Para llevar a cabo el análisis económico, es necesario evaluar el coste de los bancos de condensadores. Hay discrepancias en la literatura sobre su precio debido al elevado número de variables a analizar; como son los costes de instalación, la vida útil de los bancos de condensadores, la magnitud de potencia reactiva generada o el número de ciclos de trabajo. Según [37,38], los costos de instalación, mantenimiento y generación de potencia reactiva en las redes de distribución por parte de los bancos de condensadores que se han utilizado en el proyecto son 3.27 $/kVar. En líneas generales, se ha tenido en cuenta una vida media para los bancos de condensadores de diez años.

El rendimiento e influencia de los bancos de condensadores en la red de distribución se ha considerado similar a la de los EVs. Se han analizado los mismos escenarios de carga que anteriormente, carga inmediata y carga controlada. Asimismo, se han examinado tres escenarios distintos de penetración de los EVs teniendo en cuenta los precios horarios de la electricidad en Estados Unidos. La siguiente tabla muestra los resultados para la implementación actual del 4% de vehículos eléctricos.

	1er Escenario de Carga (Carga Inmediata)	**2^{o} Escenario de Carga (Carga Controlada)**
Costes de Carga ($)	17.20	11.48
Ahorros de Potencia Reactiva ($)	32.70	32.70
Ahorros Totales ($)	15.50	21.22

Tabla 1: Ahorros Diarios con una Implementación de EVs del 4%

La finalidad de esta sección es demostrar que con la incorporación de vehículos eléctricos proporcionando soporte de potencia reactiva no sólo se consigue mejorar los perfiles de tensión de la red, sino que desde un punto de vista económico también es rentable. Para evitar la incertidumbre de tener suficientes vehículos conectados proporcionando potencia reactiva a la red, se podría incentivar económicamente a los consumidores para conectar sus vehículos. De esta forma, tanto los consumidores como los operadores disfrutarían de los ahorros obtenidos por la introducción de los vehículos eléctricos en la red.

5. Conclusiones

En este proyecto, se ha analizado la influencia de diversos escenarios de implementación de EVs en una red de distribución de 22 nodos de acuerdo al número de vehículos disponibles, su ubicación en la red y los patrones de carga. También se han considerado las variaciones de la demanda residencial así como los porcentajes de estacionamiento de vehículos de manera horaria. Se ha demostrado que la ubicación de los EVs juega un papel fundamental en el perfil de tensiones de la red de distribución y que la inyección de potencia reactiva cerca del nudo generador es más eficaz que su generación aleatoria a lo largo de la red o su generación en los nudos finales.

Durante del proyecto se ha considerado a los EVs como demandas flexibles que pueden ser cargadas a lo largo del día y que cuando están conectadas a la red pueden proporcionar soporte de potencia reactiva para mejorar el perfil de tensiones de la red. Por consiguiente, a diferencia del escenario de carga inmediata de los vehículos, el escenario de carga controlada evita el descenso del perfil de tensiones y una posible sobrecarga del sistema. La coordinación de la carga de los vehículos produce una estabilización de los perfiles de tensión y a su vez un incremento del rendimiento del sistema que se traduce en menores pérdidas, incluso con una penetración elevada de vehículos eléctricos.

También se ha demostrado que, desde un punto de vista económico, sería factible reemplazar los bancos de condensadores en la red de distribución por vehículos eléctricos. Cuanto mayor sea el porcentaje de vehículos introducidos, mayor capacidad de transmisión de potencia reactiva y finalmente más ahorros. Los datos utilizados son los actuales y no se ha tenido en cuenta la posible futura influencia de los EVs en los precios energéticos. Debido a esto, los valores podrían variar en un futuro. Sin embargo, mientras que dicha variación no sea significativa, se ha demostrado que su conexión a la red proporcionando potencia reactiva, podría atenuar el elevado coste inicial comparado con los vehículos de combustión interna. Esto podría suponer una mejora competitiva para acelerar la penetración de los vehículos eléctricos en el sistema.

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Chapter I: BACKGROUND ON EVS

1.1 INTRODUCTION

The present age is considered by many experts as the age of electromobility. Humankind has been concerned in the last decades to reduce the amount of $C0_2$ that we emit to the atmosphere in the industrial, transportation, residential or commercial sectors, while maintaining our current living standards. According to the International Energy Outlook Report 2019, the World energy consumption is going to rise nearly 50% between 2018 and 2050 [1]. The cost of petroleum has been increasing in past years and its future is still relatively uncertain. Also, the fact that global warming is a major concern nowadays is making it imperative for governments, developed countries and industry leaders' businesses all over the world to take preventive steps to find alternative energy solutions.

Thus, an alternative for reducing greenhouse gases that governments of various countries have studied in the past years was the introduction of electric vehicles (EVs) to the market instead of conventional gasoline vehicles. The adoption rate of EVs is increasing and many countries worldwide are investing heavily in research and development. EVs produce zero or very low emission of local air pollutants, while their development and especially the improvement in their batteries could provide a completely new enhancement of the existing power system grid. In an electric power system, the demand and supply of electricity must be met constantly. Therefore, the energy storage in the automobiles and the potential of thousands of these connected to the grid could actively help with the distribution grid operation.

In a typical day, cars are not actively driven for long periods of time during which they are parked, either at home or in public spaces. These long parking periods can be considered as an excellent opportunity to provide Vehicle-to-Grid (V2G) regulation services. EVs potentially have the capability to fulfill the energy storage needs of the grid and some of the suggested benefits are voltage regulation, frequency regulation, load balance for peak shaving, reactive power compensation (inductive or capacitive) for power factor correction and providing distributed grid-connected storage as a reserve against unexpected outages [2]. The effectiveness of these services depends on the number of vehicles and on the type of chargers available. In cities specifically, the possibility for large numbers of electric vehicles could offer not only grid service but traffic regulation as well.

The first Chapter of the project presents a general overview of the EVs, their recent development, the types of EVs and the need for reactive power in the grid. Chapter 2 states the background for the EV batteries, chargers and the different levels of charging available nowadays. Moreover, the effect of reactive power operation on a simulated distribution grids with 22 nodes is analyzed in Chapter 3. The potential advantages and drawbacks of introducing EV reactive power capability for voltage support are assessed. The emphasis was put on the amount of EVs available and on their distribution throughout the distribution grid.

Additionally, Chapter 4 presents the analysis of all daily timeframes regarding the influence of different EV penetration scenarios on the voltage profiles of the 22-bus distribution network according to the location of the EVs, the number of EVs available and their charging patterns. The existing residential load variations over a 24-hour cycle as well as realistic EV residential parking occupancy were taken into account when analyzing two different charging scenarios. Finally, Chapter 5 analyzes the feasibility of replacing the existing capacitor banks in the distribution grids with the inclusion of EVs providing V2G reactive power services from an economic point of view.

1.2 HISTORY OF EVS IN THE UNITED STATES

Contrary to what may be believed by the general public, EVs are nothing new. While who created the first EV is still uncertain nowadays, it is clear that there were electric motors in use in the 19th century [3]. The first gasoline powered combustion engine that was coupled to a chart was invented in 1870. However, it was not until at least ten years later that the first successful electric vehicle was introduced. Ever since then, the popularity of EV steadily increased because their engine was quiet, easy to drive and they did not emit any pollutants. By the turn of the century, it came to a point where the proportion of electric vehicles increased up to a third of all vehicles on the road in the United States. Also, by that time was the world’s first hybrid electric car invented [4].

The years following, there was an immense increase in the gas-powered cars thanks to the discovery of crude oil in Texas, the increase of gas filling stations, the road improvements and above all the mass production of Henry Ford’s gasoline-powered Model T. This led to a vast decline of the electric vehicles sales by 1930. The situation continued to be about the same until the Oil Crisis of 1970, when the prices of gasoline began rising and the electric vehicle gained its reputation back. Around this same time, many big and small automakers began exploring options for alternative fuel vehicles, including electric cars. However, they still had the same initial issues compared to gas-powered cars. Their major drawbacks were their limited traveling range, their slow-charging time versus fast-discharging time and their lack of power.

The situation of the electric vehicle completely changed in 2008 when Tesla Motors announced they would produce luxury electric cars with a driving range of more than 200 miles and that marked the beginning of the modern EV period. At the same time, EV-chargers were installed all over the country to enable users to charge their cars in public areas.

1.3 DEVELOPMENT OF EVS

The industry of EVs has witnesses rapid evolution with the ongoing development in the automotive sector in the las few years. The market of electric cars is growing steadily. There were 2.1 million EVs sold globally in 2018, an increase of 64% compared to the total sold in 2017 [5]. Only in the U.S. 330,000 units were sold in 2019. This raise is even more impressive given the low gasoline prices that encourage remaining with the traditional internal-combustion-engine vehicles.

The increasing popularity of EVs is driven by their increased driving range, decreasing battery price, and increased number models available. Growing emission levels and stringent government regulations have compelled automakers to develop cost-efficient and environment-friendly modes of transport. The development of the EVs sales in the U.S. and their share in the market since 2010 can be seen in Figure 1. Interesting to mention is the increase in the sales of the year 2018, which was mainly because of the introduction of Tesla Model - 3 to the market. Only in the U.S., Tesla sold more than 140000 vehicles of this model, which consisted of about 39% of all electric vehicles sold that year. The decline in the sales of 2019 were mainly because Toyota phased out the 1st generation Prius without having the successor ready. Even though there has been a clear increase in the EV sales, there is still plenty of room for improvement. In 2019, the market share for EVs in the U.S was less than 3% and the government is applying incentives to increase that number.

Furthermore, not only the amount of sold electric vehicles has increased in the last decade, but also the number of electric models available to consumers. From only 4 models available in 2008, there was an increase up to 65 different models available in the market in 2018 [6].

The future is very inspiring as there are numerous initiatives to try to decrease the sale of oil cars to finally reduce the pollution in cities. Figure 2 shows the steadily increase of the EVs sales worldwide and the projected annual sales until 2040. A main drawback of electric vehicles nowadays is their market price compared to the gasoline-powered ones. Nevertheless, it is expected that thanks to the development of the EVs and their batteries the prices start decreasing and by 2023 the price of an electric vehicle can be compared to the one of a gasoline one with similar characteristics.

Furthermore, countries such as China, India, Japan, Canada, Norway, the UK, France and the Netherlands have introduced various campaigns to phase out gas and diesel vehicles and boost the adoption of EVs within the next few decades. In 2017, the Clean Energy Ministerial launched the worldwide campaign EV30@30, which is an ambitious plan to reach 30% on-road market share for electric vehicles by 2030 [7]. These governments, being Norway the leader with an electric car market share of 46%, are providing incentives and subsidies to encourage EV sales and it is expected that by 2030, 40% of new car sales will be electric globally [8].

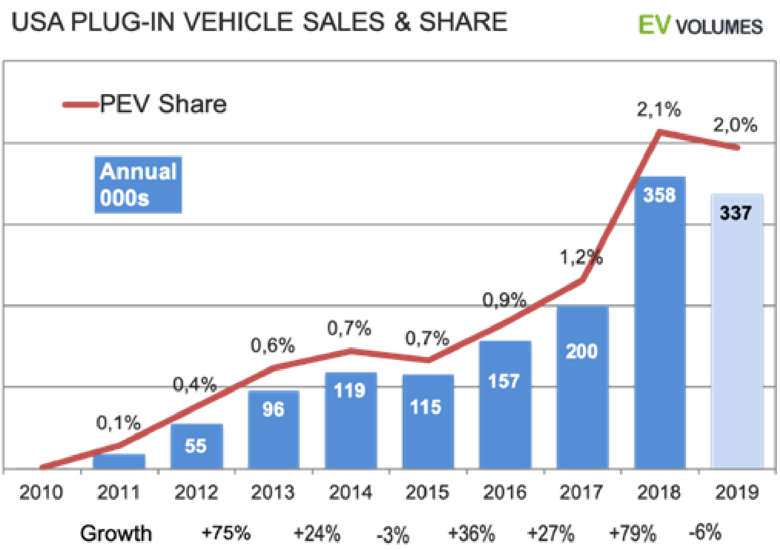

Figure 1: U.S. EVs Sales and Share in the Market [7]

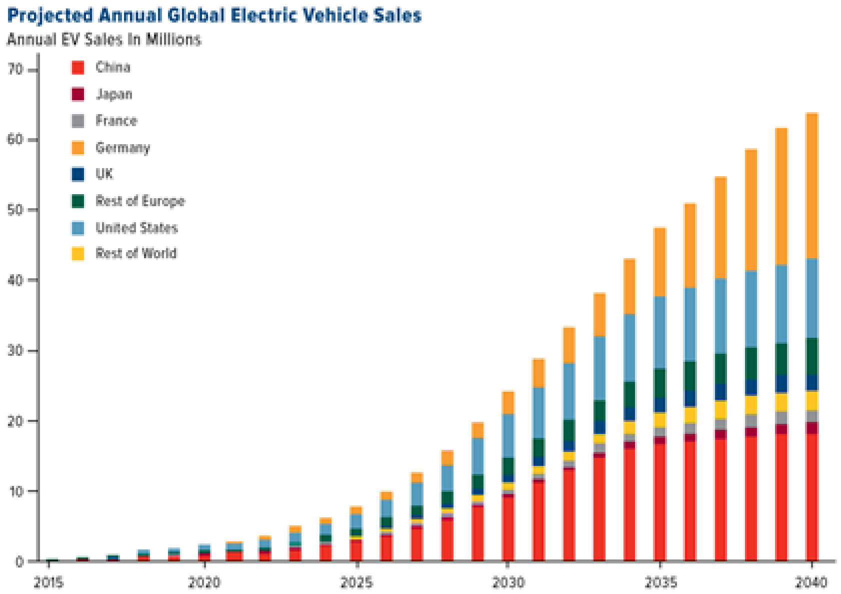

Figure 2: Projected Annual Global Electric Vehicle Sales [8]

1.4 TYPES OF EVS

An electric car is an automobile propelled by one or more electric motors. There are three main types of electric powered vehicles available on the market: Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs) and all Electric Vehicles (EVs). The differences among them are the following [8-10].

1) Hybrid Electric Vehicles (HEVs)

HEVs have the smallest size battery pack among all types. They have internal combustion engine (ICE) and an electric motor to drive at low speeds for short distances or to assist the ICE. The battery is not the principal way of feeding the engine, it just increases the gasoline mileage. HEVs lack the availability of travelling long distances with only electric power because of the short energy storage of their batteries. In addition, the battery does not have a charging connector, it is only charged by the ICE, the motion of the vehicle or through regenerative braking, a process where the electric motor uses some of the thermal energy of the brakes to convert it into electric energy.

2) Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs are similar to HEVs in the sense that they use an ICE and an electric motor. However, the battery pack is larger than the one of the HEVs and they can be recharged by an external source of electricity. PHEVs have the advantage of a long driving range since the electric battery (with a range between 10 and 40 miles) allows them to initially run on electricity and once the battery is depleted switch to gasoline for hundreds of additional miles.

3) All-electric vehicles (EVs)

EVs are fully-electric vehicles with rechargeable batteries that do not have an ICE. They run with an electric engine which is powered by a high-capacity onboard battery. As they do not have a gasoline engine, they have to store more energy than HEVs or PHEVs, thus they have the largest battery size among all types. All EVs have to be charged by external sources of power. The range of EVs can vary significantly between the different models available. Typical range values are between 100 and 130 miles, but more expensive models can have ranges up to 250 miles. Fully EVs do not emit any exhaust gases into the atmosphere while driving.

Finally, all electric vehicles regardless of their category, are limited by their weight and their space available. Both PHEVs and EVs support a battery pack that has a larger energy capacity (>4 kWh) compared to HEVs, which requires external charging of the battery pack. Although carrying the charger on-board increases the availability of charging the vehicle, it also brings added cost and weight to the vehicle. The power rating of the charger has also to be taken into consideration as it determines how fast a battery can be charged. The larger the power rating (and therefore the larger the charger), the less time it takes to fully charge the battery. For instance, an EV requires its charger to have a higher power rating as it has a larger battery size. There should be a compromise made between the charger power rating and its size.

1.5 NEED FOR REACTIVE POWER GENERATION CLOSE TO UTILIZATION AREAS

Even though customers are not billed for the reactive power consumption of their dishwashers, microwaves, A/C devices, refrigerators, etc., the grid has to provide it for their proper operation. It is transmitted from the energy source to the different distribution loads through the transmission lines, where losses and decreased efficiency occur. The electric transmission system is the largest "machine" in the world, and it can connect countries together across long distances.

When it comes to long distances, the line reactances are larger than the resistances and therefore the losses of reactive power become larger than the ones of active power. To increase the efficiency of the utility grid and reduce installation and maintenance costs, reactive power has to be generated as close as possible to the residential load [11]. Moreover, generators are limited in the reactive power they can supply and this can have a strong influence on the voltage levels of the grid.

When a network is subjected to a sudden increase of reactive power demand, the required demand is met by the reactive power reserves supplied from generators or compensation devices. Traditionally, the compensation devices mainly consisted of capacitor banks placed in optimal locations throughout the grid in order to minimize losses and voltage drops. However, the increase in the EVs available on the market nowadays and the countless possibilities they offer has been a subject of research for more than a decade because of their considerable energy reserve and the potential of thousands of these connected to a distribution grid. When connected to the grid, they have the potential of transferring power bidirectionally. The general term of sending power from the vehicle to the grid is called Vehicle-to-Grid (V2G) and the inverse process is known as Grid-to-Vehicle (G2V). Eventually, if enough EVs are available, they could be used to compensate for the reactive power requirement in distribution lines and to ensure acceptable voltage levels.

Chapter II: BACKGROUND ON EV-BATTERIES AND THEIR CHARGERS

2.1 EV-BATTERIES

Many studies have pointed out the capability of EVs to fulfill the energy storage needs of the electric grid. The energy stored in a battery determines both, the electric driving range of the vehicle and the amount of energy it would be able to transfer to the grid.

However, an important aspect to study is the possible degradation of the battery lifetime during this operation. A differentiation between the possible services provided by the vehicles batteries has to be made. While providing active power operations, such as load balance or peak shaving operations, studies show that a degradation of the battery during this operations exists and this makes it less preferable by the auto manufacturers and consumers [12]. This is a sensitive situation, as customers would not want that their expensive vehicle batteries could begin to deteriorate while not having a proper warranty that would replace it costless. In the future, there should be a way of financial compensating the customers that offer their vehicles for ancillary services, otherwise nobody would be interested.

On the other hand, other studies have shown that providing only V2G reactive power compensation (such as voltage regulation, reactive power compensation or power factor correction), having the required control structure implemented, would not affect the battery State of Charge (SoC) or the battery lifetime [11]. In addition, a vehicle can provide reactive power to the grid regardless of the battery SoC and anytime (even while charging).

An EV-battery has two important aspects that determine its lifetime. The first one is its minimum calendar life. The calendar life is the time that a battery can be inactive or with minimal use and its capacity remains above 80% of the initial one. According to [13] a general vehicle battery is awaited to operate between its margins for at least 15 years with limited degradation. The second one is the cycle life, which indicates the amount of complete charge-discharge cycles a battery can undergo before its capacity diminishes to 80% of its initial one. Depending on its daily use, a battery can undergo both deep and shallow charge-discharge cycles. A deep cycle means a complete charging and discharging of the battery usually between 20% and 90% of its SoC, whereas a shallow one has a shorter cycle of charging and discharging (approximately 40% - 60% of its SoC) and is more battery-friendly.

2.2 DEVELOPMENT OF EV-BATTERIES

For years, one of the main factors that prevented the development of the EVs was the lack of a portable and cost-affordable high-energy storage device. In recent years, a lot of research has been done in this area to develop this technology, regarding their energy storage, power, lifespan, safety and cost. Future advancements in technology would help decrease the cost of the batteries and finally the cost of EVs. The final goal is that EVs are available on the market with a similar costs compared to gasoline vehicles with similar characteristics

Thanks to deep research and government incentives, battery prices have reduced drastically in the last 8 years, as can be seen in Figure 3.

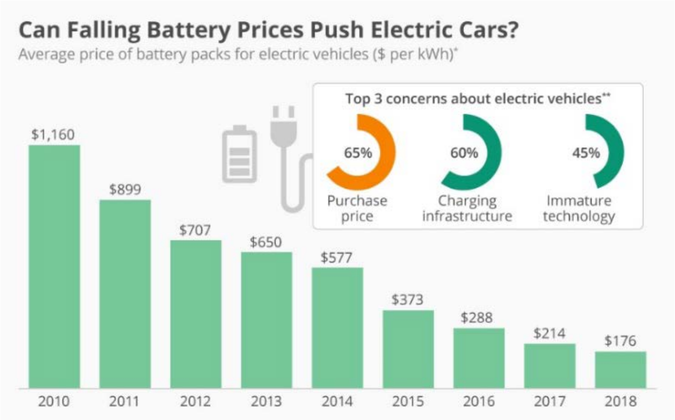

Figure 3: Average Price of Battery packs for EVs since 2010 [14]

The most important takeaway from Figure 3 is the fact that the price of the cars' battery packs has dropped from above $1,100 per kWh in 2010 to just $176 in 2018. This is a reduction of $984/kWh (about 85%) in just eight years and it has made electric vehicles more affordable for consumers. This reduction in battery costs is likely to trigger the mass production of EVs in the near future.

To truly appreciate the impact of battery prices on the EV-prices we can again consider the Tesla Model 3 as an example. There are two battery capacities the customer can choose from, 50 kWh or 75 kWh. If the customer decides on the model with 75 kWh, that car's battery costs nowadays around $13,000 instead of nearly $90,000 it would have cost eight years ago.

There are three main battery technologies that stand out from the rest. These are lead-acid, nickel metal hydride (NiMH), and Li-ion technologies and are presented in the next section.

2.3 TYPES OF EV-BATTERIES

Since reducing the size and weight of the EV-components is one of the main concerns for manufacturers, researchers tend to use energy density (watt-hour per liter) or specific energy (watt-hour per kilogram) in order to compare the different batteries. Also, instead of using power (Watt) to measure the battery power, terms like power density (Watt per liter) or specific power (Watt per kilogram) are commonly used. The power rating is also important to determine the charging time of the battery, which is usually much slower compared to the discharging one.

The following energy storage systems technologies are used in HEVs, PHEVs, and EVs [13, 15].

1) Lead-Acid Batteries

These type of batteries were the ones that the early EVs used as their technology was available at a reasonable cost at the time they were first introduced. They can be designed to have a good discharge power capacity while also being inexpensive, safe and reliable. Some of their drawbacks are their low energy density, poor cold-temperature performance, high weight and short calendar and cycle life.

2) Nickel-Metal Hydride Batteries

NiMH Batteries improved the characteristics of the lead-acid ones in terms of higher specific power, higher energy density (which leads to longer driving ranges), longer cycle and calendar life and higher resistance to damages. These batteries have been widely used for HEVs in the US. However, the main challenges with NiMH batteries are their high cost, their limitations in energy and power density, their high self-discharge rate and finally their heat generation at high temperatures. Because this technology is reaching its productive maturity and there is relatively little room for improvement, other alternatives have been researched.

3) Lithium-Ion Batteries

Lithium-ion batteries have demonstrated to supply greater discharge power for faster acceleration and higher energy-per-unit-mass for increased range compared to the other battery types. They also have a low weight, high energy efficiency, good high-temperature performance, and a low self-discharge rate. Some of the main impediments of these batteries that still have to be addressed are their short calendar and cycle life, their safety and their elevated prices.

Most of the vehicle manufacturers use lithium-ion batteries for their EVs, although the exact chemistry often varies. Research and development are ongoing to further reduce costs and extend their useful life.

2.4 EV-CHARGERS

As the amount of EVs is increasing there is also a growing need for a network of electric vehicle supply equipment (EVSE) to provide power to those vehicles. Most of the times, the EV-users will recharge their automobiles at home, however there is also a need for EVSE in public spaces.

An essential part of the connection of the EVs to the grid is the available chargers and their topology. Depending on the charging infrastructure and its characteristics, there can be considerable differences in both the charging time and the battery life for the exact same battery. A battery charger must be safe and efficient, should have high power density to decrease charging time but also be low cost and low weight. The several levels of charging, their infrastructure and the differences among them is going to be presented in the next section [16-18].

2.4.1 LEVELS OF CHARGING

There are three standard charging power levels that determine the speed with which they recharge a battery: Level 1, Level 2, and Level 3. The higher the level, the higher the power (either DC or AC) and finally shorter charging time. Charging times vary based on how depleted the battery is, its capacity, the type of EV and the level of charging and its charging equipment. It can range from less than 20 minutes to 20 hours or more.

1) Level 1 Charging - Home Charging

Level 1 charging is the slowest and most inexpensive method. These chargers have the capability of charging most EVs on the market and they are typically present at home. It only requires the standard 120 V outlet and they can deliver about 50 miles of range in an eight-hour overnight charge. The current range for this charger is between 12 A and 16 A. Unlike other chargers, level 1 chargers do not need any additional charging infrastructure. It only provides a small amount of power (maximum of 2 kW), so overnight Level 1 charging is suitable for all kinds of EVs that have a low daily driving usage. In addition, the typical driving range for more than 90% of employees in the U.S. is less than 35 miles a day, so even a relatively slow Level 1 charger will meet the daily recharging needs of most people wanting to switch from a gasoline car to an EV [19]. As of 2019, less than 5% of public charging outlets in the United States were Level 1.

2) Level 2 - Home and Public Charging

Level 2 chargers are the most common public and private chargers and it is very likely to find them in public spaces like shopping malls, parking garages, grocery stores and workplaces as well as in private homes. This method employs a specialized 208-240 V outlet, which most but not all U.S. homes have already available, with a maximum current of 80 A and a maximum power output of 19.2 kW. It is more preferred than level 1 charging because of its reduced charging time, between three and seven times faster than level 1. With a typical current of 30 A it can deliver about 160 miles of range in an eight-hour charge. The only inconvenience of this charger is that it may require special safety measurements, dedicated equipment and a connection installation for home or public units, although some vehicles like the Tesla already have these requirements onboard. As of 2019, over 80% of public outlets in the United States were Level 2.

3) Level 3 Charging - Public Charging

The final level of charging is called Fast Charging or DC Charging and as it name suggests is currently the fastest recharging method available. At these charging stations, ac voltage is first converted to dc and then the vehicle is coupled to the charging station. Charging power can go up to much higher values (up to 150 kW in some cases) compared to the other levels and charging times of a battery can be reduced to less than one hour. They can charge a battery up to 90 miles range in approximately 30 minutes so they are most useful for longer trips or for places that have limited access to home recharging.

This types of chargers are typically installed in highway rest areas and city refueling points, similar to traditional gas stations. Even though it is technically feasible, level 3 charging stations are rarely seen in residential homes because they require highly specialized equipment to install and maintain. They typically operate with a 480 V or higher voltage and currents up to 200 A. After reaching a SoC of 80%, the charging speed is reduced significantly, something that does not happen with level 2 chargers.

Not all EVs have the availability of being charged with DC chargers. There are three different plug types and each vehicle uses its own, they are not interchangeable. Japanese automakers typically use the CHAdeMO (“Charge de Move”, which means charge and go) standard, which is gaining international recognition. Most European and American makers use the Combined Charging System (CCS) and Tesla vehicles have their own Tesla’s superchargers (which can charge up to 170 miles of range in 30 minutes). As of 2019, about 15% of charging outlets in the United States were DC fast chargers.

2.4.2 COMPARISONS BETWEEN LEVELS OF CHARGING

As we have seen in the previous chapter, all three levels of charging have several differences among them. From their maximum currents, to the speed of charging and their cost. The aim of this chapter is to compare all three levels.

Figure 4 shows the charger voltage of each type of charging level and its maximum current.

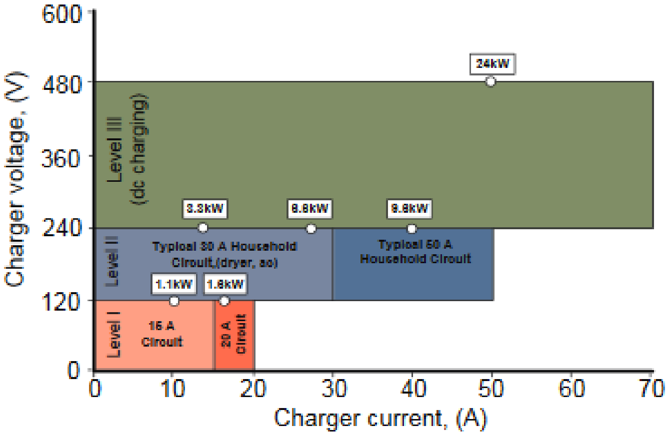

Figure 4: Charging Level Map with respect to Voltage and Current ratings for U.S. outlets [9]

All three charging levels are resumed in Table 1, including the unit cost range for every single port (excluding installation) for all three levels of charging. These costs can vary widely depending on the EVSE unit features, the charger capacity, the location and the maintenance and labor costs. It is difficult to predict EVSE costs since they are highly variable and will depend on the specific needs of each single project. In general, there is an industry consensus that the cost of EVSE units is trending downwards and will continue to decrease [20].

The cost of a single port EVSE unit ranges from $300-$1,500 for Level 1, $400-$6,500 for Level 2, and $10,000-$40,000 for DC fast charging. In addition, general maintenance costs for EVSE for storing charging cables securely, checking parts periodically and keeping the equipment clean should also be considered. While actual maintenance costs can vary, station owners should estimate maintenance costs of $400 annually, per EVSE.

At first sight, the cost of the EVSE may seem excessive. However, state and local incentives in many places encourage EVSE installation through funding and technical assistance. In order to encourage employers to install charging stations for their employees, many governments have put in place programs that reduce purchasing and installation costs, as well as different advantages for the employer [21].

	Amperage [A]	**Voltage [V]**	**Power Output [kW]**	**Typical Charging Time**	**Primary Use**	**Unit Cost [$]**
Level 1	12-16	120	Up to 2	4-6 miles of range per hour of charging	Home charging	300 - 1800
Level 2	Up to 80	208-240	Up to 19.2, typically 7.2 for residential applications	10-20 miles of range per hour of charging	Home and Public charging	400 - 6500
DC Fast Charging	Up to 200	208-600, typically 208 or 480	24-150	24-90 miles of range in about 20 minutes	Public charging	10000 - over 40000

Table 1: Analysis of Levels 1, 2 and DC Fast Charging Levels

Chapter III: ANALYSIS OF THE INFLUENCE OF EVS IN DISTRIBUTION GRIDS

3.1 INTRODUCTION TO DISTRIBUTION GRIDS

Distribution grids represent the final stage in an electrical transmission grid, where electricity is distributed for domestic, industrial and commercial load. They hold a very significant position in the power system since they are the final link between generators and consumers. A planned and effective distribution grid is essential for transferring power since about 30% - 40% of total investment in the electrical sector goes to distribution systems [22]. Power companies are interested in finding the most efficient configuration to minimize energy losses over its transmission in order to save energy and enhance the overall performance of the distribution systems. The three main requisites of a distribution grid are power accessibility, proper voltage and reliability.

Distribution lines are several miles long and have different voltage levels. The primary voltage level is typically between 2.4 kV – 33 kV and it is stepped down in power substations located throughout the grid to supply residential and commercial customers at the safe levels of 120 V or 240 V. The entire distribution grid consists of overhead and underground lines, transformers, nodes and protection equipment such as circuit breakers and switches to prevent overloads from affecting voltages at other points on the grid. The typical network scheme of a distribution network can be seen in Figure 5.

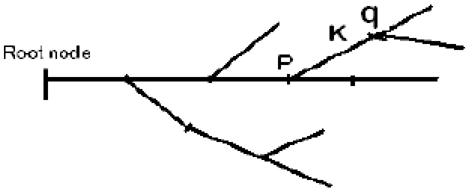

Figure 5: Radial Distribution Network Scheme [22]

3.2 GENERAL OVERVIEW OF THE CASE STUDY

3.2.1 GUIDELINES USED TO MODEL THE EVS INTO THE DISTRIBUTION GRID

A distribution network typically consists of a single generator bus that is presented in Figure 5 as the “root node” or feeder node. This generator bus in reality represents the substation where the voltage is reduced to our common household levels. Apart from the feeder, a distribution grid consists of several load buses. Each one of these buses represents a different neighborhood close to another. As can be easily figured, different neighborhoods can differ significantly in the amount of buildings and households. Furthermore, each household has their own demand requirements, some have less requirement and others have more, depending on the family members, size, location, climate, etc. In 2018, the average annual electricity consumption for a U.S. residential household customer was 10972 kWh, which makes an average of about 914 kWh per month [23].

There are several discrepancies among researchers about how to model the load demands of the typical households across the U.S. In this thesis, a wattage capacity of 8 kW per household will be utilized to meet peak load with a safety factor, according to [24] and to the data about the average monthly consumption. In addition, to complete the information given in the case study, there are 2.55 people and 1.88 vehicles per U.S. household [25].

As was explained in section 1.3 the amount of EVs on the road nowadays is still low. Only 3% of all vehicles sold in 2019 were electric in the U.S. However, this number is expected to increase steadily up to over 30% by 2030 [8]. This transition is going to be continuous over the years. In this section, we will analyze first a EV penetration of 10% and then increase it to 20% and finally 50%. Additionally, the increase in EV penetration includes an increase in the EV chargers and therefore an increase in the active power demanded. As was discussed in section 2.4 the majority of EV chargers in the United

States are Level 2 and the most typical among them have a power output of 7.2 kW. Therefore, to include their impact on the study, every EV added to the network will increase the real power demanded by 7.2 kW.

Additionally, as was discussed in section 2.1, active power support can affect the battery lifetime of the EVs. Therefore, only reactive power will be provided by the EVs, as it was demonstrated that it does not affect its natural degradation.

3.2.2 GUIDELINES USED TO ANALYZE THE DIFFERENT SCENARIOS

The guidelines that are going to be utilized to analyze the different scenarios in the case study are the voltage profiles. Viable voltage levels are essential for maintaining a proper reliable service in the network. In both a transmission grid and in a distribution grid, the voltage in every bus is determined by the balance of supply and demand of reactive power and has to be adjusted within an acceptable tolerance about their nominal value. Throughout this project, the upper and lower voltage constraints of all nodes in the distribution network will be set to 1.1 p.u. and 0.9 p.u respectively.

Every device connected to the grid was designed to work at a specific voltage including generators and loads. It is necessary to maintain viable voltage levels as the system conditions and the loads change. If the voltage is too high or too low, it can result in malfunctions of the electrical devices or poorer performances. Therefore, the ideal voltage considered throughout the analysis of the different scenarios will be 1 per unit (p.u.).

3.3 CASE STUDY OF A 22-BUS DISTRIBUTION GRID

3.3.1 DESCRIPTION OF THE 22-BUS DISTRIBUTION GRID

In this section, we will analyze the 22-Bus distribution network that can be seen in Figures 6 and 7. This network consists of one generator, 21 fixed loads and 21 branches. The data defining the network such as the voltage, the active and reactive power generated in bus one and the active and reactive power consumed by the loads and transferred through the branches without the introduction of EVs can be found in Appendix II.

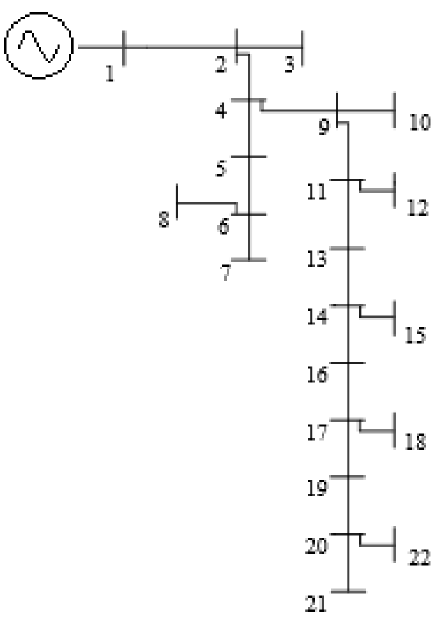

Figure 6: Practical Radial 22-Bus Distribution Network

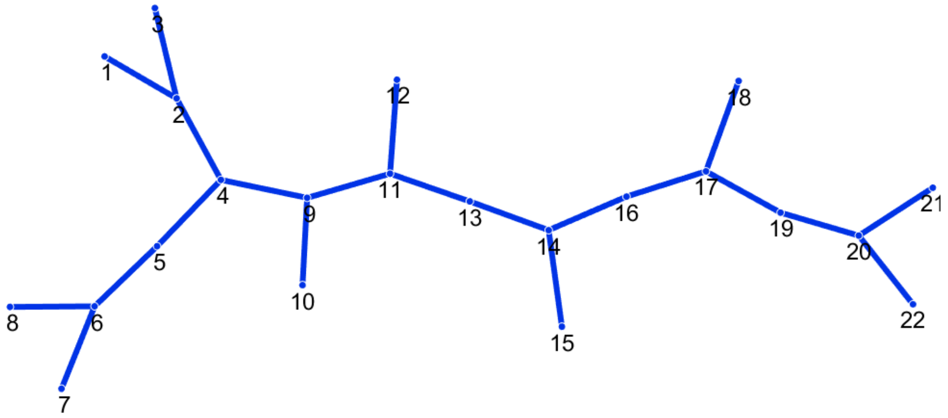

Figure 7: Matpower Scheme of the 22-Bus Distribution Network

Initially, the voltage profile running the power flow simulations without the addition of any EVs can be seen in Figure 8.

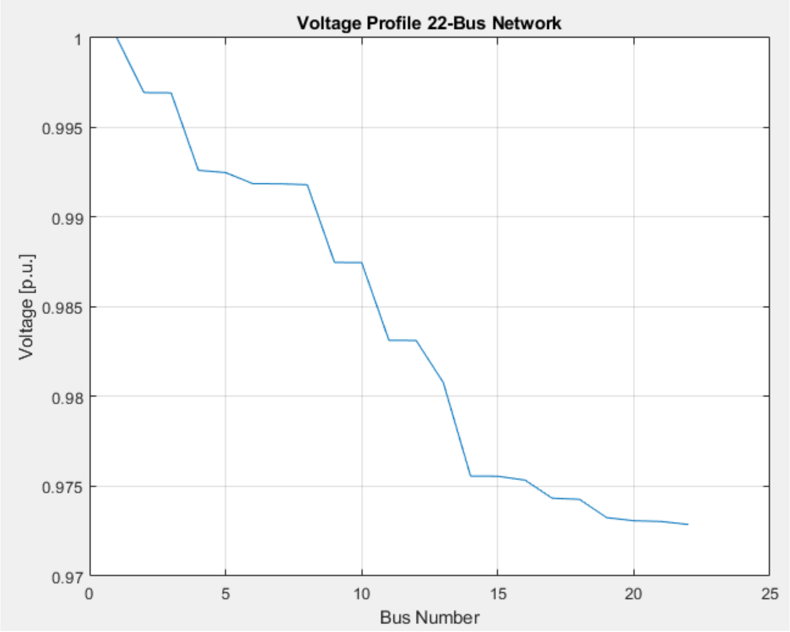

Figure 8: Voltage Profile for the 22-Bus Distribution Network without EVs

3.3.2 Inclusion of EVs

In this section, the amount of active power consumed by every load bus will be first analyzed. Depending on the amount of power, the number of households will be determined with the relation 8 kW/household that was mentioned previously. Then, according to a 10% EV penetration to the market, that amount of EVs will be added to each node. Consequently, the increase in the demanded load will be taken into account as 7.2 kW per EV. Finally, the aim of including the EVs is to provide reactive power support, so each EV will be modeled to provide V2G support to the network.

According to the aforementioned guidelines, the 22-bus grid represents a small distribution network with a total of 82 households and 154 vehicles. Among the 154 vehicles the amount of EVs is 13 and their distribution is presented in Table 2.

	Bus Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Number of EVs	0	0	0	1	0	0	0	0	0	0	0	0	2	1	1	2	1	1	1	1	1	1

Table 2: Distribution of 10% EVs in the 22-Bus Distribution Network

After the inclusion of the EVs to the network and taking into account the corresponding increase in the power demanded for each node, two different voltage profiles can be seen in Figure 9 depending on the maximum amount of reactive power provided per EV, which are 2 kVar and 5 kVar respectively.

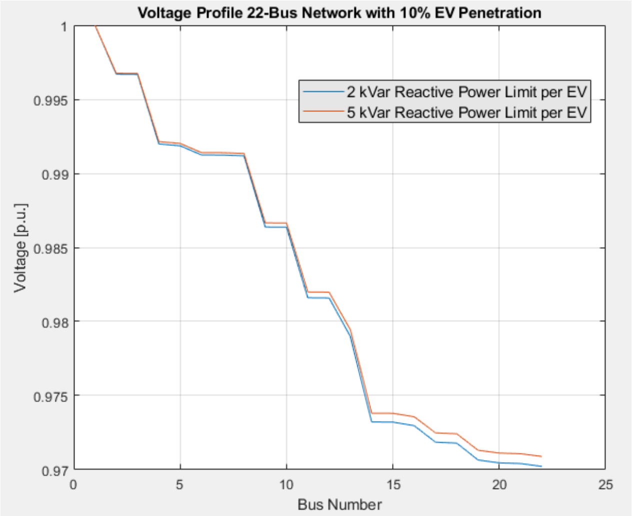

Figure 9: Voltage Profile for the 22-Bus Distribution Network with 10% EVs providing a maximum amount of 2 kVar or 5 kVar

In order to compare voltage profiles, the goal is that every voltage in every bus is as close as possible to 1 p.u. The remaining data defining the network such as the voltage, the active and reactive power generated and consumed by each node can be seen in Appendix II.

3.3.3 COMPARISON OF THE RESULTS WITH THE IDEAL CASE

Ideally, it was expected that because of the inclusion of the EVs into the load buses in the network, the voltage in the buses should be closer to 1 p.u. compared to the initial case presented in Figure 8. However, comparing Figure 8 with Figure 9 it can be observed that the voltage in the original case is equal or closer to 1 p.u. compared to the others in every node. A reason for this is that the amount of reactive power provided by the EVs is too small to improve the voltage profiles. This can be improved by either adding more EVs or by increasing the maximum reactive power provided by each of the vehicles. Therefore, observing only Figures 9, it can be seen that the voltage profile is slightly better in the case where the maximum reactive power provided was 5 kVar compared to the one of 2 kVar, which matches the expectations.

Finally, an ideal scenario will be analyzed. In this case, the amount of EVs needed to reach the desired voltage profile has been proposed. As was mentioned previously, the goal of the case study is to reach a voltage profile where all nodes are as close as possible to 1 p.u. Regarding this, two possible scenarios have been analyzed. In the first one, EVs have only been connected to the buses that already had at least one EV in their nodes whereas in the second scenario, EVs are distributed along every bus of the network. In both scenarios, the reactive power limit was set to 5 kVar. The voltage profile for both scenarios can be seen in Figure 10.

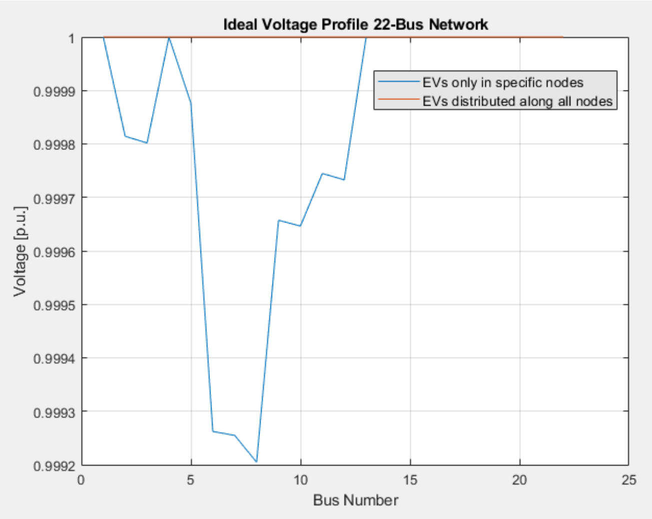

Figure 10: Ideal Voltage Profile for the 22-Bus Distribution Network with EVs in specific nodes or distributed along the grid providing a maximum individual amount of 5 kVar

While doing a simple inspection of the ideal voltage profile, it can be observed that the majority of the buses' voltage is 1 p.u. In the case where the EVs where distributed among all buses, the voltage is always 1 p.u. in every node and in the other case, bus number 8 is the furthest from the objective and its value is 0.9992 p.u., which is also very close to the ideal value. The amount of EVs and their distribution to reach the ideal case in both scenarios is presented in Tables 3 and 4.

	Bus Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Number of EVs	0	0	0	98	0	0	0	0	0	0	0	0	86	25	22	51	32	32	27	25	24	21

Table 3: Distribution of EVs in the 22-Bus Distribution Network to reach the Ideal Voltage Profile with EVs only in specified nodes

	Bus Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Number of EVs	0	27	11	25	8	7	6	9	17	9	13	10	49	22	19	45	29	29	25	22	22	18

Table 4: Distribution of EVs in the 22-Bus Distribution Network to reach the Ideal Voltage Profile with EVs located in every node

Comparing Table 3 with Table 2, it is easy noticeable that the amount of EVs needed has increased steadily. As was mentioned, only EVs have been included to the same nodes that previously had at least one. From 13 EVs in the original case, the number has increased to 443 EVs, about 34 times the initial amount. Regarding the amount of households to reach this value, instead of the initial 82 that the distribution grid represented in the original case, about 2356 households would be needed to reach that amount of EVs.

Regarding the case which is presented in Table 4, where every bus has EVs, the total amount of EVs is lower than in the other case and is 422. This means that even though some nodes may cause an overall greater impact than others, it is generally beneficial to have reactive power support in every node of the distribution grid. Overall, both ideal scenarios picture too many EVs for the distribution grid that was studied.

The main takeaway here is that with an EV density of only 10%, a proper regulation of the voltage profiles in a distribution grid only with EVs is not feasible. In following chapters, a higher EV penetration will be analyzed.

3.3.4 ANALYSIS OF DIFFERENT SCENARIOS ON THE 22-BUS DISTRIBUTION NETWORK

In this section, a further analysis of the 22 – bus distribution grid will be done. It has been proofed that, as could be expected, the amount of EVs is a critical factor to provide feasible V2G support. However, the aim of this section is to study if the location of the EVs plays a role here. In order to do it, two different scenarios will be analyzed each with a different EV penetration of 20% and 50%. The first scenario consists of the concentration of the EVs close to the feeder whereas in the second one, the EVs are mostly concentrated at the end of the line. In every case, first the voltage profile without EVs will be analyzed, then with the inclusion of EVs but without providing reactive power and finally with the inclusion of EVs providing a maximum amount of 2 kVar.

3.3.4.1 First Scenario: 20% EV-Penetration

The first scenario will be analyzed with a 20% of EV penetration. According to the power demanded by each bus in the network, 20% of EVs means that there are 33 EVs available. The normal distribution across the grid would be the one in Table 5. The voltage profile in every case for the original distribution of the EVs can be seen in Figure 11.

	Bus Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Number of EVs	0	1	1	2	1	0	0	1	1	1	1	1	4	2	2	4	2	2	2	2	2	1

Table 5: Distribution of EVs in the 22-Bus Distribution Network with a 20% EV Penetration

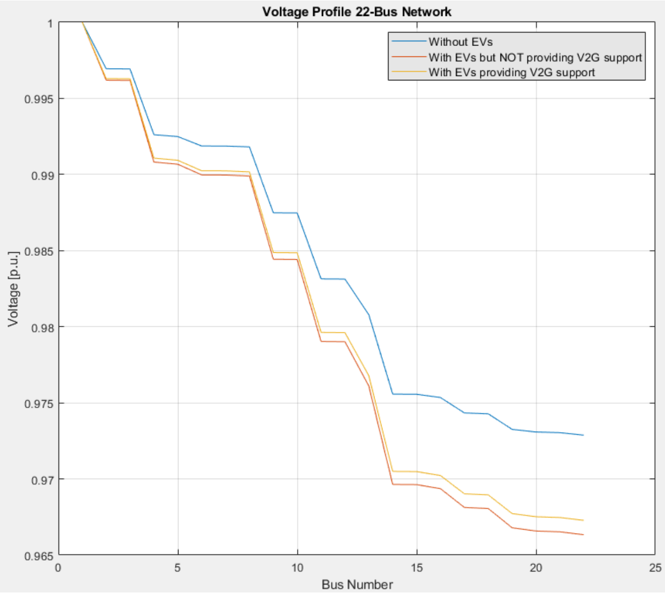

Figure 11: Voltage Profile Differences for the 22 - Bus Distribution Network with a 20% EV Penetration

The results are pretty similar compared to the case with an EV penetration of 10%. It can be seen that the worst scenario is when the EVs are connected to the grid but not providing any reactive power support. However, even while providing V2G services, the voltage profile is worse than when there are no EVs connected. The remaining data defining the network with a 20% EV penetration providing V2G support such as the active and reactive power generated and consumed by each node can be seen in Appendix II.

Furthermore, the same procedure will be done with the same amount of EVs. However, this time the EVs will be mostly concentrated close to the feeder or “root bus”, which is represented by the node 1 in Figures 6 and 7. About 80% of all EVs will be located between nodes 2 and 10, being the second node the one with the largest number of EVs. The voltage profile for this scenario is presented in Figure 12.

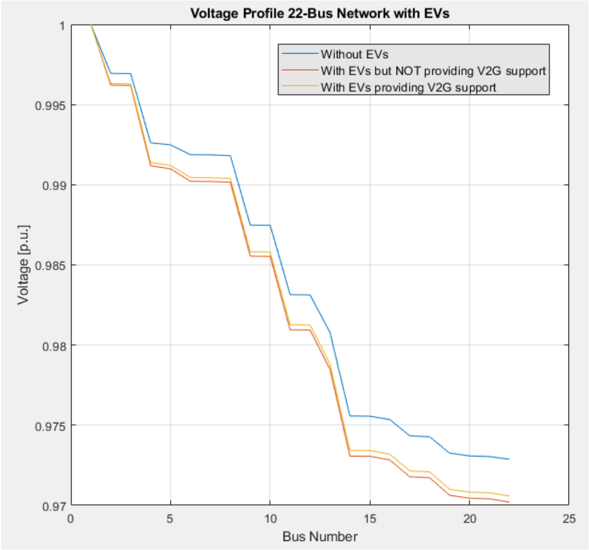

Figure 12: Voltage Profile Differences for the 22 - Bus Distribution Network with a 20% EV Penetration close to the Feeder Bus

The tendency of the voltage profile is the same. However, interesting to mention is that both voltage profiles are closer to the original case compared to Figure 11, which means that injecting reactive power close to the feeder bus is more effective than having it randomly distributed throughout the grid. The remaining data defining the network with a 20% EV penetration providing V2G support close to the feeder node can be seen in Appendix II.

Finally, the same procedure will be run, but this time the EVs will be mostly concentrated at the end of the distribution line, far away from the generator node. This time, about 85% of EVs will be located between nodes 15 and 22, being the latter one the one with most EVs. The voltage profile for this scenario is presented in Figure 13.

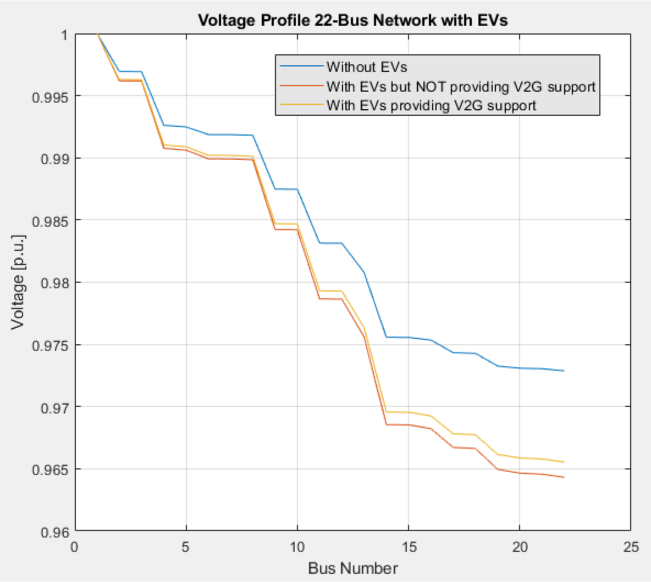

Figure 13: Voltage Profile Differences for the 22 - Bus Distribution Network with a 20% EV Penetration at the End of the Line

Comparing Figures 12 and 13, it becomes clear that the location of the EVs plays an essential role in the voltage profile. In the worst scenario in Figure 13, the lowest voltage takes place in bus 22 with a voltage of 0.9655 p.u. and this is the lowest among all cases studied so far.

3.3.4.2 Second Scenario: 50% EV-Penetration

The second scenario will be analyzed with a 50% of EV penetration. According to the power demanded by each bus in the network, 50% of EVs means that there are 78 EVs available. For the first time so far, all load nodes in the network have at least one EV connected. The normal distribution across the grid would be the one in Table 6. The voltage profile in every case for the original distribution of the 50% EVs can be seen in Figure 14.

	Bus Number																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Number of EVs	0	2	2	4	2	1	1	2	2	2	2	2	10	4	4	9	6	6	5	4	4	4

Table 6: Distribution of EVs in the 22-Bus Distribution Network with a 50% EV Penetration

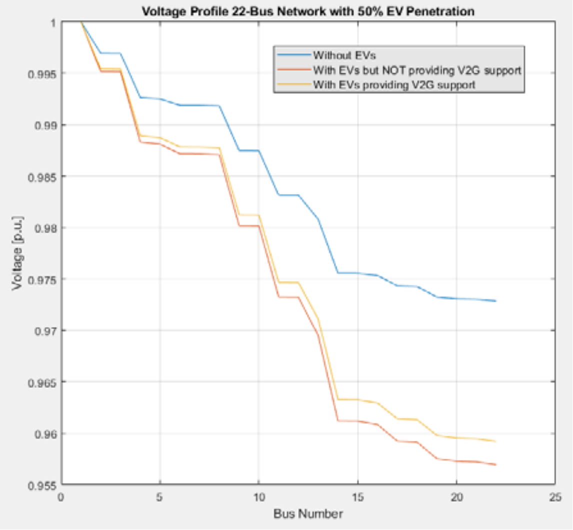

Figure 14: Voltage Profile Differences for the 22 - Bus Distribution Network with a 50% EV Penetration

The main takeaway from Figure 14 is that by adding more EVs to the distribution network, the power demanded is larger and therefore, the voltage decreases compared to the original case and the cases with a penetration of 10% and 20%. However, when providing reactive power support, there is still an increase in the voltage profile values compared to when not. The remaining data defining the network with a 50% EV penetration providing V2G support can be seen in Appendix II.

Furthermore, as was done with the previous example, the same procedure will be done with the same 78 EVs, but distributed differently. In Figure 15 can the voltage profile be observed when the majority of the EVs are located near the feeder node. In this case, about 82% of all EVs are connected between nodes 2 and 12 of the distribution grid, being the second node the one with the largest number of EVs.

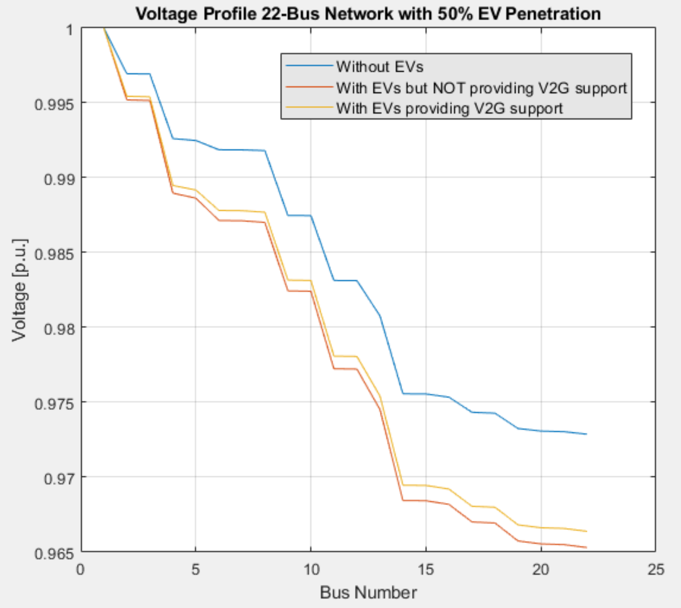

Figure 15: Voltage Profile Differences for the 22 - Bus Distribution Network with a 50% EV Penetration close to the Feeder Bus

As in the case with a 20% EV penetration, the voltage profile is closer to the original case compared to Figure 14, which means that injecting reactive power close to the feeder bus is more effective than having it randomly distributed throughout the grid. The remaining data defining the network with a 50% EV penetration providing V2G support close to the feeder node can be seen in Appendix II.

Finally, as in the previous example, the EVs will be mostly concentrated at the end of the distribution line, far away from the generator node. This time, about 83% of EVs will be located between nodes 13 and 22. The voltage profile for this scenario is presented in Figure 16.

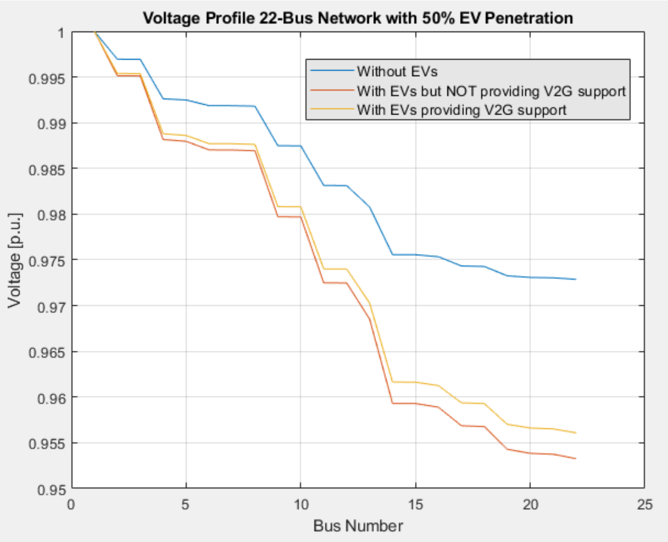

Figure 16: Voltage Profile Differences for the 22 - Bus Distribution Network with a 50% EV Penetration at the End of the Line

Comparing Figure 15 with Figure 16, it can be observed that the voltage profile is worse when the EVs are included at the final nodes of the distribution network rather than close to the feeder bus both when providing V2G support and when not. Because in this scenario the largest amount of EVs were incorporated, the voltage in the node 22 is the lowest among all previously examined scenarios with a value of 0.9533 p.u. To conclude this scenario, it was demonstrated that the location of EVs is a critical factor in determining the voltage profile of the distribution network.

3.4 OPTIMAL PLACEMENT OF CAPACITOR BANKS IN THE 22-BUS DISTRIBUTION NETWORK AND THE ANALYSIS OF THEIR REPLACEMENT WITH EVS

The optimal location and sizing of capacitor banks in the electrical network is a procedure that aims towards reducing power losses and minimizing the sum of costs and voltage variability. There are many variables involved in the problem such as the site, the available resources and the climatic conditions, and the outcomes usually include reactive power compensation, improved voltage levels and increased energy efficiency. The use of capacitor banks located at the distribution side is a feasible solution with both technical and economic benefits.

There are numerous papers with different formulations of the problem and their solution methods published [26]. All of them include some sort of iterative algorithms to find the optimal location in any distribution grid to install the capacitors like the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Direct Search Algorithm (DSA), the Bat Optimization Algorithm (BOA) or the Clustering Based Optimization (CBO). The goal is always to minimize the total losses and costs while maintaining acceptable voltage levels throughout the whole network.

According to [26,27], both papers utilize the Direct Search Algorithm (DSA) and they determine that the optimal size and location of the shunt capacitors in the 22-Bus distribution network with nominal load and with the objective of minimizing costs is the one of Table 7.

According to [26], with this capacitor distribution, there is a reduction of 45.39% in active power loss. Additionally, the total cost of energy losses decrease from $10302 per year without voltage compensation to $5576 per year after capacitor placement. Including the purchase of the capacitor banks, the total annual savings are found to be $1576.

Bus Number	**Capacitor Size (kVar)**
4	150
13	300
16	150
17	150
Total	750

Table 7: Capacitive Compensation for the 22-Bus System using the DSA Algorithm

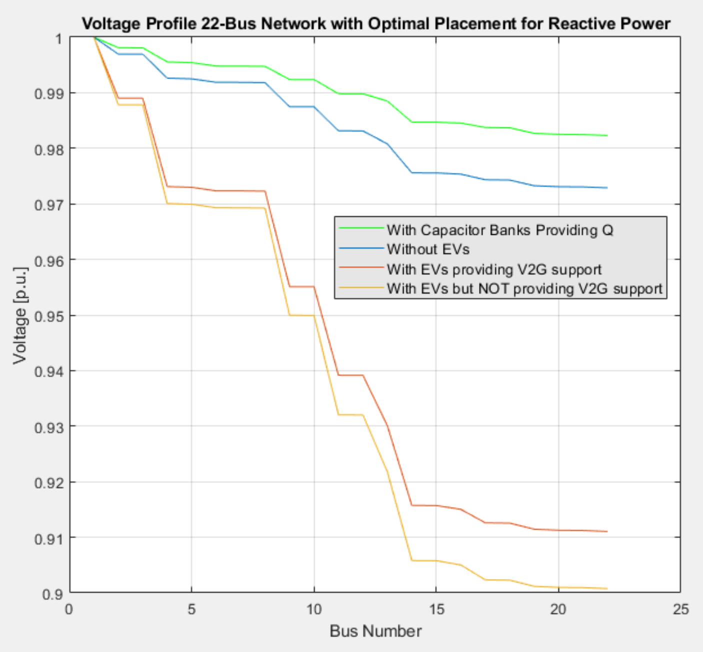

Figure 17: Voltage Profile with Capacitive Compensation using the DSA Algorithm

The feasibility of this scenario will be analyzed with the inclusion of EVs. Figure 17 presents the voltage profile in the original case, with the distribution of capacitor banks of Table 7 and with the inclusion of EVs replacing the capacitor banks providing the same amount of reactive power.

As was discussed, there are several formulations published where different solutions are provided. Another possible distribution using the CBO Method will be the one of Table 8 [27]. This method has the unique feature compared to the others of placing the capacitors more evenly throughout the network. As the capacitor size is smaller than in the previous case, less EV penetration will be necessary to reach that amount of reactive power. In this case, the power losses in the system are greater than with the DSA and account for $6361 per year after capacitor placement, $785 more than in the previous case. However, less capacitor banks are included so the total overall cost is smaller and accounts for $7711. The different voltage profile for this scenario are provided in Figure 18.

Bus Number	**Capacitor Size (kVar)**
18	300
20	150
Total	450

Table 8: Capacitive Compensation for the 22 - Bus System using the CBO Method

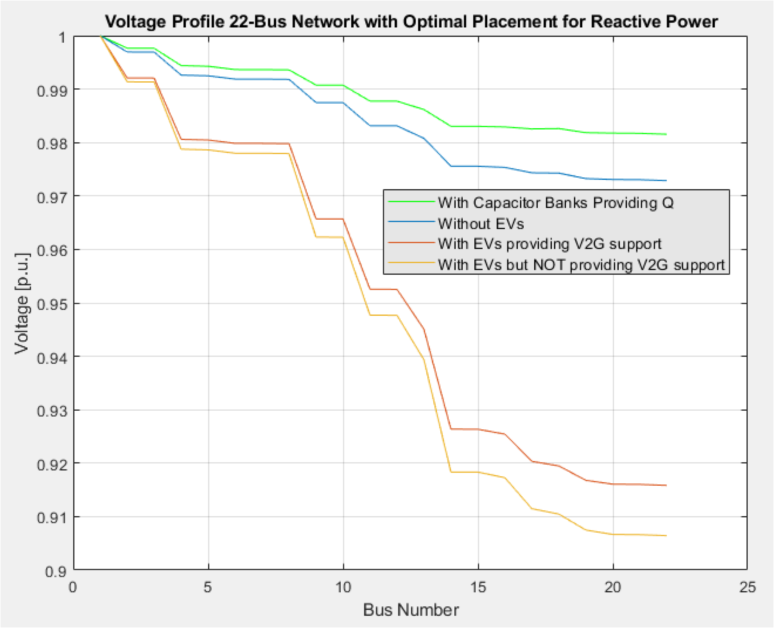

Figure 18: Voltage Profile with Capacitive Compensation using the CBO Method

The main takeaway from this chapter is that capacitor banks improve the voltage profile of the network considerably. Additionally, one of the goals of the capacitors is reducing the overall losses of the system. This can also be observed in the remaining data contained in Appendix II, where both the active and reactive power losses in the system are minimal when the DSA Algorithm and the CBO Method are applied to find the optimal sizing and location of the capacitor banks. However, they cost money to install and to maintain. Therefore, if enough EVs were available on the market to provide this reactive power, they would provide this service with no extra cost of operation and the savings would be even larger. With the inclusion of EVs, the outcomes of Figure 18 were the expected ones. In both scenarios, with the DSA Algorithm and the CBO Method, there is a prominent increase in the load as the amount of EVs introduced was considerable. This increase in the load produces the descend in the voltage profiles, which is in part compensated when the EVs are providing V2G reactive power support. If the EVs were not drawing power from the grid and only providing support, the results would be much closer to the scenario with only capacitor banks. This will be analyzed in the following chapter.

Chapter IV: ANALYSIS OF DIFFERENT TIMEFRAMES ON A 24-HOUR PERIOD

4.1 HOURLY LOAD VARIATION

In the last section, several scenarios were analyzed with different EV penetrations and a different distribution throughout the network. However, they all had in common that the nominal load was utilized. This is not always the general case. In fact, the load demand varies significantly depending on several aspects like the weekday, weather, customer usage patterns, season, holidays, etc. Even though the total average amount of energy consumed by different households may be the same, their consumption patterns can be very different and that has to be considered while examining the distribution network coefficients related to the nominal values.

	Hours											
	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Coefficients	0.72	0.66	0.61	0.59	0.65	0.71	0.85	0.94	1.08	1.02	1.01	0.99
	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Coefficients	1.01	1.05	1.03	1.01	1.02	1.06	1.18	1.22	1.19	1.04	0.96	0.83

Table 9: Hourly Coefficients Determining Load Variation

According to [28-30] and to the distribution load data of [31], the coefficients that will determine the hourly load for the 24-hour period of the distribution network are presented in Table 9 and Figure 19. These coefficients are calculated using the average load and are referred to the nominal load values that were examined in the previous section. An example of the hourly data obtained from [31] can be found in Appendix III.

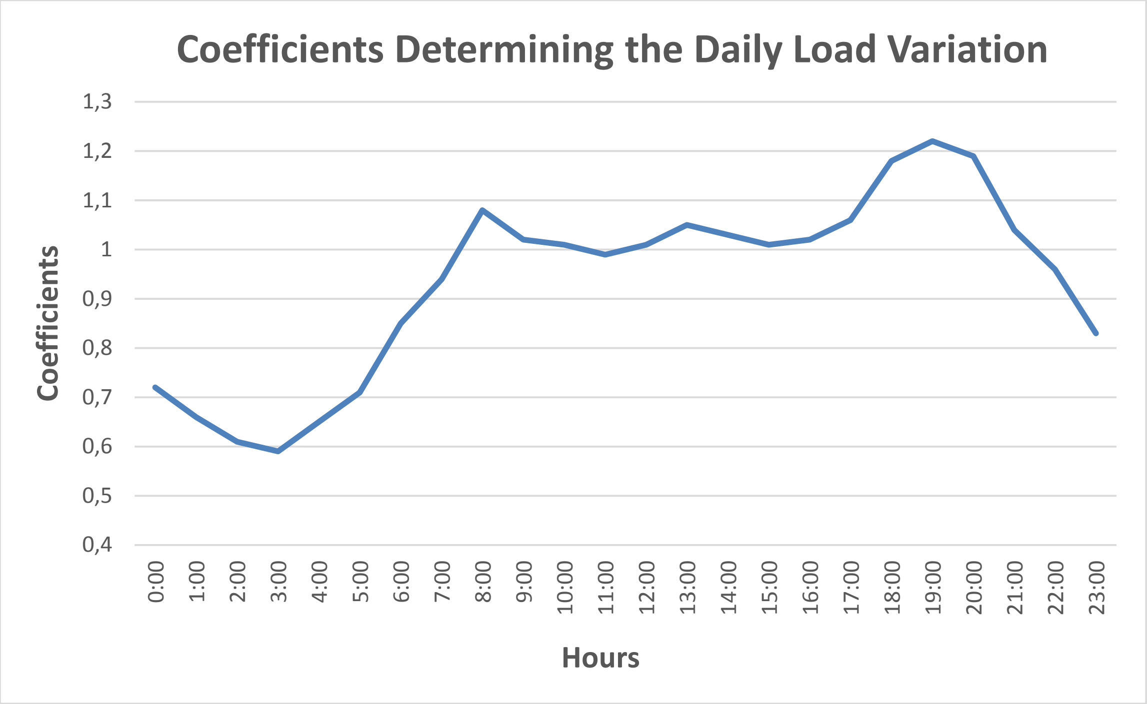

Figure 19: Hourly Coefficients Determining Load Variation

4.2 HOURLY EV RESIDENTIAL PARKING OCCUPANCY

Furthermore, the charging and driving behavior of the EV drivers can have a tremendous impact on the interaction between the EVs and the power distribution network. One of the main problems regarding the introduction of EVs into the distribution grid is predicting the mobility behavior of the EVs, which differs from individual to individual. Seasonal and location effects as well as distinctions between the different types of EVs will be disregarded due to the limited amount of available data. Additionally, the travelling patterns of the EV owners can differ a lot between working days and holidays, therefore the following analysis focuses only on working days. Essential aspects to analyze are the charging times and the length and charging locations of the EVs.

EV-load scheduling is an important aspect to model the influence of EVs into the distribution network. The actual behavior of EV drivers has been utilized to model the mobility patterns and parking availability in different scenarios. From historical data and from a survey of EV users behavior analysis, the percentage of the residential parking availability patterns of the EVs was determined in [32,33] and can be seen in Figure 20 and Table 10.

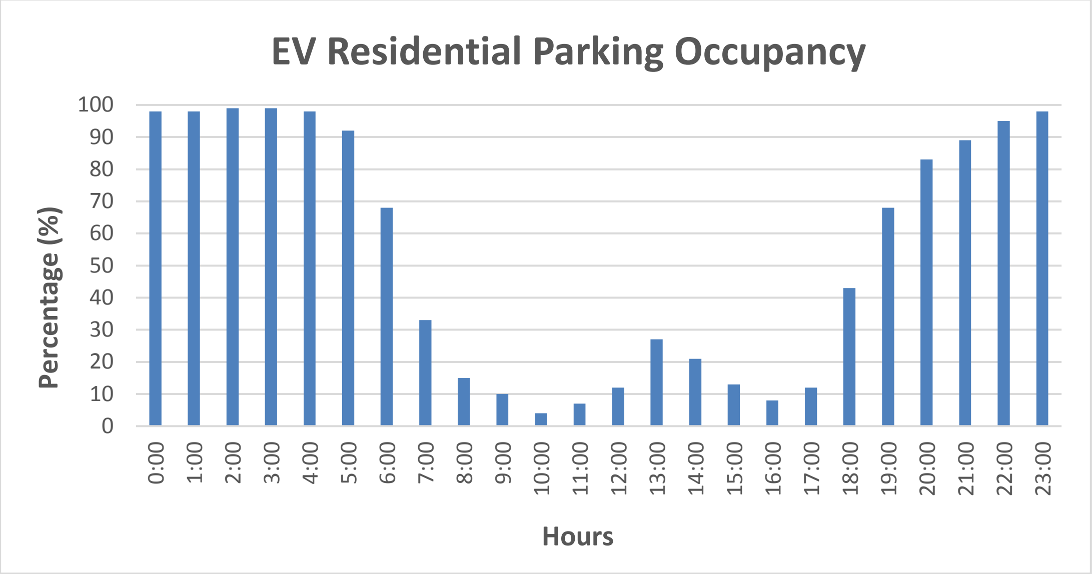

Figure 20: Hourly EV Residential Parking Occupancy

	Hours											
	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
Parking Occupancy (%)	98	98	99	99	98	92	68	33	15	10	4	7
	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
Parking Occupancy (%)	12	27	21	13	8	12	43	68	83	89	95	98

Table 10: Hourly EV Residential Parking Occupancy

4.3 INFLUENCE OF EV CHARGING SCENARIOS ON THE VOLTAGE PROFILE

In this section, what will be analyzed is the variation in the 22-bus distribution network voltage profile on an hourly basis. All daily timeframes will be evaluated regarding the amount of EVs that are connected to the network, the amount that are being charged and the ones that are providing V2G regulation services depending on two different EV charging scenarios. Also, two different EV penetration cases will be studied, a low penetration of 10% and a larger EV penetration of 50% into the network. As was mentioned in the previous chapter, the majority of EV chargers in the United States are Level 2 and the most typical among them have a power output of 7.2 kW installed in the residential power network. An appropriate charging time for most EVs with that charger level that will be considered in this section is between two and three hours [34]. It will be assumed that all EV batteries are fully charged throughout the day so that they are totally available for the next day.

EVs can be modelled as mobility loads with several charging pattern options. According to the parking patterns of the EVs described in Figure 20, there is the need of planning when and for how long the charging will take place. The inclusion of the charging EVs into the network can affect the peak demand ant the technical limits of the network such as current or voltage violation in the buses.

First, the home plugging in times of the EVs will be analyzed according to Figure 20 and Table 10. At 17:00 there are 12% EVs connected and at 22:59 this number has increased to 95%. This means that in these six hours, 83% of all EVs have returned home and are plugged in. This period coincides with the period of peak load demand. After that, between 23:00 and 05:59, an additional 5% of all EVs are plugged in. This period coincides with the valley load demand. The lasting 12% EVs are plugged in during the remaining times of the day, between 06:00 and 16:59. From that 12%, the great majority takes place between 12:00 and 15:59, which is the period where the loads are closest to the nominal values.

Once the parking patterns of the EVs have been analyzed, two different EV charging scenarios will be studied. In order to better understand the impact the EVs can have on the distribution network, each scenario will be analyzed with two different EV penetration, first with 10% of EVs and then with 50%. Additionally, as in the previous section, active power support will not be considered as it affects the EV battery lifetime. Also, if the EVs are connected to the grid, it will be considered that they are capable of providing V2G reactive power support.

4.3.1 HOURLY ANALYSIS OF THE EV-DISTRIBUTION IN THE FIRST CHARGING SCENARIO

The first scenario consists that the EVs start charging immediately after they have been plugged in and it takes three hours to completely charge them. To include this with what was previously discussed, three different charging times each of three hours will be assessed. 5% of all EVs will be charging between 01:00 and 03:59. An additional 12% of all EVs will be charging between 12:00 and 14:59. Finally, the majority of EVs (83%) will be charging between 20:00 and 22:59.

The following Table 11 summarizes the aforementioned scenario on an hourly basis. It includes the percentage of the connected EVs, the percentage of which are being charged and the percentage of which are not and finally the load coefficients from Table 9.

From	To	Connected EVs (%)	NOT Connected EVs (%)	Charging EVs (%)	Connected but NOT Charging EVs (%)	Load Coefficients
0:00	0:59	98	2	0	100	0,72
1:00	1:59	98	2	5	95	0,66
2:00	2:59	99	1	5	95	0,61
3:00	3:59	99	1	5	95	0,59
4:00	4:59	98	2	0	100	0,65
5:00	5:59	92	8	0	100	0,71
6:00	6:59	68	32	0	100	0,85
7:00	7:59	33	67	0	100	0,94
8:00	8:59	15	85	0	100	1,08
9:00	9:59	10	90	0	100	1,02
10:00	10:59	4	96	0	100	1,01
11:00	11:59	7	93	0	100	0,99
12:00	12:59	12	88	12	88	1,01
13:00	13:59	27	73	12	88	1,05
14:00	14:59	21	79	12	88	1,03
15:00	15:59	13	87	0	100	1,01
16:00	16:59	8	92	0	100	1,02
17:00	17:59	12	88	0	100	1,06
18:00	18:59	43	57	0	100	1,18
19:00	19:59	68	32	0	100	1,22
20:00	20:59	83	17	83	17	1,19
21:00	21:59	89	11	83	17	1,04
22:00	22:59	95	5	83	17	0,96
23:00	23:59	98	2	0	100	0,83

Table 11: Table Summarizing Charging Scenario 1 in Percentage of EVs

4.3.1.1 Analysis of the Different Timeframes of the First Charging Scenario

Examining the voltage profiles and the input data, it can be observed that several hours are very similar to one another in both scenarios with 10% and 50% EV penetration. To study all different cases during the 24-hour period, ten different timeframes according to the number of connected EVs, the number of charging EVs, the number of connected but not charging EVs and the load coefficients have been analyzed. To compare all different timeframes with each other, the reference will be the voltage profile for the 22-Bus distribution network without any EVs connected.

The analysis of the different timeframes can be found in Figure 21.

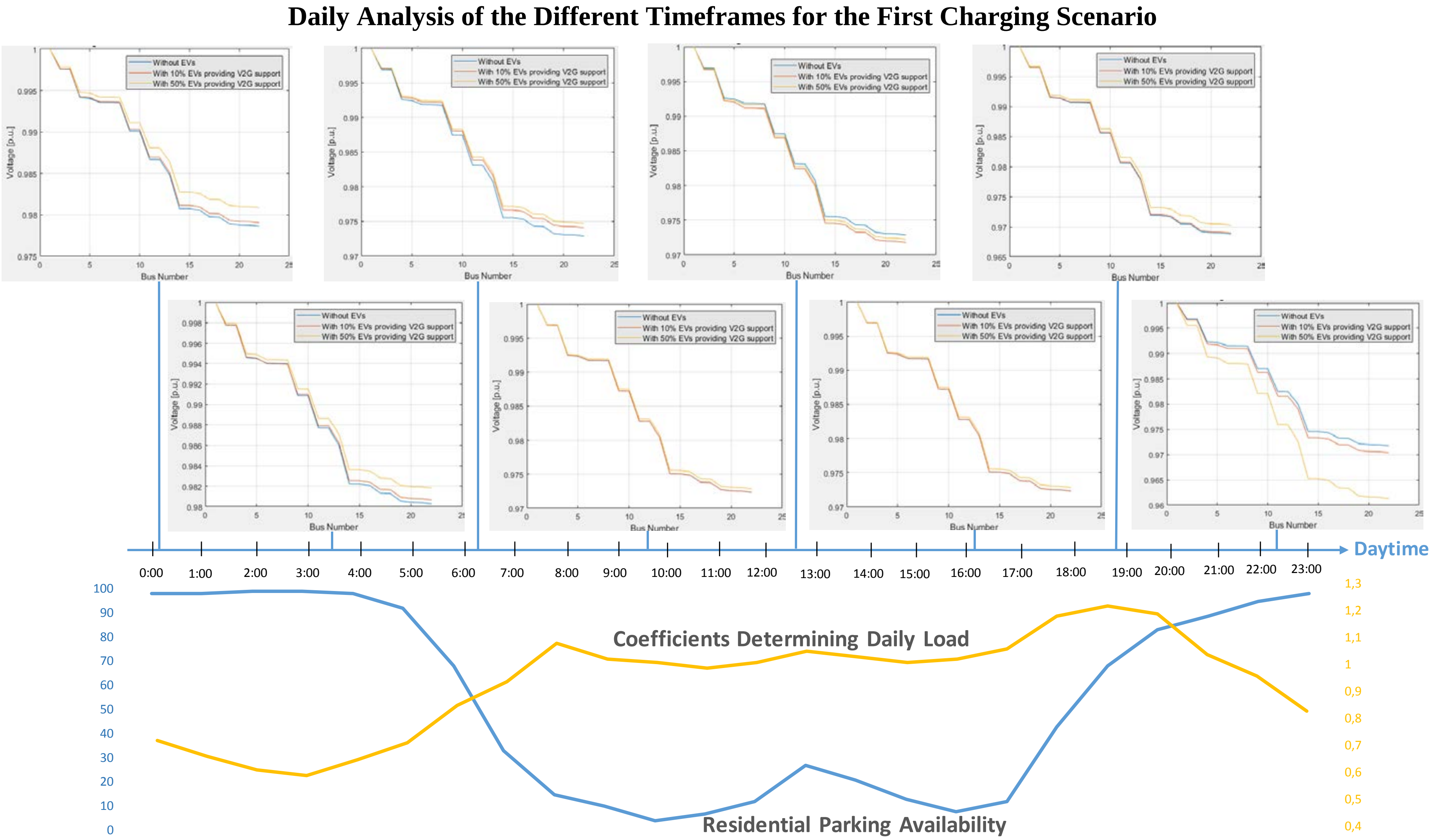
Daily Analysis of the Different Timeframes for the First Charging Scenario

Figure 21: Daily Analysis of the Different Timeframes for the First Charging Scenario

4.3.1.2 Results of the First Charging Scenario

The main takeaway from the first charging scenario is that during the periods when none EVs are being charged, the voltage profile improves when there is both 10% or 50% EV penetration providing V2G reactive power support. This becomes more remarkable in the case with 50% EVs, as the more EVs are available, the more will be connected to the network and finally, the more reactive power they could supply. Furthermore, it was demonstrated that the coefficient load only plays a role in scaling the voltage profiles curves, but not in their shape. The higher the coefficient, the further down the voltage profile will be compared to a lower coefficient.

When observing the cases where small percentages of EVs, about 5% of all EVs, are being charged, it can be seen that the voltage profile is not significantly affected by the slight increase in power demanded. However, if the number of charging EVs increases to 12% of all EVs, it is shown that the voltage profiles tend to deteriorate. This occurs even though the EVs are providing V2G reactive power support, because there is an increase in the power demanded. This can be best examined in the period between 20:00 and 22:59, when 83% of all EVs are being charged. It can be observed that with a 50% EV penetration, its voltage profile differs significantly from the curves without EVs and with only 10% EVs. This is because there has been a considerable increase in the power demanded by all bus nodes. As the EVs cannot provide active power because it would deteriorate the battery lifetime, this extra power has to be generated by the feeder node, and this produces the decrease in the voltage profile. With 10% EV penetration, this decrease is not that significant because less EVs have to be charged.

Additionally, when the number of connected EVs is low (less than 10% of all available EVs), their influence in the voltage profile curves is minimal. The difference between 10% and 50% EV-penetration also becomes insignificant as there are only few EVs connected.

4.3.2 HOURLY ANALYSIS OF THE EV-DISTRIBUTION IN THE SECOND CHARGING SCENARIO

The second charging scenario is also known as a controlled charging scheme. With this scheme, the EVs charging process is delayed to avoid peak demand periods. The consequence of this is that the largest percentage of the EVs will be charged during valley demand hours. Even though the EVs are still connected to the grid as soon as they arrive home, the charging process is controlled by the utility grid and with this scheme 80% of EVs are charged between 01:00 and 03:59, coinciding with the valley load period. Then, 15% of the EVs are still charged during peak demand hours, between 20:00 and 22:59, and the remaining 5% are charged between 12:00 and 14:59.

It should be noted that in this scenario, drivers should agree to having their EVs connected but not being charged. Monetary compensation could be given in this scenario to incentive the delayed charging of the EVs. This could eventually produce a new peak demand during night hours if the amount of plugged in EVs is large enough.

The following Table 12 summarizes the aforementioned scenario on an hourly basis. It includes the percentage of the connected EVs, the percentage of which are being charged and the percentage of which are not and finally the load coefficients.

From	**To**	**Connected EVs (%)**	**NOT Connected EVs (%)**	**Charging EVs (%)**	**Connected but NOT Charging EVs (%)**	**Load Coefficients**
0:00	0:59	98	2	0	100	0,72
1:00	1:59	98	2	80	20	0,66
2:00	2:59	99	1	80	20	0,61
3:00	3:59	99	1	80	20	0,59
4:00	4:59	98	2	0	100	0,65
5:00	5:59	92	8	0	100	0,71
6:00	6:59	68	32	0	100	0,85
7:00	7:59	33	67	0	100	0,94
8:00	8:59	15	85	0	100	1,08
9:00	9:59	10	90	0	100	1,02
10:00	10:59	4	96	0	100	1,01
11:00	11:59	7	93	0	100	0,99
12:00	12:59	12	88	5	95	1,01
13:00	13:59	27	73	5	95	1,05
14:00	14:59	21	79	5	95	1,03
15:00	15:59	13	87	0	100	1,01
16:00	16:59	8	92	0	100	1,02
17:00	17:59	12	88	0	100	1,06
18:00	18:59	43	57	0	100	1,18
19:00	19:59	68	32	0	100	1,22
20:00	20:59	83	17	15	85	1,19
21:00	21:59	89	11	15	85	1,04
22:00	22:59	95	5	15	85	0,96
23:00	23:59	98	2	0	100	0,83

Table 12: Table Summarizing Charging Scenario 2 in Percentage of EVs

4.3.2.1 Analysis of the Different Timeframes of the Second Charging Scenario

Examining the voltage profiles and the input data, it can be observed that several hours are very similar to one another in both scenarios with 10% and 50% EV penetration. To study all different cases during the 24-hour period, ten different timeframes according to the number of connected EVs, the number of charging EVs, the number of connected but not charging EVs and the load coefficients have been analyzed. To compare all different timeframes with each other, the reference will be the voltage profile for the 22-bus distribution network without any EVs connected.

The analysis of the different timeframes for the second charging scenario can be found in Figure 22.

Daily Analysis of the Different Timeframes for the Second Charging Scenario

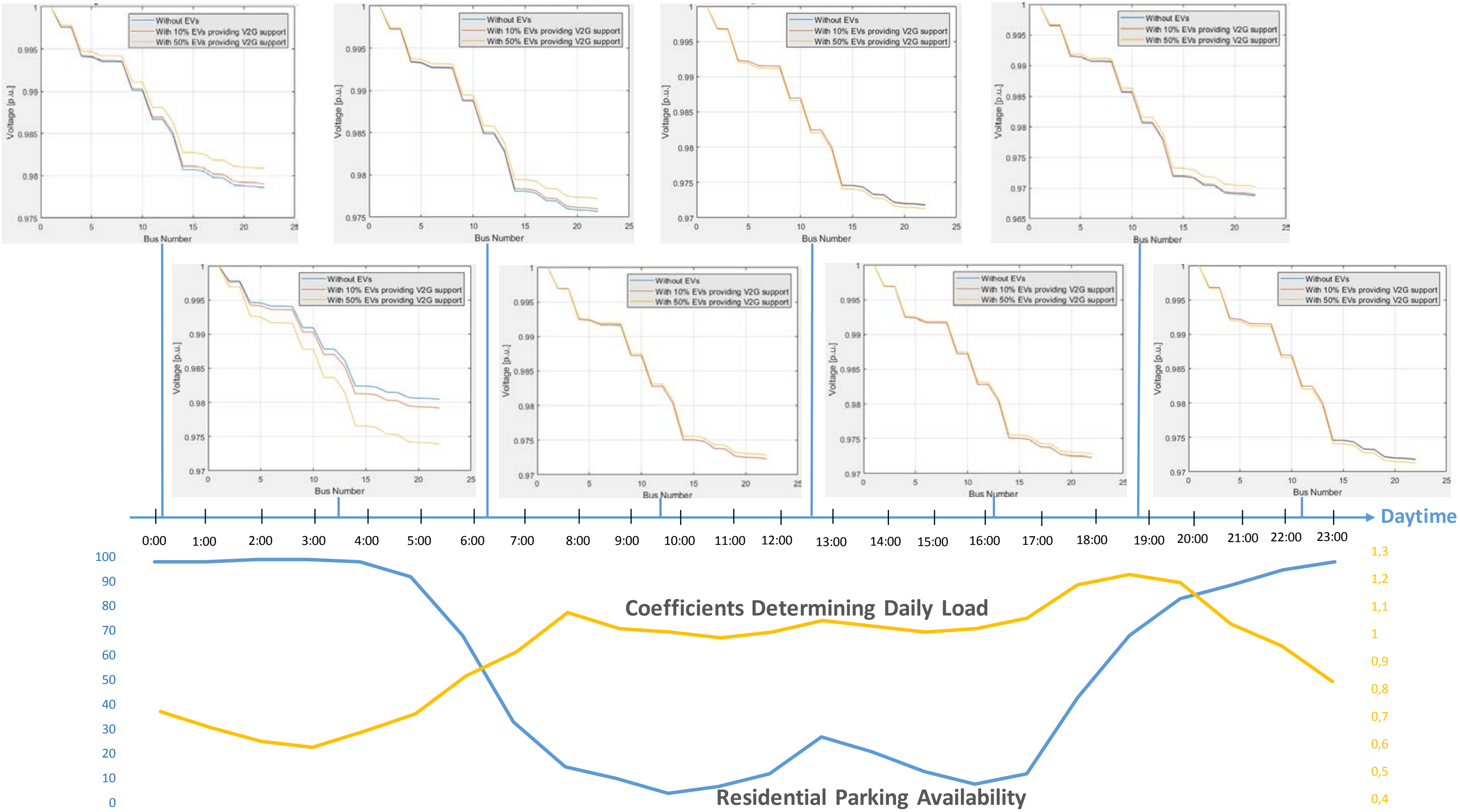

Figure 22: Daily Analysis of the Different Timeframes for the Second Charging Scenario

4.3.2.2 Results of the Second Charging Scenario

This charging scenario further confirms the results extracted from the first charging scenario where the EVs were charged once they arrived. When the EVs are connected and they are not being charged, it is a great opportunity to provide V2G reactive power support to improve the voltage profiles. Therefore, as was expected, the more EV penetration, the higher the reactive power support and the better the expected outcome will be. Overall, during the times of the day when the number of connected EVs is low, their influence on the voltage profiles stops being remarkable.

Furthermore, when the amount of charging EVs is low (close to 5% of all EVs), their overall impact on the voltage profile overcomes the fact that there is a slight increase in the power demanded. However, if the number of charging EVs increases to 15%, the voltage profiles tend to decrease even when the EVs are providing V2G reactive power support.

4.4 COMPARISON OF THE RESULTS IN BOTH CHARGING SCENARIOS

The main difference between both charging scenarios is the time of the day when the majority of the EVs are being charged. In the first scenario, this happened during the peak load demands, between 20:00 and 22:59. However, during the second scenario, the majority of the EVs were charged overnight, during the valley load times of 1:00 and 3:59. When comparing the voltage profiles for both scenarios when the majority of the EVs are being charged, a main conclusion can be drawn. Even though in both scenarios the voltage profile has decreased because of the increase in the power demanded, such decrease is not as significant when the EVs are charged during valley loads. This is because the coefficient load during that timeframe is half the size compared to the peak loads.

The results in the second charging scenario indicate that during peak demand, the voltage profile tends to remain close to the initial scenario without any EVs connected because only a few EVs are being charged, unlike in the first scenario. This could be a way of preventing peak load voltages and currents which would finally lead to increased costs and losses.

It can also be observed that the values of the voltage profiles are more stable throughout the whole timeframe for the second charging scenario. This could allow in the future higher EV penetration into the distribution grids without the need of enhancing the existing network infrastructure.

Chapter V: ECONOMIC ANALYSIS OF THE RESULTS

5.1 INTRODUCTION

The aim of this section is to analyze the replacement of the existing capacitor banks in the distribution grids with the utilization of EVs providing V2G reactive power support. Traditionally, the reactive power needed to improve the overall efficiency in the grid and to reduce losses was generated by capacitor banks placed in optimal locations throughout the grid. However, with the future increase in the number of available EVs, they have the potential of replacing the capacitor banks and therefore reduce costs.

EVs have the possibility of transferring reactive power to the grid even while charging without affecting the lifetime of the battery. All the reactive power they generate is inherent to their batteries and is free to use by the distribution grid operators. Thus, if they generate enough reactive power to maintain the network between its operation margins, the capacitor banks would not be necessary. This would mean considerable savings in the installation, maintenance and generation of reactive power by the capacitor banks.

In the previous section, the variations in the coefficient loads for the distribution grids were analyzed on an hourly basis. In this section, the prices of the electricity will be analyzed on an hourly basis too. The objective of this is to determine the cost of charging the EVs in the distribution grid. The prices vary significantly throughout the day because of the change in load demand.

According to [35,36] the hourly residential electricity prices for a typical working day in the U.S. are presented in Table 13 and Figure 23. The average is found to be 0.13 $/kWh.

Hours	**Price (¢/kWh)**
0:00	11,3
1:00	9,4
2:00	9
3:00	9,1
4:00	9
5:00	9,7
6:00	11,2
7:00	13,1
8:00	14,1
9:00	14,7
10:00	14,6
11:00	14,4
12:00	14
13:00	13,6
14:00	13,3
15:00	13,2
16:00	13,5
17:00	13,8
18:00	15
19:00	16,1
20:00	16,9
21:00	16,7
22:00	15,9
23:00	13,6

Table 13: Hourly Residential Electricity Prices

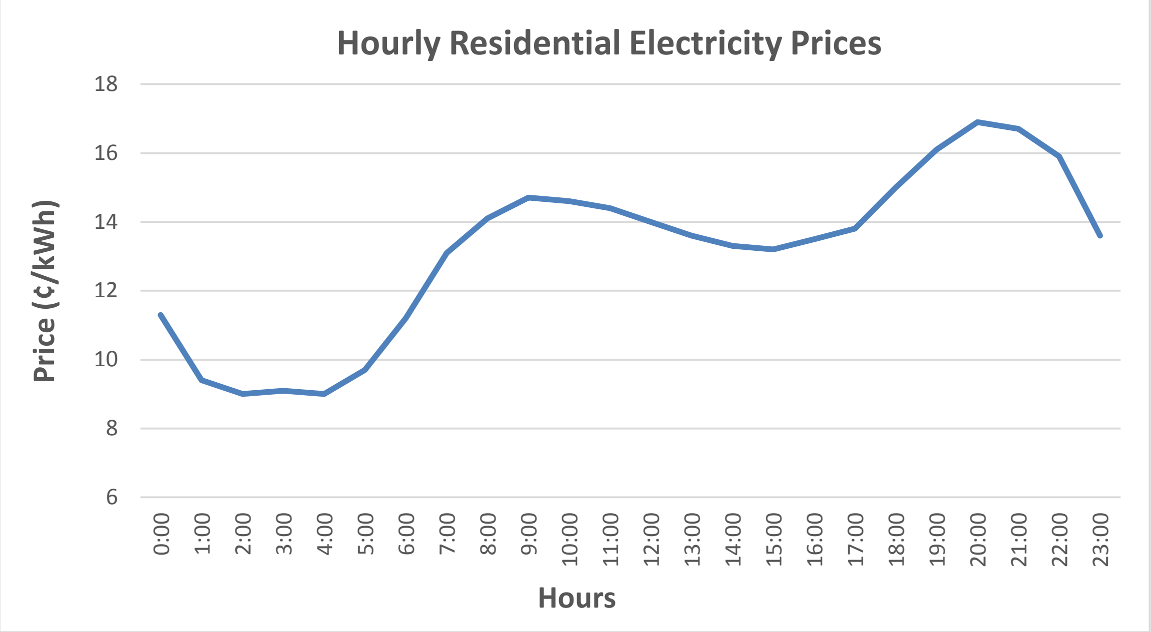

Figure 23: Hourly Residential Electricity Prices

There are discrepancies in the literature about the cost of the capacitor banks in the distribution grids. It is a complex issue with many variables involved. Some of this variables include the installation costs, the service lifetime of the capacitor banks, the reactive power generation sizes and the number of working cycles. The values of these variables can change significantly from installation to installation, thus finding an overall average value is a challenging task. According to [37,38] the installation costs and the reactive power generation costs of capacitor banks in distribution grids that will be utilized in this section is 3.27 $/kVar. As they do not have any moving parts, the maintenance costs are low and are also included in the value. The aforementioned value for the reactive power generation cost by the capacitor banks can change and it could affect the cost analysis, but as long as the value does not change drastically, the values should not change significantly. Overall, an average life for the capacitor banks of 10 years has been examined.

In this section, the efficiency of the capacitor banks and their influence on the distribution grid will be considered similar to the reactive power generated by the EVs. Both charging scenarios from the previous section will be analyzed. As a reminder, the first charging scenario consisted that the majority of the EVs were charged immediately after they arrived home, coinciding with the peak demand period. However, in the second scenario, the charging process was delayed to coincide with the load valley demand, when the prices are the lowest. The amount of energy utilized in the project to completely charge an EV is 21.6 kWh and the price depends on the time when it is being charged.

The economic analysis will be done according to three different EV penetration scenarios. In the first scenario, the actual situation of the EVs will be analyzed, which means a 4% of EV penetration into the distribution network. The second scenario will be with a 20% EV penetration, which would depict the situation in five to ten years' time. Finally, a 50% penetration of EVs into the distribution network will be analyzed, which would represent the situation in more than 20 years. All the costs and the savings are calculated on a daily basis according to the electricity prices of a typical working day contained in Figure 23.

5.2 ANALYSIS FOR 4% EV-PENETRATION

This scenario aims to analyze the actual situation of the EVs in the distribution network. The amount of existing EVs is low and therefore their overall impact on the distribution grid is not that significant. The results for a typical working day with 4% EV penetration are shown in Table 14.

	1st Charging Scenario (Immediately Charging)	**2nd Charging Scenario (Controlled Charging)**
Charging Costs ($)	17.20	11.48
Reactive Power Savings ($)	32.70	32.70
Total Savings ($)	15.50	21.22

Table 14: Total Savings for the Replacement of Capacitor Banks with 4% EVs

5.3 ANALYSIS FOR 20% EV-PENETRATION

According to the worldwide campaign EV30@30 introduced by the Clean Energy Ministerial in 2017, the objective is to reach a 30% on-road market share for EVs by 2030 [7]. Therefore, a 20% EV penetration will be expected in the upcoming five years and the results can be observed in Table 15.

	1st Charging Scenario (Immediately Charging)	**2nd Charging Scenario (Controlled Charging)**
Charging Costs ($)	111.97	75.19
Reactive Power Savings ($)	215.82	215.82
Total Savings ($)	103.85	140.63

Table 15: Total Savings for the Replacement of Capacitor Banks with 20% EVs

5.4 ANALYSIS FOR 50% EV-PENETRATION

This scenario focuses on the distant future where EVs reach half of all automobiles percentage. Analyzing both previous scenarios, it was demonstrated that an increase in the percentage of EVs providing V2G reactive power support brings an increase in the overall total savings. The results for this scenario are contained in Table 16.

	1st Charging Scenario (Immediately Charging)	**2nd Charging Scenario (Controlled Charging)**
Charging Costs ($)	266.08	177.31
Reactive Power Savings ($)	510.12	510.12
Total Savings ($)	244.04	332.81

Table 16: Total Savings for the Replacement of Capacitor Banks with 50% EVs

5.5 COMPARISON OF THE RESULTS

The economic analysis focuses on a 24-hour timeframe for a typical working day in the U.S. However, the results can be extrapolated to monthly or annually timeframes by simple proportionality of the data.

The aim of this section was to demonstrate that with the inclusion of EVs providing reactive power support, not only would the voltage profiles improve, but also it would make sense from an economic point of view. In the future, the EVs would be a feasible way of replacing the capacitor banks. The more EVs are connected to the network, the higher the reactive power generated and the greater savings. This happens even though the increase in EVs produces an increase in the charging costs. Additionally, it was proofed that the second charging scenario is more profitable as the prices of the electricity during valley loads are significantly lower than during peak times and thus are the charging costs reduced.

All the cost and savings included in the economic analysis are based on the actual data of energy prices. This data is obtained without the potential future influence of the EVs. Therefore, the prices could possibly change in the future, but as long as the values do not change drastically, it was demonstrated that the EVs could potentially mitigate the high initial investment compared to the traditional gasoline automobiles. This could improve the competitiveness of the EVs and trigger their future penetration into the system.

The only drawback is the uncertainty of the number of connected EVs to the grid, but with an elevated percentage of EVs, there should be enough providing reactive power compensation to replace the existing capacitor banks. The savings included in the economic analysis correspond to operational system savings. In order to incentive the EV owners to connect their EVs to the grid to provide V2G reactive power support, there could be a monetary stimulus. This economic stimulus could consist of a certain discount in their monthly electric rates. Initially, a feasible distribution of the money would be 50%-50%. That way, both the customer and the grid operators would enjoy the savings produced by the inclusion of EVs and an elevated number of connected EVs would be ensured.

Chapter VI: CONCLUSIONS AND FUTURE WORK

This thesis studies the influence of different EV penetrations scenarios on the voltage profiles of a 22-bus distribution network according to the location of the EVs, the number of EVs available and their charging patterns. The existing residential load variations over a 24-hour cycle as well as realistic EV residential parking occupancy were taken into account. It was demonstrated that the location of the EVs plays an essential role in the voltage profiles of the distribution network and that injecting reactive power close to the feeder bus is more effective than having it randomly distributed throughout the grid or having it generated at the final nodes of the line.

EVs are considered as flexible loads that could be charged throughout the day. When connected to the grid, the EVs could provide V2G reactive power support to improve the operation of the distribution network in terms of voltage profile. Two different charging scenarios have been analyzed. In the first scenario, the EVs are charged immediately after they arrive home, which produces a decrease in the voltage profile because of the augmented power demanded, and a potential system overloading. To avoid this problem, the second scenario consists of delaying the charging process of the EVs to avoid peak demand periods. This coordination of EV charging produces an overall stabilization of the voltage profiles for the 24-hour timeframe.

Furthermore, the system peak demand is not significantly affected by the controlled charging scheme, which is more favorable from a standpoint of preventing overloads. This would also improve the overall system efficiency and finally reduce system losses even with a high EV penetration. Additionally, it was proofed that the second charging scenario is more profitable as the prices of the electricity during valley loads are significantly lower than during peak times and thus are the charging costs reduced.

It was also demonstrated that, from an economic point of view, the EVs would be a feasible option to replace the existing capacitor banks in the distribution network. The higher the EV penetration, the more reactive power would be introduced into the grid and finally the greater system savings would be made. To avoid the uncertainty of having enough EVs providing V2G reactive power support in the network to replace the existing capacitor banks, a monetary incentive could be given to the customers for connecting their EVs. This economic stimulus could consist of a certain discount in their monthly electric rates. That way, both the customer and the grid operators would enjoy the savings produced by the inclusion of EVs and an elevated number of connected EVs would be ensured.

As for the future work in the subject, a wide range of scenarios were analyzed in the project. However, there are still numerous uncertainties about the charging processes of the EVs and their load distribution models in the future smart grid distribution networks. Moreover, the battery charging patterns can be significantly influenced by the future increase of renewable sources during the daytimes with high solar irradiance.

Additionally, the economic analysis data are based on the actual data of energy prices. This data is obtained without the potential future influence of the EVs. Therefore, the prices could possibly change in the future, but as long as the values do not change drastically, it was demonstrated that the connection of EVs to the grid providing reactive power operations could potentially mitigate the high initial investment compared to the traditional gasoline automobiles. This could improve the competitiveness of the EVs and trigger their future penetration into the system.

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APPENDIX I

Integration of the Sustainable Development Goals

The Sustainable Development Goals (SDGs) are a collection of 17 objectives that aim towards achieving an improved and more sustainable future for humankind and for the planet. Some of the goals adopted by the United Nations (UNs) focus on ending poverty and other deprivations while improving health and education, reducing inequality, fighting climate change and preserving the oceans and forests. The SDGs are sustained on three main dimensions: Biosphere, Society and Economy.

The primary SDG this project focuses on is the goal number 13: Take urgent action to combat climate change and its impacts, from the Biosphere dimension. One of the project's goals is to incentive the penetration of the EVs into the market to reduce the CO_2 emissions and fight climate change. The greenhouse gas emissions have increased steadily in the last decades and climate change is occurring at rates much faster than expected. One of the main causes of global warming emissions is the spread of internal combustion engine vehicles in our society. They are a main source of ozone, particulate matter and other smog-forming emissions that pollute cities worldwide.

One of the objectives of the project consists of demonstrating that the connection of EVs to the grid providing reactive power operations could potentially mitigate the high initial investment compared to the traditional gasoline automobiles. One of the main reasons why the EV penetration rates are not as high as expected globally is because gasoline automobiles with similar performance are significantly cheaper. If EV users could benefit from connecting their vehicles to the grid to provide reactive power support operations, their competitiveness would improve and customers would be more interested in them.

A secondary SDG the project assesses is goal number 7: Ensure access to affordable, reliable, sustainable and modern energy for all, form the Society dimension. A high level penetration of EVs into the market providing reactive power support would be the first step in the development of smart grids. The efficiency of the electric transmission network would improve and it would allow access to electricity in less developed areas. Additionally, the development of Smart Grids could potentially mitigate the dependence of fossil fuels to generate clean electricity.

Finally, another SDG the project focuses on is goal number 9: Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation, from the Economy dimension. The development of EVs and their batteries could be highly beneficial for a faster implementation of renewable energy sources in our society. A lot of research and investment has been done regarding the utilization of wind or solar resources to charge the EV batteries. This would also allow access to electricity and transportation in areas with a difficult access to the electric network like small island or rural areas. Additionally, transportation services could be improved with the implementation of EVs. These services could be of the form of electric car sharing implementations or electric buses.

The quantification of the SDGs in the project is a complex issue with many variables involved. According to [39], fossil-fueled cars generally emit more CO_2 to the atmosphere than EVs in all phases of a life cycle. The study shows that EVs emissions in terms of carbon footprint are 18% lower than gasoline cars. Therefore, if the inclusion of EVs providing reactive power support helps with increasing the penetration of EVs, each vehicle will reduce the emission of pollutants. The value is likely going to increase in the future to a 36% due to the decrease in the emission factor of electricity. Additionally, the recycling of EVs materials can also play an essential role in their overall future lifecycle emissions.

A summary of the SDGs the project examines is given in Table 17.

SDG Dimension	**SDG Identified**	**Role**	**Goal**
Biosphere	**SDG 13:** Take urgent action to combat climate change and its impacts	**Primary**	Mitigate the high initial investment compared to traditional gasoline automobiles to incentive the penetration of the EVs into the market to reduce the CO_2 emissions and fight climate change.
Society	**SDG 7:** Ensure access to affordable, reliable, sustainable and modern energy for all	**Secondary**	Development of smart grids to improve the efficiency of the electric transmission network and allow access to electricity in less developed areas.
Economy	**SDG 9:** Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	**Secondary**	Research and investment in the utilization of wind or solar resources to charge the EV batteries to allow access to electricity and transportation in areas with a difficult access to the electric network.

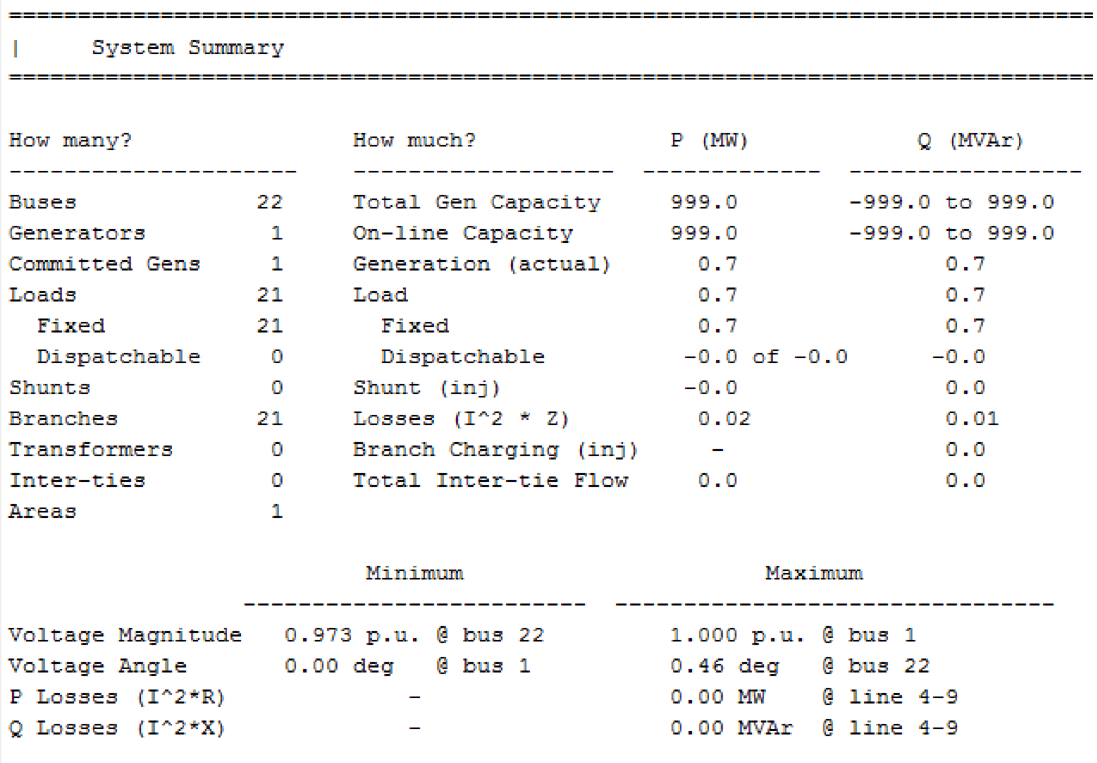
Table 17: Summary of the SDGs Involved in the Project

APPENDIX II

Data Defining the 22-Bus Distribution Network

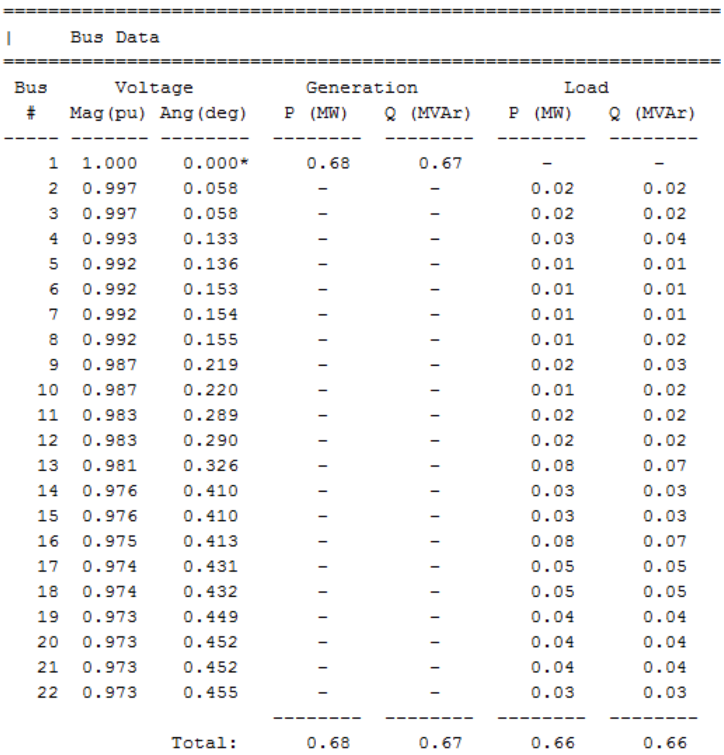
The following Appendix II contains the remaining data defining the 22-Bus distribution network for some of the analyzed scenarios.

Data of the 22 – Bus Distribution Network without the Inclusion of EVs; Figures 24, 25 and 26:



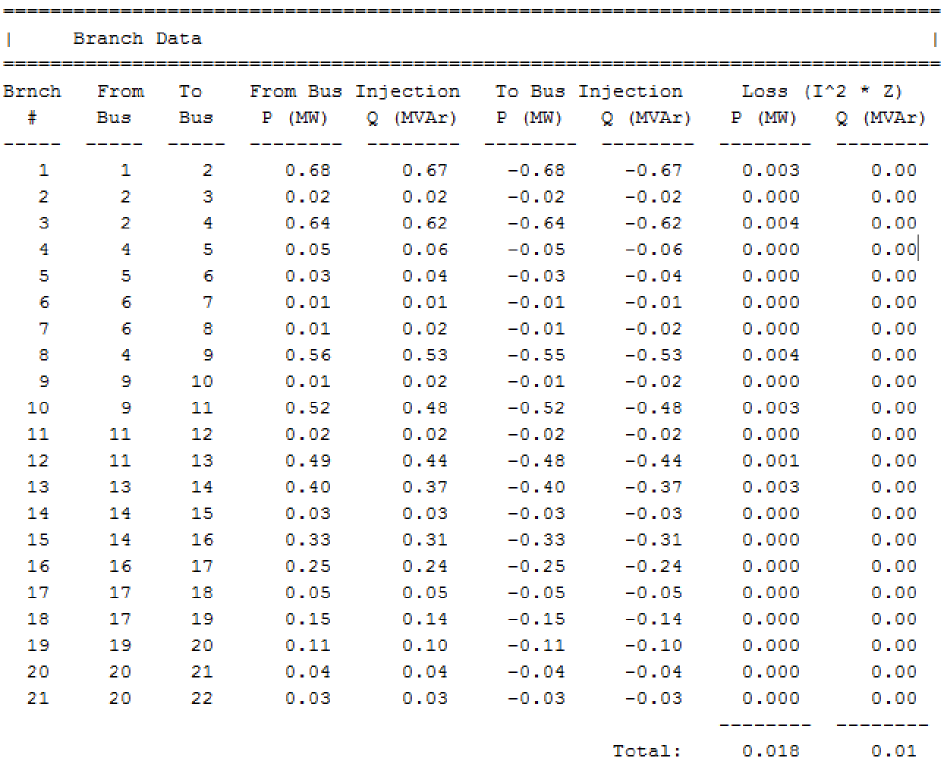
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses             22     Total Gen Capacity     999.0         -999.0 to 999.0
Generators         1     On-line Capacity       999.0         -999.0 to 999.0
Committed Gens     1     Generation (actual)      0.7               0.7
Loads             21     Load                     0.7               0.7
  Fixed           21       Fixed                  0.7               0.7
  Dispatchable     0       Dispatchable          -0.0 of -0.0      -0.0
Shunts             0     Shunt (inj)             -0.0               0.0
Branches          21     Losses (I^2 * Z)         0.02              0.01
Transformers       0     Branch Charging (inj)     -                0.0
Inter-ties         0     Total Inter-tie Flow     0.0               0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.973 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle       0.00 deg   @ bus 1          0.46 deg   @ bus 22
P Losses (I^2*R)             -                  0.00 MW    @ line 4-9
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 4-9
```

Figure 24: System Summary of the 22-Bus Distribution Grid



```
================================================================
|     Bus Data
================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000   0.000*     0.68      0.67        -         -
    2  0.997   0.058       -         -         0.02      0.02
    3  0.997   0.058       -         -         0.02      0.02
    4  0.993   0.133       -         -         0.03      0.04
    5  0.992   0.136       -         -         0.01      0.01
    6  0.992   0.153       -         -         0.01      0.01
    7  0.992   0.154       -         -         0.01      0.01
    8  0.992   0.155       -         -         0.01      0.02
    9  0.987   0.219       -         -         0.02      0.03
   10  0.987   0.220       -         -         0.01      0.02
   11  0.983   0.289       -         -         0.02      0.02
   12  0.983   0.290       -         -         0.02      0.02
   13  0.981   0.326       -         -         0.08      0.07
   14  0.976   0.410       -         -         0.03      0.03
   15  0.976   0.410       -         -         0.03      0.03
   16  0.975   0.413       -         -         0.08      0.07
   17  0.974   0.431       -         -         0.05      0.05
   18  0.974   0.432       -         -         0.05      0.05
   19  0.973   0.449       -         -         0.04      0.04
   20  0.973   0.452       -         -         0.04      0.04
   21  0.973   0.452       -         -         0.04      0.04
   22  0.973   0.455       -         -         0.03      0.03
                        --------  --------  --------  --------
               Total:     0.68      0.67      0.66      0.66
```

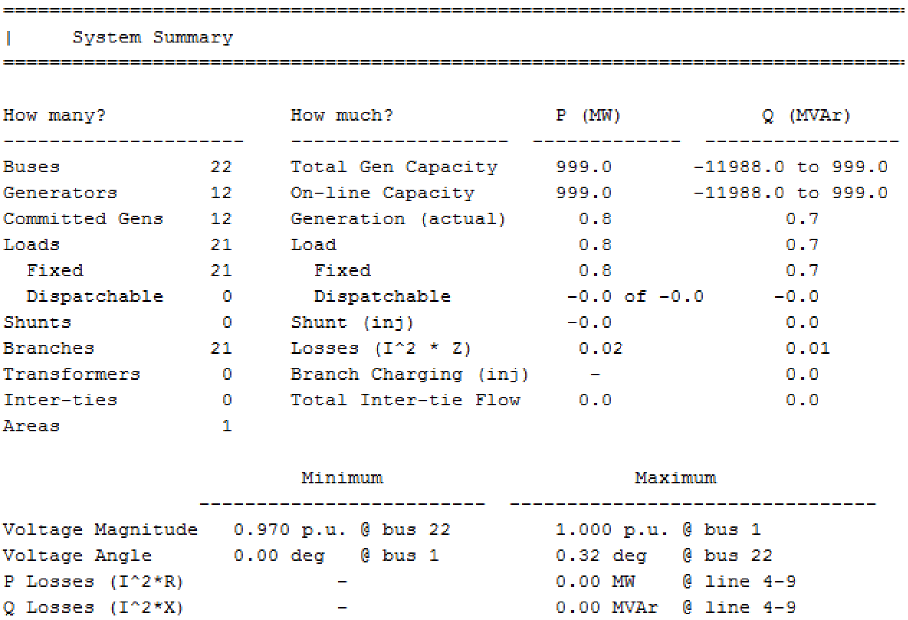
Figure 25: Voltage and Power Generated and Consumed in every of the 22-Bus nodes



```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     0.68      0.67     -0.68     -0.67     0.003      0.00
   2      2      3     0.02      0.02     -0.02     -0.02     0.000      0.00
   3      2      4     0.64      0.62     -0.64     -0.62     0.004      0.00
   4      4      5     0.05      0.06     -0.05     -0.06     0.000      0.00
   5      5      6     0.03      0.04     -0.03     -0.04     0.000      0.00
   6      6      7     0.01      0.01     -0.01     -0.01     0.000      0.00
   7      6      8     0.01      0.02     -0.01     -0.02     0.000      0.00
   8      4      9     0.56      0.53     -0.55     -0.53     0.004      0.00
   9      9     10     0.01      0.02     -0.01     -0.02     0.000      0.00
  10      9     11     0.52      0.48     -0.52     -0.48     0.003      0.00
  11     11     12     0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13     0.49      0.44     -0.48     -0.44     0.001      0.00
  13     13     14     0.40      0.37     -0.40     -0.37     0.003      0.00
  14     14     15     0.03      0.03     -0.03     -0.03     0.000      0.00
  15     14     16     0.33      0.31     -0.33     -0.31     0.000      0.00
  16     16     17     0.25      0.24     -0.25     -0.24     0.000      0.00
  17     17     18     0.05      0.05     -0.05     -0.05     0.000      0.00
  18     17     19     0.15      0.14     -0.15     -0.14     0.000      0.00
  19     19     20     0.11      0.10     -0.11     -0.10     0.000      0.00
  20     20     21     0.04      0.04     -0.04     -0.04     0.000      0.00
  21     20     22     0.03      0.03     -0.03     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.018      0.01
```

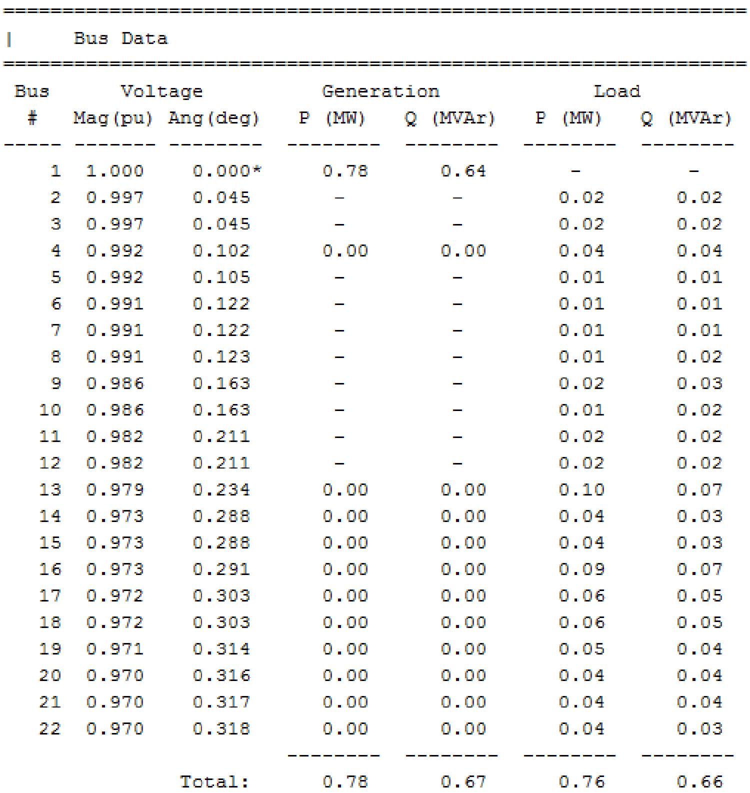
Figure 26: Branch Data from the 22-Bus Distribution Grid

Data of the 22 – Bus Distribution Network with the Inclusion of 10% EVs providing a Maximum Amount of 2 kVar in Specific Nodes; Figures 27, 28 and 29:



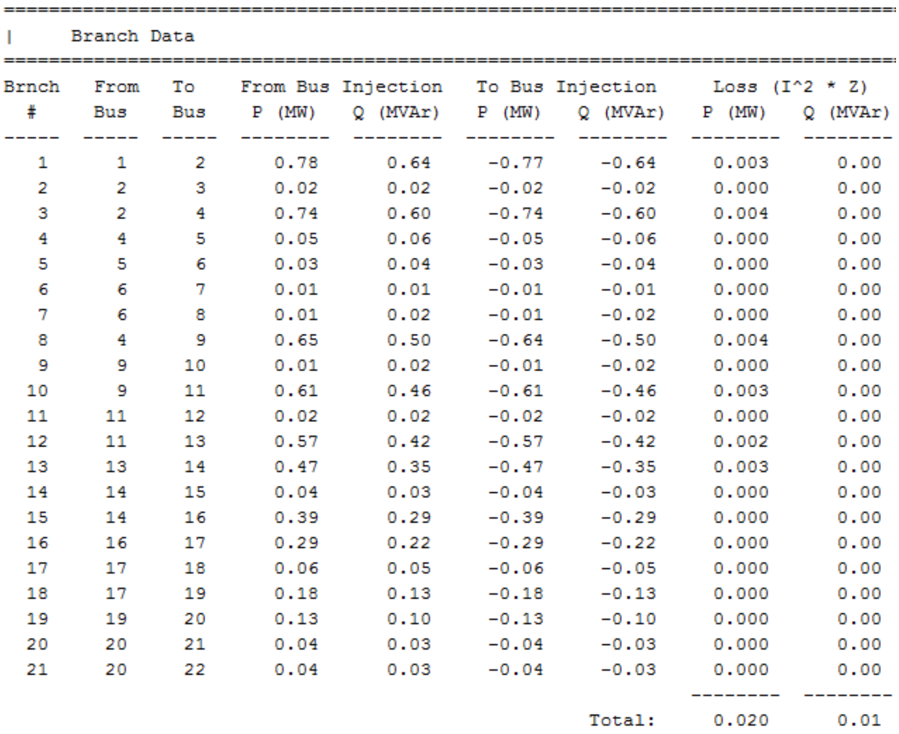
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses             22     Total Gen Capacity     999.0       -11988.0 to 999.0
Generators        12     On-line Capacity       999.0       -11988.0 to 999.0
Committed Gens    12     Generation (actual)      0.8               0.7
Loads             21     Load                     0.8               0.7
  Fixed           21       Fixed                  0.8               0.7
  Dispatchable     0       Dispatchable          -0.0 of -0.0      -0.0
Shunts             0     Shunt (inj)             -0.0               0.0
Branches          21     Losses (I^2 * Z)         0.02              0.01
Transformers       0     Branch Charging (inj)     -                0.0
Inter-ties         0     Total Inter-tie Flow     0.0               0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.970 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle       0.00 deg   @ bus 1          0.32 deg   @ bus 22
P Losses (I^2*R)             -                  0.00 MW    @ line 4-9
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 4-9
```

Figure 27: System Summary of the 22-Bus Distribution Grid with EVs providing a maximum amount of 2 kVar



```
================================================================
|     Bus Data
================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000   0.000*     0.78      0.64       -         -
    2  0.997   0.045       -         -        0.02      0.02
    3  0.997   0.045       -         -        0.02      0.02
    4  0.992   0.102      0.00      0.00      0.04      0.04
    5  0.992   0.105       -         -        0.01      0.01
    6  0.991   0.122       -         -        0.01      0.01
    7  0.991   0.122       -         -        0.01      0.01
    8  0.991   0.123       -         -        0.01      0.02
    9  0.986   0.163       -         -        0.02      0.03
   10  0.986   0.163       -         -        0.01      0.02
   11  0.982   0.211       -         -        0.02      0.02
   12  0.982   0.211       -         -        0.02      0.02
   13  0.979   0.234      0.00      0.00      0.10      0.07
   14  0.973   0.288      0.00      0.00      0.04      0.03
   15  0.973   0.288      0.00      0.00      0.04      0.03
   16  0.973   0.291      0.00      0.00      0.09      0.07
   17  0.972   0.303      0.00      0.00      0.06      0.05
   18  0.972   0.303      0.00      0.00      0.06      0.05
   19  0.971   0.314      0.00      0.00      0.05      0.04
   20  0.970   0.316      0.00      0.00      0.04      0.04
   21  0.970   0.317      0.00      0.00      0.04      0.04
   22  0.970   0.318      0.00      0.00      0.04      0.03
                        --------  --------  --------  --------
               Total:     0.78      0.67      0.76      0.66
```

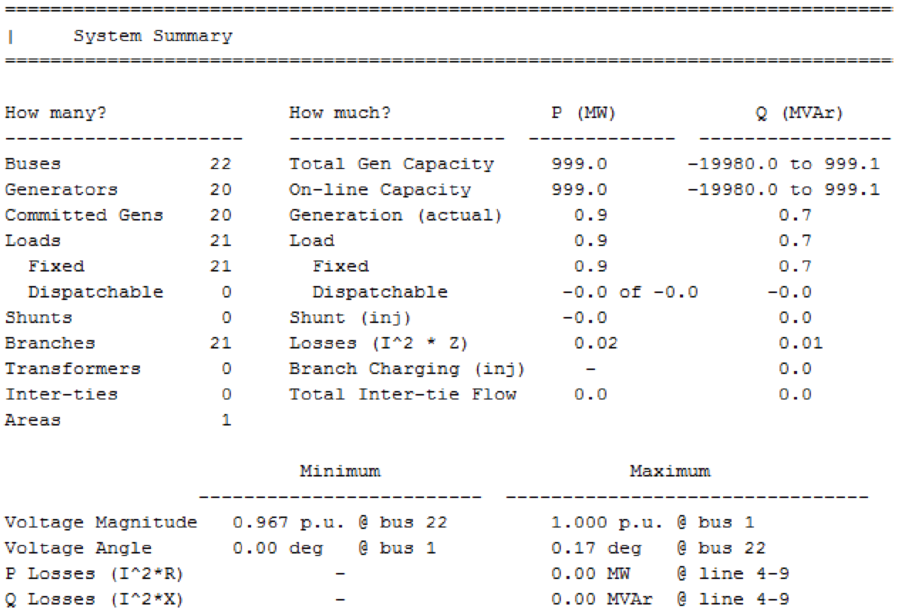
Figure 28: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with the inclusion of EVs providing a maximum amount of 2 kVar



```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     0.78      0.64     -0.77     -0.64     0.003      0.00
   2      2      3     0.02      0.02     -0.02     -0.02     0.000      0.00
   3      2      4     0.74      0.60     -0.74     -0.60     0.004      0.00
   4      4      5     0.05      0.06     -0.05     -0.06     0.000      0.00
   5      5      6     0.03      0.04     -0.03     -0.04     0.000      0.00
   6      6      7     0.01      0.01     -0.01     -0.01     0.000      0.00
   7      6      8     0.01      0.02     -0.01     -0.02     0.000      0.00
   8      4      9     0.65      0.50     -0.64     -0.50     0.004      0.00
   9      9     10     0.01      0.02     -0.01     -0.02     0.000      0.00
  10      9     11     0.61      0.46     -0.61     -0.46     0.003      0.00
  11     11     12     0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13     0.57      0.42     -0.57     -0.42     0.002      0.00
  13     13     14     0.47      0.35     -0.47     -0.35     0.003      0.00
  14     14     15     0.04      0.03     -0.04     -0.03     0.000      0.00
  15     14     16     0.39      0.29     -0.39     -0.29     0.000      0.00
  16     16     17     0.29      0.22     -0.29     -0.22     0.000      0.00
  17     17     18     0.06      0.05     -0.06     -0.05     0.000      0.00
  18     17     19     0.18      0.13     -0.18     -0.13     0.000      0.00
  19     19     20     0.13      0.10     -0.13     -0.10     0.000      0.00
  20     20     21     0.04      0.03     -0.04     -0.03     0.000      0.00
  21     20     22     0.04      0.03     -0.04     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.020      0.01
```

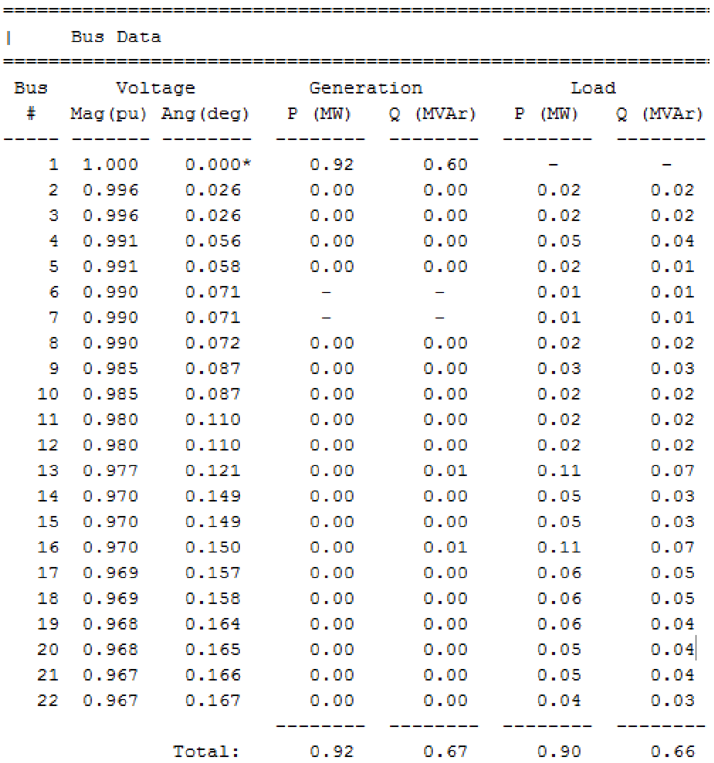
Figure 29: Branch Data from the 22-Bus Distribution Grid with EVs providing a maximum amount of 2 kVar

Data of the 22 – Bus Distribution Network with the inclusion of 20% EVs providing a Maximum Amount of 2 kVar in Specific Nodes; Figures 30, 31 and 32:



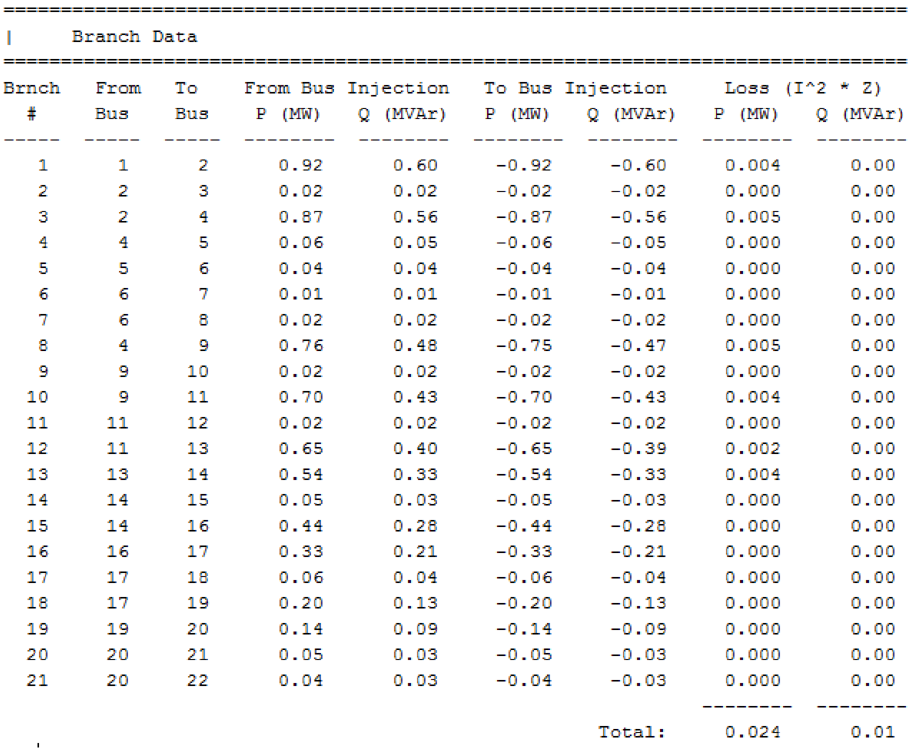
```
================================================================================
|     System Summary                                                           |
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses                22   Total Gen Capacity     999.0       -19980.0 to 999.1
Generators           20   On-line Capacity       999.0       -19980.0 to 999.1
Committed Gens       20   Generation (actual)      0.9                0.7
Loads                21   Load                     0.9                0.7
  Fixed              21     Fixed                  0.9                0.7
  Dispatchable        0     Dispatchable          -0.0 of -0.0       -0.0
Shunts                0   Shunt (inj)             -0.0                0.0
Branches             21   Losses (I^2 * Z)         0.02               0.01
Transformers          0   Branch Charging (inj)     -                 0.0
Inter-ties            0   Total Inter-tie Flow     0.0                0.0
Areas                 1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.967 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle       0.00 deg   @ bus 1          0.17 deg   @ bus 22
P Losses (I^2*R)             -                  0.00 MW    @ line 4-9
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 4-9
```

Figure 30: System Summary of the 22-Bus Distribution Grid with 20% EVs providing a maximum amount of 2 kVar



```
================================================================
|     Bus Data
================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu)  Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     0.92      0.60        -         -
    2  0.996    0.026      0.00      0.00      0.02      0.02
    3  0.996    0.026      0.00      0.00      0.02      0.02
    4  0.991    0.056      0.00      0.00      0.05      0.04
    5  0.991    0.058      0.00      0.00      0.02      0.01
    6  0.990    0.071       -         -        0.01      0.01
    7  0.990    0.071       -         -        0.01      0.01
    8  0.990    0.072      0.00      0.00      0.02      0.02
    9  0.985    0.087      0.00      0.00      0.03      0.03
   10  0.985    0.087      0.00      0.00      0.02      0.02
   11  0.980    0.110      0.00      0.00      0.02      0.02
   12  0.980    0.110      0.00      0.00      0.02      0.02
   13  0.977    0.121      0.00      0.01      0.11      0.07
   14  0.970    0.149      0.00      0.00      0.05      0.03
   15  0.970    0.149      0.00      0.00      0.05      0.03
   16  0.970    0.150      0.00      0.01      0.11      0.07
   17  0.969    0.157      0.00      0.00      0.06      0.05
   18  0.969    0.158      0.00      0.00      0.06      0.05
   19  0.968    0.164      0.00      0.00      0.06      0.04
   20  0.968    0.165      0.00      0.00      0.05      0.04
   21  0.967    0.166      0.00      0.00      0.05      0.04
   22  0.967    0.167      0.00      0.00      0.04      0.03
                        --------  --------  --------  --------
               Total:      0.92      0.67      0.90      0.66
```

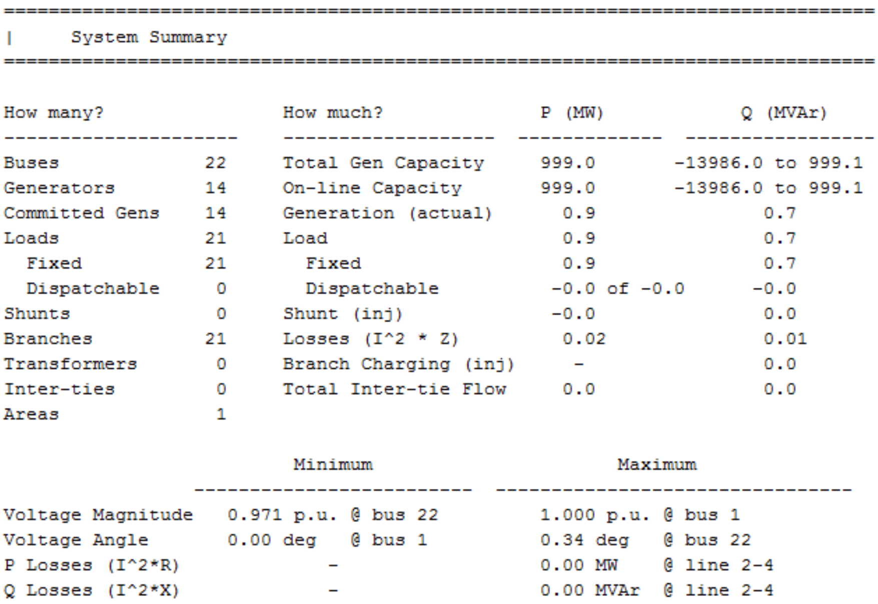
Figure 31: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with the inclusion of 20% EVs providing a maximum amount of 2 kVar



```
================================================================================
|     Branch Data
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     0.92      0.60     -0.92     -0.60     0.004      0.00
   2      2      3     0.02      0.02     -0.02     -0.02     0.000      0.00
   3      2      4     0.87      0.56     -0.87     -0.56     0.005      0.00
   4      4      5     0.06      0.05     -0.06     -0.05     0.000      0.00
   5      5      6     0.04      0.04     -0.04     -0.04     0.000      0.00
   6      6      7     0.01      0.01     -0.01     -0.01     0.000      0.00
   7      6      8     0.02      0.02     -0.02     -0.02     0.000      0.00
   8      4      9     0.76      0.48     -0.75     -0.47     0.005      0.00
   9      9     10     0.02      0.02     -0.02     -0.02     0.000      0.00
  10      9     11     0.70      0.43     -0.70     -0.43     0.004      0.00
  11     11     12     0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13     0.65      0.40     -0.65     -0.39     0.002      0.00
  13     13     14     0.54      0.33     -0.54     -0.33     0.004      0.00
  14     14     15     0.05      0.03     -0.05     -0.03     0.000      0.00
  15     14     16     0.44      0.28     -0.44     -0.28     0.000      0.00
  16     16     17     0.33      0.21     -0.33     -0.21     0.000      0.00
  17     17     18     0.06      0.04     -0.06     -0.04     0.000      0.00
  18     17     19     0.20      0.13     -0.20     -0.13     0.000      0.00
  19     19     20     0.14      0.09     -0.14     -0.09     0.000      0.00
  20     20     21     0.05      0.03     -0.05     -0.03     0.000      0.00
  21     20     22     0.04      0.03     -0.04     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.024      0.01
```

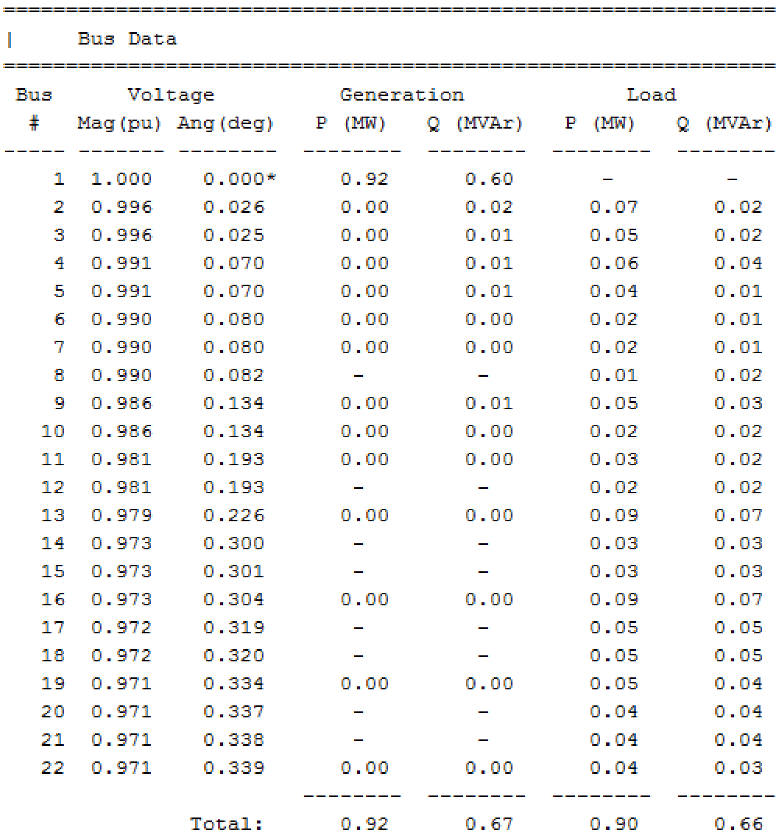
Figure 32: Branch Data from the 22-Bus Distribution Grid with 20% EVs providing a maximum amount of 2 kVar

Data of the 22 – Bus Distribution Network with the Inclusion of 20% EVs providing V2G Reactive Power Support close to the Feeder Node; Figures 33, 34 and 35:



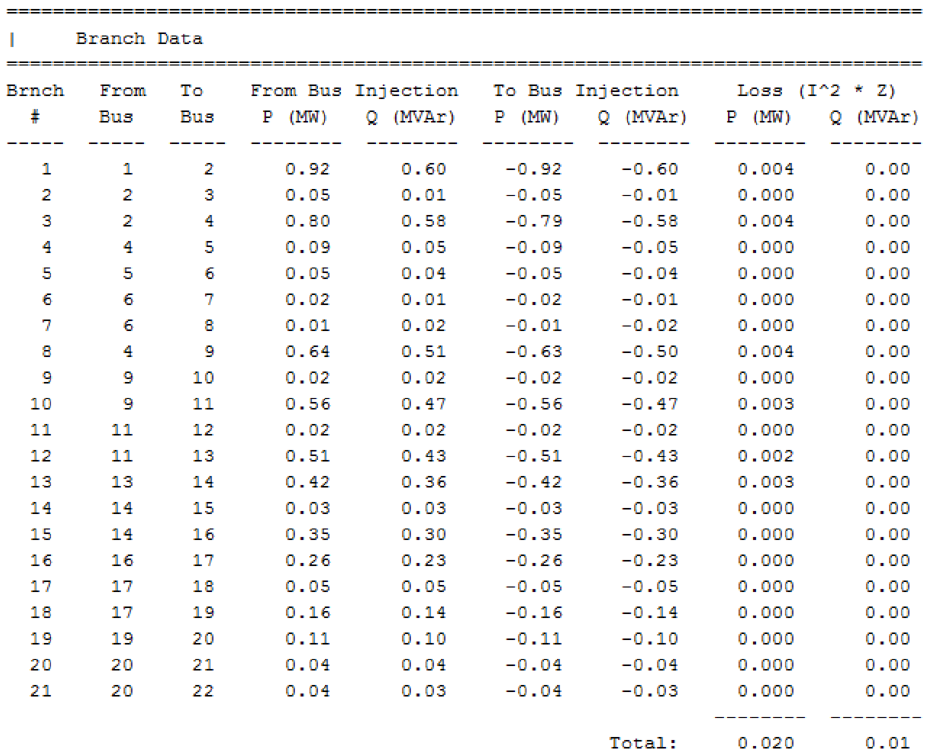
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses                22     Total Gen Capacity     999.0       -13986.0 to 999.1
Generators           14     On-line Capacity       999.0       -13986.0 to 999.1
Committed Gens       14     Generation (actual)      0.9               0.7
Loads                21     Load                     0.9               0.7
  Fixed              21       Fixed                  0.9               0.7
  Dispatchable        0       Dispatchable          -0.0 of -0.0      -0.0
Shunts                0     Shunt (inj)             -0.0               0.0
Branches             21     Losses (I^2 * Z)         0.02              0.01
Transformers          0     Branch Charging (inj)     -                0.0
Inter-ties            0     Total Inter-tie Flow     0.0               0.0
Areas                 1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.971 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle       0.00 deg   @ bus 1          0.34 deg   @ bus 22
P Losses (I^2*R)             -                  0.00 MW    @ line 2-4
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 2-4
```

Figure 33: System Summary of the 22-Bus Distribution Grid with 20% EVs providing V2G support close to the feeder node



```
================================================================================
|     Bus Data
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     0.92      0.60       -         -
    2  0.996    0.026      0.00      0.02      0.07      0.02
    3  0.996    0.025      0.00      0.01      0.05      0.02
    4  0.991    0.070      0.00      0.01      0.06      0.04
    5  0.991    0.070      0.00      0.01      0.04      0.01
    6  0.990    0.080      0.00      0.00      0.02      0.01
    7  0.990    0.080      0.00      0.00      0.02      0.01
    8  0.990    0.082       -         -        0.01      0.02
    9  0.986    0.134      0.00      0.01      0.05      0.03
   10  0.986    0.134      0.00      0.00      0.02      0.02
   11  0.981    0.193      0.00      0.00      0.03      0.02
   12  0.981    0.193       -         -        0.02      0.02
   13  0.979    0.226      0.00      0.00      0.09      0.07
   14  0.973    0.300       -         -        0.03      0.03
   15  0.973    0.301       -         -        0.03      0.03
   16  0.973    0.304      0.00      0.00      0.09      0.07
   17  0.972    0.319       -         -        0.05      0.05
   18  0.972    0.320       -         -        0.05      0.05
   19  0.971    0.334      0.00      0.00      0.05      0.04
   20  0.971    0.337       -         -        0.04      0.04
   21  0.971    0.338       -         -        0.04      0.04
   22  0.971    0.339      0.00      0.00      0.04      0.03
                        --------  --------  --------  --------
               Total:      0.92      0.67      0.90      0.66
```

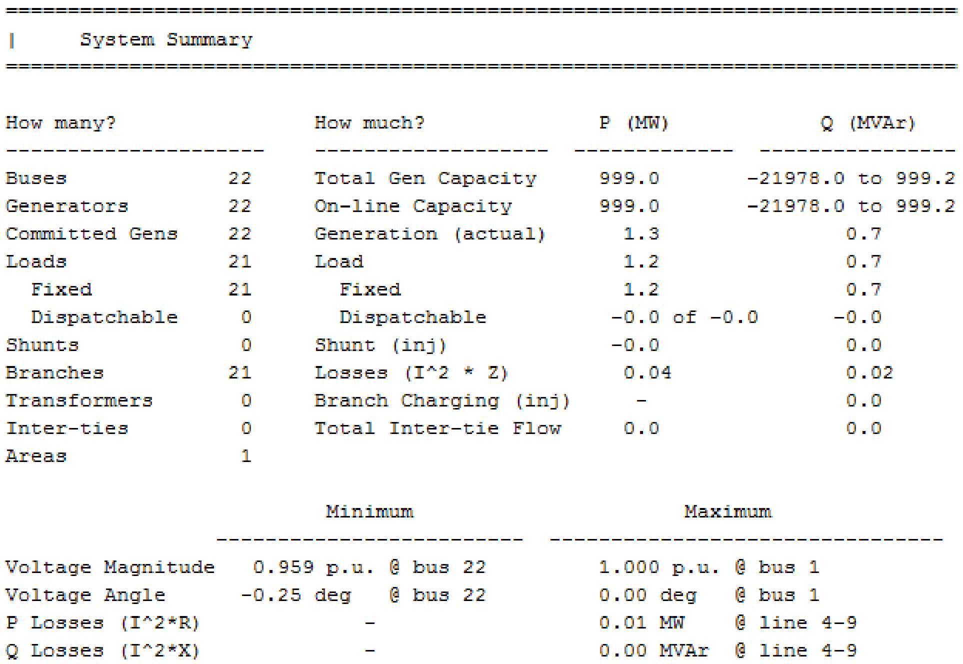
Figure 34: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with the inclusion of 20% EVs providing V2G support close to the feeder node



```
================================================================================
|     Branch Data
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss  (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2      0.92      0.60     -0.92     -0.60     0.004      0.00
   2      2      3      0.05      0.01     -0.05     -0.01     0.000      0.00
   3      2      4      0.80      0.58     -0.79     -0.58     0.004      0.00
   4      4      5      0.09      0.05     -0.09     -0.05     0.000      0.00
   5      5      6      0.05      0.04     -0.05     -0.04     0.000      0.00
   6      6      7      0.02      0.01     -0.02     -0.01     0.000      0.00
   7      6      8      0.01      0.02     -0.01     -0.02     0.000      0.00
   8      4      9      0.64      0.51     -0.63     -0.50     0.004      0.00
   9      9     10      0.02      0.02     -0.02     -0.02     0.000      0.00
  10      9     11      0.56      0.47     -0.56     -0.47     0.003      0.00
  11     11     12      0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13      0.51      0.43     -0.51     -0.43     0.002      0.00
  13     13     14      0.42      0.36     -0.42     -0.36     0.003      0.00
  14     14     15      0.03      0.03     -0.03     -0.03     0.000      0.00
  15     14     16      0.35      0.30     -0.35     -0.30     0.000      0.00
  16     16     17      0.26      0.23     -0.26     -0.23     0.000      0.00
  17     17     18      0.05      0.05     -0.05     -0.05     0.000      0.00
  18     17     19      0.16      0.14     -0.16     -0.14     0.000      0.00
  19     19     20      0.11      0.10     -0.11     -0.10     0.000      0.00
  20     20     21      0.04      0.04     -0.04     -0.04     0.000      0.00
  21     20     22      0.04      0.03     -0.04     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.020      0.01
```

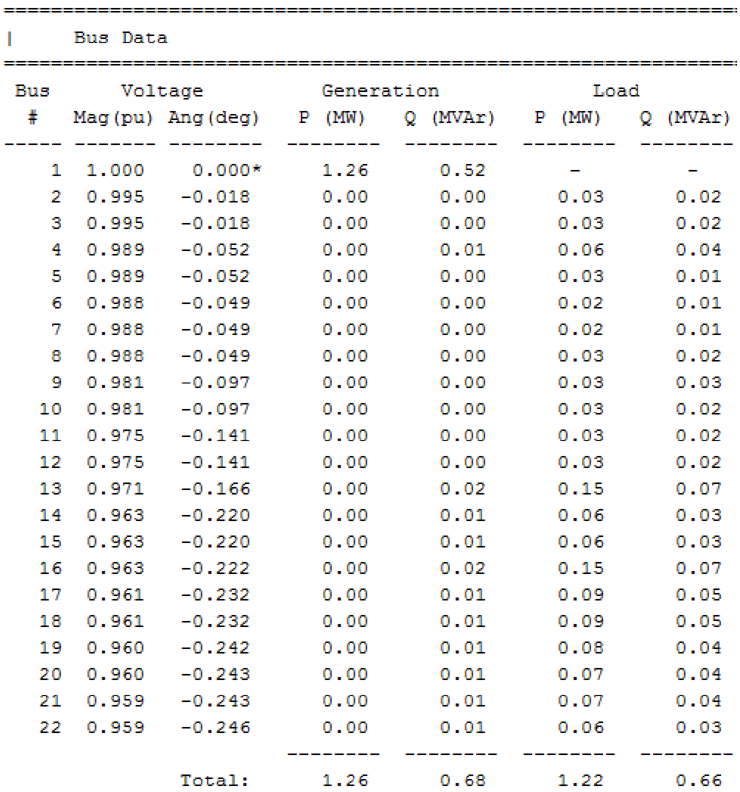
Figure 35: Branch Data from the 22-Bus Distribution Grid with 20% EVs providing V2G support close to the feeder node

Data of the 22 – Bus Distribution Network with the Inclusion of 50% EVs providing V2G Reactive Power Support; Figures 36, 37 and 38:



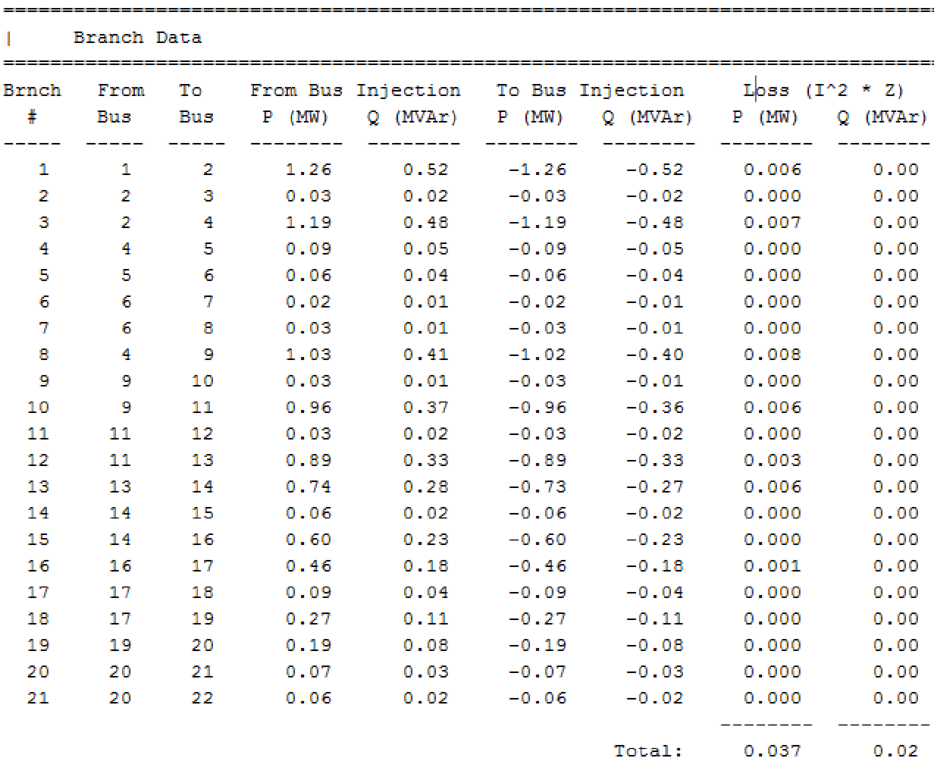
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses             22     Total Gen Capacity     999.0       -21978.0 to 999.2
Generators        22     On-line Capacity       999.0       -21978.0 to 999.2
Committed Gens    22     Generation (actual)      1.3               0.7
Loads             21     Load                     1.2               0.7
  Fixed           21       Fixed                  1.2               0.7
  Dispatchable     0       Dispatchable          -0.0 of -0.0      -0.0
Shunts             0     Shunt (inj)             -0.0               0.0
Branches          21     Losses (I^2 * Z)         0.04              0.02
Transformers       0     Branch Charging (inj)     -                0.0
Inter-ties         0     Total Inter-tie Flow     0.0               0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.959 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle      -0.25 deg   @ bus 22         0.00 deg   @ bus 1
P Losses (I^2*R)             -                  0.01 MW    @ line 4-9
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 4-9
```

Figure 36: System Summary of the 22-Bus Distribution Grid with 50% EVs providing reactive power support



```
================================================================================
|     Bus Data                                                                 |
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     1.26      0.52       -         -
    2  0.995   -0.018      0.00      0.00      0.03      0.02
    3  0.995   -0.018      0.00      0.00      0.03      0.02
    4  0.989   -0.052      0.00      0.01      0.06      0.04
    5  0.989   -0.052      0.00      0.00      0.03      0.01
    6  0.988   -0.049      0.00      0.00      0.02      0.01
    7  0.988   -0.049      0.00      0.00      0.02      0.01
    8  0.988   -0.049      0.00      0.00      0.03      0.02
    9  0.981   -0.097      0.00      0.00      0.03      0.03
   10  0.981   -0.097      0.00      0.00      0.03      0.02
   11  0.975   -0.141      0.00      0.00      0.03      0.02
   12  0.975   -0.141      0.00      0.00      0.03      0.02
   13  0.971   -0.166      0.00      0.02      0.15      0.07
   14  0.963   -0.220      0.00      0.01      0.06      0.03
   15  0.963   -0.220      0.00      0.01      0.06      0.03
   16  0.963   -0.222      0.00      0.02      0.15      0.07
   17  0.961   -0.232      0.00      0.01      0.09      0.05
   18  0.961   -0.232      0.00      0.01      0.09      0.05
   19  0.960   -0.242      0.00      0.01      0.08      0.04
   20  0.960   -0.243      0.00      0.01      0.07      0.04
   21  0.959   -0.243      0.00      0.01      0.07      0.04
   22  0.959   -0.246      0.00      0.01      0.06      0.03
                        --------  --------  --------  --------
               Total:      1.26      0.68      1.22      0.66
```

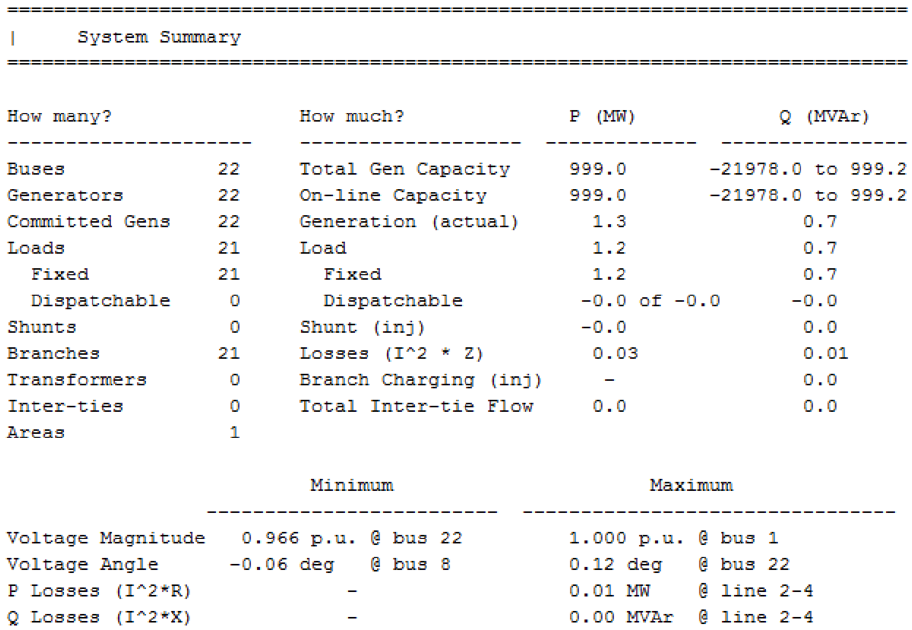
Figure 37: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with an inclusion of 50% EVs providing V2G support



```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2      1.26      0.52     -1.26     -0.52     0.006      0.00
   2      2      3      0.03      0.02     -0.03     -0.02     0.000      0.00
   3      2      4      1.19      0.48     -1.19     -0.48     0.007      0.00
   4      4      5      0.09      0.05     -0.09     -0.05     0.000      0.00
   5      5      6      0.06      0.04     -0.06     -0.04     0.000      0.00
   6      6      7      0.02      0.01     -0.02     -0.01     0.000      0.00
   7      6      8      0.03      0.01     -0.03     -0.01     0.000      0.00
   8      4      9      1.03      0.41     -1.02     -0.40     0.008      0.00
   9      9     10      0.03      0.01     -0.03     -0.01     0.000      0.00
  10      9     11      0.96      0.37     -0.96     -0.36     0.006      0.00
  11     11     12      0.03      0.02     -0.03     -0.02     0.000      0.00
  12     11     13      0.89      0.33     -0.89     -0.33     0.003      0.00
  13     13     14      0.74      0.28     -0.73     -0.27     0.006      0.00
  14     14     15      0.06      0.02     -0.06     -0.02     0.000      0.00
  15     14     16      0.60      0.23     -0.60     -0.23     0.000      0.00
  16     16     17      0.46      0.18     -0.46     -0.18     0.001      0.00
  17     17     18      0.09      0.04     -0.09     -0.04     0.000      0.00
  18     17     19      0.27      0.11     -0.27     -0.11     0.000      0.00
  19     19     20      0.19      0.08     -0.19     -0.08     0.000      0.00
  20     20     21      0.07      0.03     -0.07     -0.03     0.000      0.00
  21     20     22      0.06      0.02     -0.06     -0.02     0.000      0.00
                                                             --------  --------
                                                    Total:     0.037      0.02
```

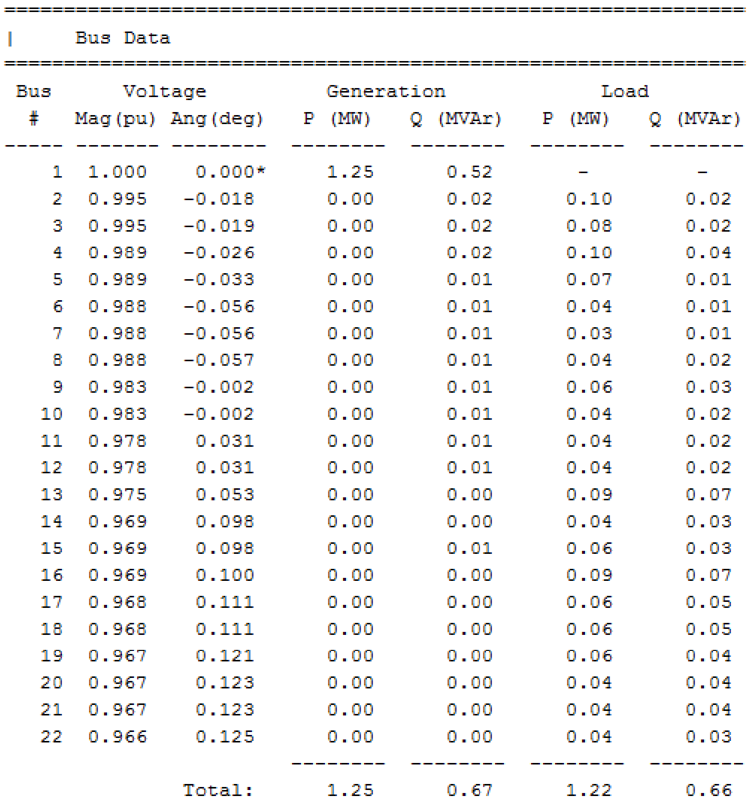
Figure 38: Branch Data from the 22-Bus Distribution Grid with 50% EVs providing V2G support

Data of the 22 – Bus Distribution Network with the inclusion of 50% EVs providing V2G Reactive Power Support close to the Feeder Node; Figures 39, 40 and 41:



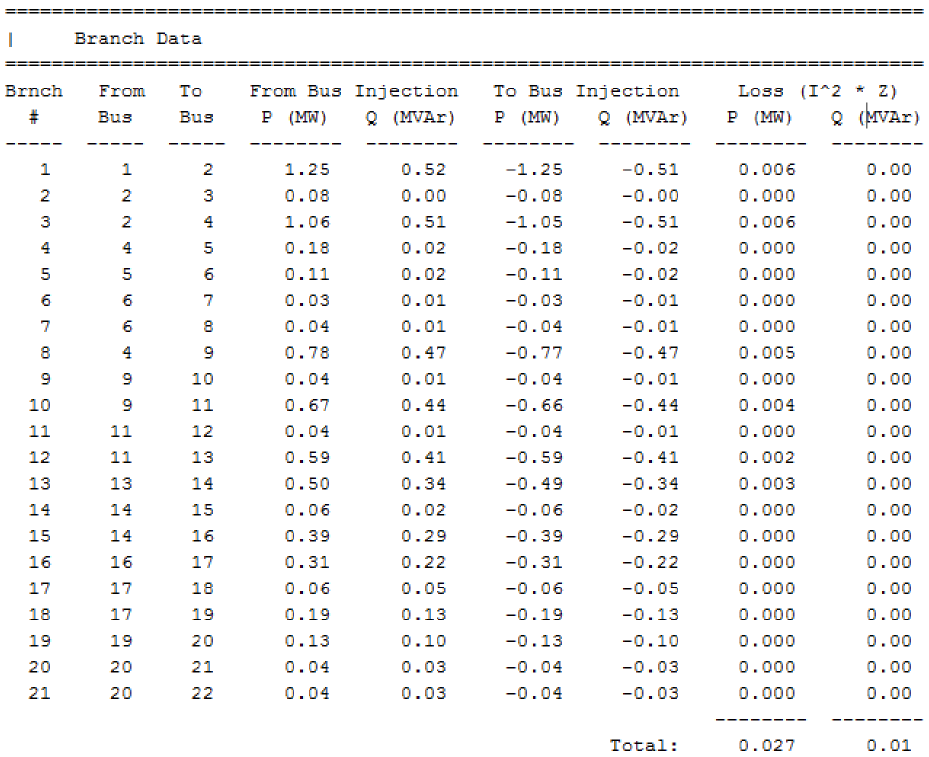
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses                 22   Total Gen Capacity     999.0       -21978.0 to 999.2
Generators            22   On-line Capacity       999.0       -21978.0 to 999.2
Committed Gens        22   Generation (actual)      1.3               0.7
Loads                 21   Load                     1.2               0.7
  Fixed               21     Fixed                  1.2               0.7
  Dispatchable         0     Dispatchable        -0.0 of -0.0        -0.0
Shunts                 0   Shunt (inj)             -0.0               0.0
Branches              21   Losses (I^2 * Z)         0.03              0.01
Transformers           0   Branch Charging (inj)     -                0.0
Inter-ties             0   Total Inter-tie Flow     0.0               0.0
Areas                  1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.966 p.u. @ bus 22          1.000 p.u. @ bus 1
Voltage Angle      -0.06 deg   @ bus 8           0.12 deg   @ bus 22
P Losses (I^2*R)             -                   0.01 MW    @ line 2-4
Q Losses (I^2*X)             -                   0.00 MVAr  @ line 2-4
```

Figure 39: System Summary of the 22-Bus Distribution Grid with 50% EVs providing reactive power support close to the Feeder Node



```
================================================================
|     Bus Data
================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     1.25      0.52       -         -
    2  0.995   -0.018      0.00      0.02      0.10      0.02
    3  0.995   -0.019      0.00      0.02      0.08      0.02
    4  0.989   -0.026      0.00      0.02      0.10      0.04
    5  0.989   -0.033      0.00      0.01      0.07      0.01
    6  0.988   -0.056      0.00      0.01      0.04      0.01
    7  0.988   -0.056      0.00      0.01      0.03      0.01
    8  0.988   -0.057      0.00      0.01      0.04      0.02
    9  0.983   -0.002      0.00      0.01      0.06      0.03
   10  0.983   -0.002      0.00      0.01      0.04      0.02
   11  0.978    0.031      0.00      0.01      0.04      0.02
   12  0.978    0.031      0.00      0.01      0.04      0.02
   13  0.975    0.053      0.00      0.00      0.09      0.07
   14  0.969    0.098      0.00      0.00      0.04      0.03
   15  0.969    0.098      0.00      0.01      0.06      0.03
   16  0.969    0.100      0.00      0.00      0.09      0.07
   17  0.968    0.111      0.00      0.00      0.06      0.05
   18  0.968    0.111      0.00      0.00      0.06      0.05
   19  0.967    0.121      0.00      0.00      0.06      0.04
   20  0.967    0.123      0.00      0.00      0.04      0.04
   21  0.967    0.123      0.00      0.00      0.04      0.04
   22  0.966    0.125      0.00      0.00      0.04      0.03
                        --------  --------  --------  --------
               Total:      1.25      0.67      1.22      0.66
```

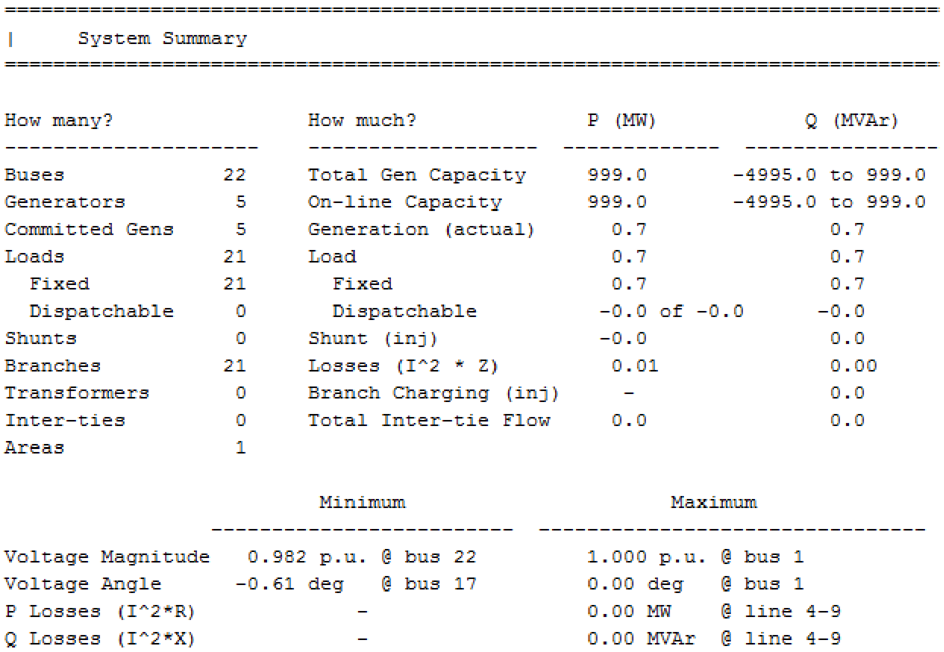
Figure 40: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with an inclusion of 50% EVs providing V2G support close to the Feeder node



```
================================================================================
|     Branch Data
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss  (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     1.25      0.52     -1.25     -0.51     0.006      0.00
   2      2      3     0.08      0.00     -0.08     -0.00     0.000      0.00
   3      2      4     1.06      0.51     -1.05     -0.51     0.006      0.00
   4      4      5     0.18      0.02     -0.18     -0.02     0.000      0.00
   5      5      6     0.11      0.02     -0.11     -0.02     0.000      0.00
   6      6      7     0.03      0.01     -0.03     -0.01     0.000      0.00
   7      6      8     0.04      0.01     -0.04     -0.01     0.000      0.00
   8      4      9     0.78      0.47     -0.77     -0.47     0.005      0.00
   9      9     10     0.04      0.01     -0.04     -0.01     0.000      0.00
  10      9     11     0.67      0.44     -0.66     -0.44     0.004      0.00
  11     11     12     0.04      0.01     -0.04     -0.01     0.000      0.00
  12     11     13     0.59      0.41     -0.59     -0.41     0.002      0.00
  13     13     14     0.50      0.34     -0.49     -0.34     0.003      0.00
  14     14     15     0.06      0.02     -0.06     -0.02     0.000      0.00
  15     14     16     0.39      0.29     -0.39     -0.29     0.000      0.00
  16     16     17     0.31      0.22     -0.31     -0.22     0.000      0.00
  17     17     18     0.06      0.05     -0.06     -0.05     0.000      0.00
  18     17     19     0.19      0.13     -0.19     -0.13     0.000      0.00
  19     19     20     0.13      0.10     -0.13     -0.10     0.000      0.00
  20     20     21     0.04      0.03     -0.04     -0.03     0.000      0.00
  21     20     22     0.04      0.03     -0.04     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.027      0.01
```

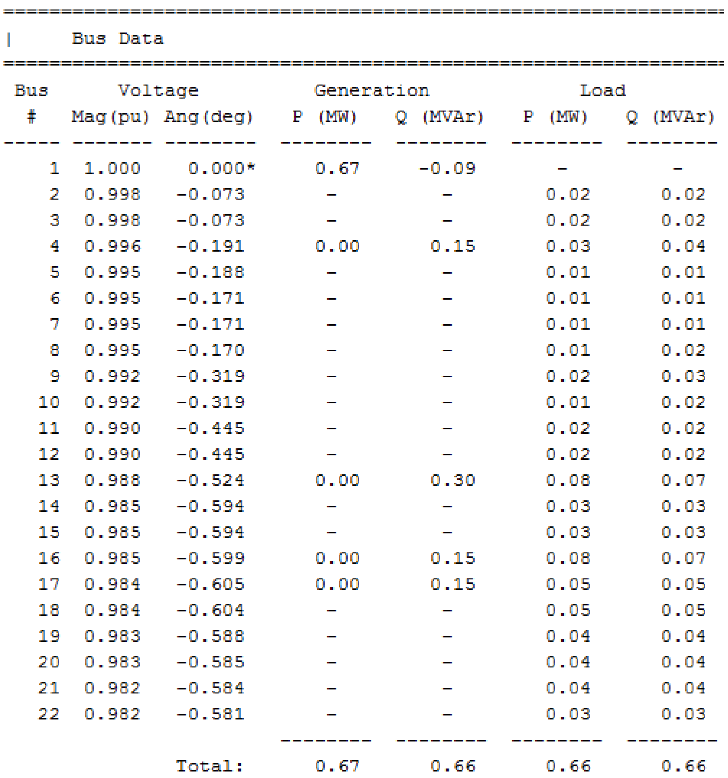
Figure 41: Branch Data from the 22-Bus Distribution Grid with 50% EVs providing V2G support close to the Feeder node

Data of the 22 – Bus Distribution Network with Capacitive Compensation for the 22-Bus System using the DSA Algorithm; Figures 42, 43 and 44:



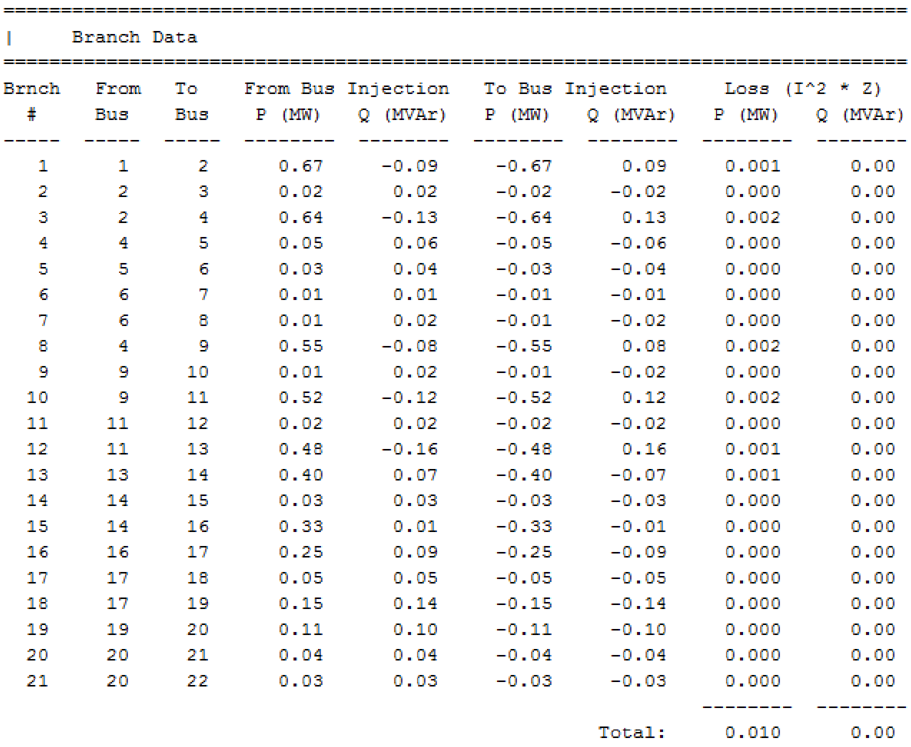
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses             22     Total Gen Capacity     999.0       -4995.0 to 999.0
Generators         5     On-line Capacity       999.0       -4995.0 to 999.0
Committed Gens     5     Generation (actual)      0.7                0.7
Loads             21     Load                     0.7                0.7
  Fixed           21       Fixed                  0.7                0.7
  Dispatchable     0       Dispatchable          -0.0 of -0.0       -0.0
Shunts             0     Shunt (inj)             -0.0                0.0
Branches          21     Losses (I^2 * Z)         0.01               0.00
Transformers       0     Branch Charging (inj)     -                 0.0
Inter-ties         0     Total Inter-tie Flow     0.0                0.0
Areas              1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.982 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle      -0.61 deg   @ bus 17         0.00 deg   @ bus 1
P Losses (I^2*R)             -                  0.00 MW    @ line 4-9
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 4-9
```

Figure 42: System Summary of the 22-Bus Distribution Grid with Capacitive Compensation using the DSA Algorithm



```
================================================================
|     Bus Data                                                 |
================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     0.67     -0.09       -         -
    2  0.998   -0.073       -         -        0.02      0.02
    3  0.998   -0.073       -         -        0.02      0.02
    4  0.996   -0.191      0.00      0.15      0.03      0.04
    5  0.995   -0.188       -         -        0.01      0.01
    6  0.995   -0.171       -         -        0.01      0.01
    7  0.995   -0.171       -         -        0.01      0.01
    8  0.995   -0.170       -         -        0.01      0.02
    9  0.992   -0.319       -         -        0.02      0.03
   10  0.992   -0.319       -         -        0.01      0.02
   11  0.990   -0.445       -         -        0.02      0.02
   12  0.990   -0.445       -         -        0.02      0.02
   13  0.988   -0.524      0.00      0.30      0.08      0.07
   14  0.985   -0.594       -         -        0.03      0.03
   15  0.985   -0.594       -         -        0.03      0.03
   16  0.985   -0.599      0.00      0.15      0.08      0.07
   17  0.984   -0.605      0.00      0.15      0.05      0.05
   18  0.984   -0.604       -         -        0.05      0.05
   19  0.983   -0.588       -         -        0.04      0.04
   20  0.983   -0.585       -         -        0.04      0.04
   21  0.982   -0.584       -         -        0.04      0.04
   22  0.982   -0.581       -         -        0.03      0.03
                        --------  --------  --------  --------
               Total:      0.67      0.66      0.66      0.66
```

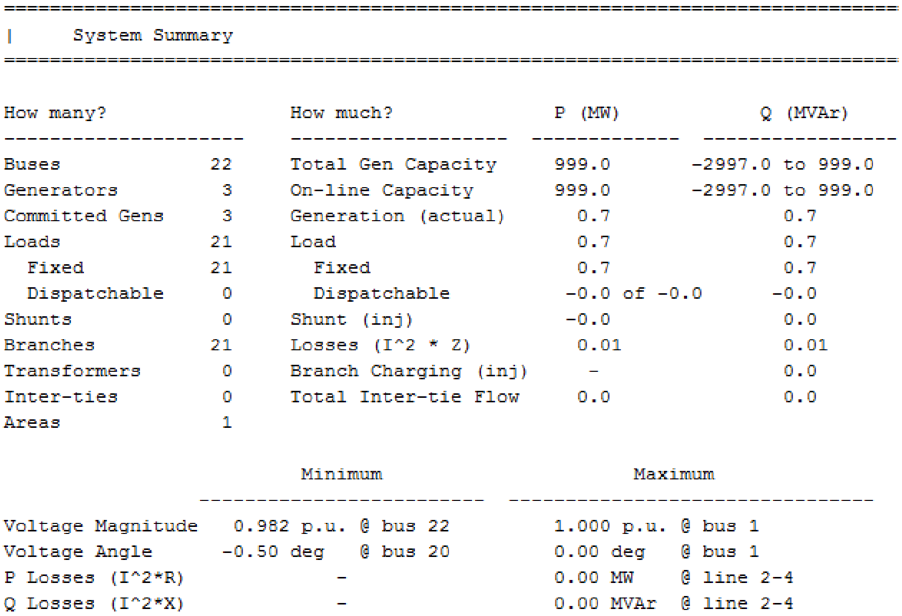
Figure 43: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with Capacitive Compensation using the DSA Algorithm



```
================================================================================
|     Branch Data                                                              |
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     0.67     -0.09     -0.67      0.09     0.001      0.00
   2      2      3     0.02      0.02     -0.02     -0.02     0.000      0.00
   3      2      4     0.64     -0.13     -0.64      0.13     0.002      0.00
   4      4      5     0.05      0.06     -0.05     -0.06     0.000      0.00
   5      5      6     0.03      0.04     -0.03     -0.04     0.000      0.00
   6      6      7     0.01      0.01     -0.01     -0.01     0.000      0.00
   7      6      8     0.01      0.02     -0.01     -0.02     0.000      0.00
   8      4      9     0.55     -0.08     -0.55      0.08     0.002      0.00
   9      9     10     0.01      0.02     -0.01     -0.02     0.000      0.00
  10      9     11     0.52     -0.12     -0.52      0.12     0.002      0.00
  11     11     12     0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13     0.48     -0.16     -0.48      0.16     0.001      0.00
  13     13     14     0.40      0.07     -0.40     -0.07     0.001      0.00
  14     14     15     0.03      0.03     -0.03     -0.03     0.000      0.00
  15     14     16     0.33      0.01     -0.33     -0.01     0.000      0.00
  16     16     17     0.25      0.09     -0.25     -0.09     0.000      0.00
  17     17     18     0.05      0.05     -0.05     -0.05     0.000      0.00
  18     17     19     0.15      0.14     -0.15     -0.14     0.000      0.00
  19     19     20     0.11      0.10     -0.11     -0.10     0.000      0.00
  20     20     21     0.04      0.04     -0.04     -0.04     0.000      0.00
  21     20     22     0.03      0.03     -0.03     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.010      0.00
```

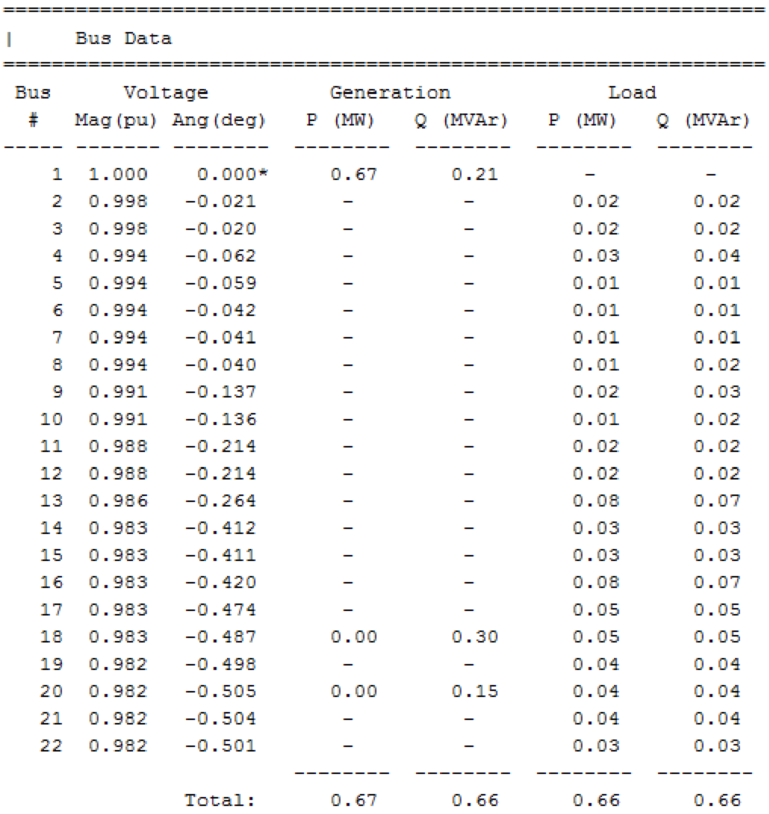
Figure 44: Branch Data from the 22-Bus Distribution Grid with Capacitive Compensation using the DSA Algorithm

Data of the 22 – Bus Distribution Network with Capacitive Compensation for the 22-Bus System using the CBO Method; Figures 45, 46 and 47:



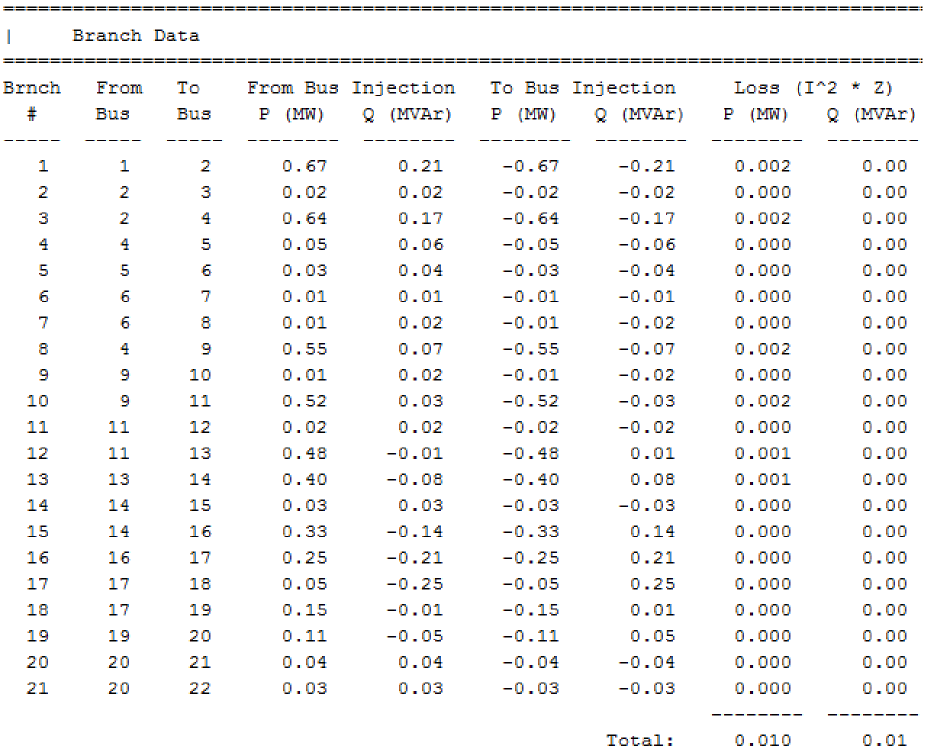
```
================================================================================
|     System Summary
================================================================================

How many?                How much?              P (MW)            Q (MVAr)
---------------------    -------------------  -------------  -----------------
Buses              22    Total Gen Capacity     999.0       -2997.0 to 999.0
Generators          3    On-line Capacity       999.0       -2997.0 to 999.0
Committed Gens      3    Generation (actual)      0.7               0.7
Loads              21    Load                     0.7               0.7
  Fixed            21      Fixed                  0.7               0.7
  Dispatchable      0      Dispatchable          -0.0 of -0.0      -0.0
Shunts              0    Shunt (inj)             -0.0               0.0
Branches           21    Losses (I^2 * Z)         0.01              0.01
Transformers        0    Branch Charging (inj)     -                0.0
Inter-ties          0    Total Inter-tie Flow     0.0               0.0
Areas               1

                          Minimum                      Maximum
                 -------------------------  --------------------------------
Voltage Magnitude   0.982 p.u. @ bus 22         1.000 p.u. @ bus 1
Voltage Angle      -0.50 deg   @ bus 20         0.00 deg   @ bus 1
P Losses (I^2*R)             -                  0.00 MW    @ line 2-4
Q Losses (I^2*X)             -                  0.00 MVAr  @ line 2-4
```

Figure 45: System Summary of the 22-Bus Distribution Grid with Capacitive Compensation using the CBO Method



```
================================================================================
|     Bus Data
================================================================================
 Bus      Voltage          Generation             Load
  #   Mag(pu) Ang(deg)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
----- ------- --------  --------  --------  --------  --------
    1  1.000    0.000*     0.67      0.21       -         -
    2  0.998   -0.021       -         -        0.02      0.02
    3  0.998   -0.020       -         -        0.02      0.02
    4  0.994   -0.062       -         -        0.03      0.04
    5  0.994   -0.059       -         -        0.01      0.01
    6  0.994   -0.042       -         -        0.01      0.01
    7  0.994   -0.041       -         -        0.01      0.01
    8  0.994   -0.040       -         -        0.01      0.02
    9  0.991   -0.137       -         -        0.02      0.03
   10  0.991   -0.136       -         -        0.01      0.02
   11  0.988   -0.214       -         -        0.02      0.02
   12  0.988   -0.214       -         -        0.02      0.02
   13  0.986   -0.264       -         -        0.08      0.07
   14  0.983   -0.412       -         -        0.03      0.03
   15  0.983   -0.411       -         -        0.03      0.03
   16  0.983   -0.420       -         -        0.08      0.07
   17  0.983   -0.474       -         -        0.05      0.05
   18  0.983   -0.487     0.00      0.30       0.05      0.05
   19  0.982   -0.498       -         -        0.04      0.04
   20  0.982   -0.505     0.00      0.15       0.04      0.04
   21  0.982   -0.504       -         -        0.04      0.04
   22  0.982   -0.501       -         -        0.03      0.03
                        --------  --------  --------  --------
               Total:     0.67      0.66      0.66      0.66
```

Figure 46: Voltage and Power Generated and Consumed in every of the 22-Bus nodes with Capacitive Compensation using the CBO Method



```
================================================================================
|     Branch Data
================================================================================
Brnch   From   To    From Bus Injection   To Bus Injection     Loss (I^2 * Z)
  #     Bus    Bus    P (MW)   Q (MVAr)   P (MW)   Q (MVAr)   P (MW)   Q (MVAr)
-----  -----  -----  --------  --------  --------  --------  --------  --------
   1      1      2     0.67      0.21     -0.67     -0.21     0.002      0.00
   2      2      3     0.02      0.02     -0.02     -0.02     0.000      0.00
   3      2      4     0.64      0.17     -0.64     -0.17     0.002      0.00
   4      4      5     0.05      0.06     -0.05     -0.06     0.000      0.00
   5      5      6     0.03      0.04     -0.03     -0.04     0.000      0.00
   6      6      7     0.01      0.01     -0.01     -0.01     0.000      0.00
   7      6      8     0.01      0.02     -0.01     -0.02     0.000      0.00
   8      4      9     0.55      0.07     -0.55     -0.07     0.002      0.00
   9      9     10     0.01      0.02     -0.01     -0.02     0.000      0.00
  10      9     11     0.52      0.03     -0.52     -0.03     0.002      0.00
  11     11     12     0.02      0.02     -0.02     -0.02     0.000      0.00
  12     11     13     0.48     -0.01     -0.48      0.01     0.001      0.00
  13     13     14     0.40     -0.08     -0.40      0.08     0.001      0.00
  14     14     15     0.03      0.03     -0.03     -0.03     0.000      0.00
  15     14     16     0.33     -0.14     -0.33      0.14     0.000      0.00
  16     16     17     0.25     -0.21     -0.25      0.21     0.000      0.00
  17     17     18     0.05     -0.25     -0.05      0.25     0.000      0.00
  18     17     19     0.15     -0.01     -0.15      0.01     0.000      0.00
  19     19     20     0.11     -0.05     -0.11      0.05     0.000      0.00
  20     20     21     0.04      0.04     -0.04     -0.04     0.000      0.00
  21     20     22     0.03      0.03     -0.03     -0.03     0.000      0.00
                                                             --------  --------
                                                    Total:     0.010      0.01
```

Figure 47: Branch Data from the 22-Bus Distribution Grid with Capacitive Compensation using the CBO Method

APPENDIX III

Hourly Data to shape Demand Load

This data was utilized to calculate the hourly load coefficients of Section 4.1. The data represents the hourly load consumption of several residential distribution networks in the state of New York for January 2020.

Year	Month	Day	0:00	1:00	2:00	3:00	4:00	5:00	6:00	7:00	8:00	9:00	10:00	11:00
2020	1	1	15417	14891	14506	14226	14211	14404	14789	15135	15476	15945	16280	16675
2020	1	2	15082	14666	14481	14400	14661	15458	16907	18067	18467	18503	18299	18023
2020	1	3	14772	14219	13922	13810	13997	14742	16154	17387	17981	18406	18701	18732
2020	1	4	14600	14026	13701	13538	13563	13860	14432	15192	15930	16713	17238	17504
2020	1	5	14755	14212	14073	13961	13992	14252	14712	15301	15958	16567	16811	16957
2020	1	6	15244	14855	14607	14552	14841	15797	17456	18741	19182	19544	19602	19291
2020	1	7	15400	14958	14739	14719	14979	15940	17625	18904	19197	19170	19076	19016
2020	1	8	15448	15022	14762	14736	14998	15897	17562	18813	19110	19258	19200	19160
2020	1	9	16709	16295	16051	16018	16302	17212	18966	20171	20345	20143	19899	19645
2020	1	10	16242	15717	15366	15222	15401	16222	17752	18948	19246	19504	19651	19625
2020	1	11	14723	14151	13760	13609	13617	13856	14414	15051	15608	16066	16253	16244
2020	1	12	13845	13360	13023	12835	12863	13054	13462	14004	14586	15143	15479	15629
2020	1	13	14334	13987	13831	13833	14150	15172	16929	18182	18488	18803	19013	19070
2020	1	14	14887	14356	14131	14073	14325	15265	16982	18229	18568	18664	18585	18535
2020	1	15	14673	14148	13869	13830	14075	15013	16711	17963	18128	18071	17910	17775
2020	1	16	14740	14278	13983	13894	14171	15088	16774	18072	18365	18578	18463	18513
2020	1	17	16219	15831	15619	15646	16006	17012	18763	20005	20308	20281	20188	20047
2020	1	18	17337	16802	16467	16337	16361	16689	17317	18132	18854	19371	19681	19810
2020	1	19	16093	15501	15162	14955	14906	15084	15526	16053	16634	17052	17307	17582
2020	1	20	16350	15986	15812	15836	16132	16921	18029	19022	19617	19912	19969	19863
2020	1	21	17078	16667	16455	16380	16676	17685	19347	20539	20742	20587	20427	20276
2020	1	22	16792	16313	16084	16015	16307	17259	18944	20125	20281	20058	19812	19475
2020	1	23	16176	15742	15537	15490	15803	16775	18518	19689	19771	19553	19285	19043
2020	1	24	15637	15148	14907	14880	15155	16049	17682	18839	19031	18811	18465	18127

2020	1	25	15254	14707	14404	14281	14327	14638	15271	16051	16894	17588	18068	18276
2020	1	26	14926	14425	14117	13949	13970	14241	14718	15267	15811	16264	16497	16685
2020	1	27	14846	14457	14202	14215	14521	15505	17182	18335	18651	18775	18844	18872
2020	1	28	15107	14653	14371	14343	14600	15569	17283	18472	18808	18920	18821	18744
2020	1	29	15459	15045	14828	14800	15057	16006	17824	18950	19246	19140	18826	18548
2020	1	30	16247	15847	15648	15628	15977	16974	18789	19830	19875	19622	19363	19042

Year	**Month**	**Day**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**	**23:00**
2020	1	1	17147	17331	17429	17569	18263	19149	19052	18766	18344	17726	16786	15799
2020	1	2	17835	18061	18219	18421	19099	19989	19837	19395	18766	17930	16783	15636
2020	1	3	18654	18647	18594	18592	19072	19572	19247	18754	18224	17457	16458	15387
2020	1	4	17514	17439	17306	17357	17894	18489	18396	18040	17735	17225	16491	15696
2020	1	5	17078	17103	17226	17600	18444	19519	19436	19118	18669	17935	16924	15937
2020	1	6	18943	18971	18851	19012	19667	20631	20527	20151	19532	18665	17440	16252
2020	1	7	19014	19013	18949	19187	19898	20609	20501	20105	19513	18594	17382	16242
2020	1	8	19133	19035	19165	19588	20380	21466	21502	21182	20599	19767	18534	17458
2020	1	9	19518	19486	19605	19974	20755	21644	21581	21180	20549	19580	18357	17136
2020	1	10	19329	18989	18807	18801	19239	19774	19433	18897	18287	17572	16594	15544
2020	1	11	16201	16195	16339	16440	16886	17592	17488	17147	16723	16139	15417	14606
2020	1	12	15747	15821	15953	16281	16966	18006	18050	17785	17391	16761	15841	14936
2020	1	13	18985	18924	18842	18944	19463	20064	19875	19473	18838	17966	16836	15731
2020	1	14	18470	18419	18468	18729	19334	20039	19865	19438	18795	17859	16690	15551
2020	1	15	17616	17539	17546	17811	18471	19514	19547	19212	18675	17809	16647	15552
2020	1	16	18483	18557	18723	18944	19607	20605	20630	20298	19816	19002	17927	16903
2020	1	17	19830	19688	19653	19947	20626	21530	21517	21193	20721	20043	19089	18120
2020	1	18	19882	20105	20110	20099	20419	20993	20836	20320	19666	18792	17856	16857
2020	1	19	17716	17685	17751	18093	18676	19679	19736	19447	19053	18487	17745	16951
2020	1	20	19673	19547	19536	19797	20542	21740	21895	21561	20960	20093	18928	17852
2020	1	21	20093	19958	19952	20225	20814	21841	21890	21553	20936	19984	18767	17602
2020	1	22	19104	18942	18910	19170	19856	20969	21089	20733	20209	19313	18112	16988
2020	1	23	18845	18796	18841	19025	19544	20435	20429	20051	19535	18667	17520	16402
2020	1	24	17835	17709	17757	18040	18598	19451	19431	19036	18505	17824	16941	16016
2020	1	25	18341	18227	18103	18088	18214	18643	18594	18219	17713	17129	16378	15583
2020	1	26	16760	16848	16978	17238	17852	18744	18820	18507	18016	17355	16439	15499
2020	1	27	18902	18974	18921	18966	19424	20184	20162	19757	19167	18212	16995	15888
2020	1	28	18768	18822	18893	19105	19612	20399	20421	20070	19492	18576	17382	16223
2020	1	29	18328	18259	18288	18602	19363	20508	20790	20513	20017	19186	18013	16932
2020	1	30	18722	18713	18730	19017	19651	20670	20831	20566	20013	19121	17938	16889

Table 18: Hourly Demand Load in Residential Distribution Networks