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Investigation on The Electrical Vehicles Effects on The Electrical Power Grid

Meral KILIÇARSLAN OUACH[1a], Ertuğrul ÇAM[1b]

[1]Kırıkkale Üniversitesi, Mühendislik Fakültesi, Elektrik-Elektronik Mühendisliği Bölümü. 71450
Kırıkkale/TÜRKİYE
m.kilicarslan@kku.edu.tr

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Abstract: The advantages of electrical vehicles compared to internal combustion ones have increased more importantly up to this day. Therefore, their usage has also increased. However, these vehicles have started to be damaging to the grid during charging. In this study, the effects of electric vehicles on the grid when they are simultaneously charged in houses, malls, and charging stations have been analyzed. Additionally, based on the data of the city of Kırıkkale in Turkey, the locations of the stations that can be established were also determined. A Probability Density Function was obtained in Matlab Software with the help of this data, and a charging model was created with Monte-Carlo algorithm in Matlab as well. After that, all models were applied to the grid with Quasi-Dynamic simulation using Digsilent Powerfactory software. The line status and transformer capacities in Kırıkkale has been investigated with all these operations. Thus, valid models were created for investors and Energy Distribution Company. Additionally, Kırıkkale grid was also examined in this sense.

Keywords: Electric Vehicles (EVs), Charging Stations, Charging Models, Monte-Carlo Simulation, Quasi-Dynamic Simulation.

Elektrikle Çalışan Araçların Elektrik Şebekesine Olan Etkilerinin İncelenmesi

Öz: Elektrikli araçların içten yanmalı olanlara göre avantajları günümüze kadar daha da artmıştır. Bu nedenle kullanımları da artmıştır. Ancak, bu araçlar şarj esnasında şebekeye zarar vermeye başlamıştır Bu çalışmada elektrikli araçların aynı anda evlerde, alışveriş merkezlerinde ve şarj istasyonlarında şarj edildiklerinde şebeke üzerindeki etkileri analiz edilmiştir. Ayrıca Türkiye'deki Kırıkkale ilinin verilerine dayanarak kurulabilecek istasyonların yerleri de tespit edilmiştir. Bu verilerle Matlab Yazılımı ile bir Olasılık Yoğunluk Fonksiyonu elde edilmiş ve Matlab'daki Monte-Carlo algoritması ile de bir şarj modeli oluşturulmuştur. Daha sonra, tüm modeller Digsilent Powerfactory yazılımı kullanılarak Quasi-Dynamic simülasyonu ile şebekeye uygulanmıştır. Tüm bu operasyonlarla Kırıkkale'deki hat durumu ve trafo kapasiteleri araştırılmıştır. Böylece yatırımcılar ve Enerji Dağıtım Şirketi için geçerli modeller oluşturulmuştur. Ayrıca Kırıkkale'nin şebekesi de bu anlamda incelenmiştir.

Anahtar Kelimeler: Elektrikli araçlar, şarj istasyonları, şarj modelleri, Monte-Carlo simülasyonu, Quasi-Dynamic simülasyonu.

1. Introduction

International EV sales have increased dramatically in the wake of this century for many reasons and sales expectations in the future are higher [1]. There have been some improvements in batteries such as high specific energy and power, long life, high safety, fast charging, wide operation ranges, low self-discharge, reduced toxicity, and long shelf life [2]. These improvements are the main efficacy to make EVs secure, have long-range, and higher market value.

Bu makaleye atıf yapmak için
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ORCID ID : [a]0000-0002-1086-5273; [b]0000-0001-6491-9225

Users are encouraged to start using EVs (Electric Vehicles) by lots of advantages such as zero fuel consumption, environment friendliness, and lower maintenance costs [3]. There is also a tendency in many countries to reduce taxes on EVs for their previously stated advantages. As their numbers are increasing, a few challenges have been brought by EVs especially while they are getting charged. Unless highly detailed plans are well set, the power grid will be undermined by EVs' charging simultaneously using different technologies at different charging points.

At the same time, the life expectancy of batteries depends on charging speed, state of charging and discharging, temperature and the age of the battery itself [4].

Countries that have broad EV usage have taken some precautions to regain both power quality and voltage stability, they are deteriorated while EVs are charging [5, 6]. Charging habits of EV users are needed to avoid this pitfall. Some indicators such as the overall infrastructural development of the countries, regional traffic jams, proportion of EVs amongst motor vehicle fleet, charging points abundance/accessibility and governmental incentives to encourage EVs usage are important parameters to determine the habits of EV users [7, 8]. There are various studies to predict charging habits [9-12]. Charging habits of EV users which are described by reports were used in this study.

The constantly growing number of EVs has brought up the importance of the charging points abundance and their penetration to grids with a minimal negative effect. Charging EVs without any coordination brings up some problems such as deterioration of power quality, overloads, excessive losses, voltage drops, and over costs [13, 14].

Uncoordinated fast charging harms the grid even more. Mostly this kind of charging coincides with peak hours and this multiplies losses [15]. Many solutions have been developed to eliminate these problems. At [13, 16-17] EV users were encouraged to charge at off-peak hours by implementing electricity rates that were being changed throughout the day. At [18] charging from renewable energy sources, at [18-19] optimal charging station location, at [20-21] solutions by energy transfers between vehicle to grid (V2G) and at [22-24] smart charging systems were suggested to minimize the negative effects on grids caused by charging EVs. But some of these studies ignored users' habits and some of them were only applicable to specific geographical regions.

In this study, different technologies were used by the charging process at different locations were also taken into consideration. Locations of the optimal charging stations were determined after a flexible charging model that can be applied to any grid was developed. Changes in the grid were calculated during well-defined intervals. The power grid of Kırıkkale was examined. Firstly, fast-charging stations locations were determined considering the grid and the business opportunities on the road amongst other reasons. Then, the charging model was created for these stations, households, and the only mall in the city. Monte-Carlo simulations and Probability Density Function (PDF) were used for the charging model. Then, for a chosen busy day of the grid at an interval of every half an hour power flow analysis was executed via Quasi-Dynamic Simulations by Digsilent Powefactory program. Loading of lines, the capacity factor of transformers, and bus voltages have increased at some intervals considering all possible scenarios of the charging model. This charging model can be considered as a base case and applicable to any grid after making sensitivity analyses by changing the number of cars that are integrated into the grid.

The rest of the paper proceeds as follows: Section II introduces the selected charging technologies for the grid, determining EV fast-charging stations on the grid, calculating EV charging pattern, generation scenarios, and reducing them using Monte-Carlo simulation and Probability Density Function. Calculations of the index for EV which represent the index of voltage violation, index of line loading violation, and capacity factor of high voltage transformers are detailed in Section III. The grid with and without EV integration with modeled charge pattern simulated in Digsilent

Powerfactory Program using Quasi-Dynamic simulations in Section IV and indexes for EVs calculated followed by conclusions and recommendations in Section V. In this study, the method of evaluation of the effect of EVs on the grid is proposed without focusing on the number of EVs as an input to design a methodology. The exampled grid has no overloading however load increment will eventually lead to overloading. This proposed method is independent of both the base loading and the grid.

2. System model

2.1. Type of Model

Charging types: In this study, charging types at Table 1 were chosen to determine common charging patterns for different charging locations.

Table 1. EV Charging Parameters Used in Modelled Network

Charging Location	Public	DC Stations	Residential
Charging Type	AC (Mode 3)	DC (Mode 4)	AC (Mode 2)
Charging Capacity (kW)	22	175	3
Charging Time	~4 hours	20 mins	~8 hours
Charging Rate (km/30 mins)	~40	~300	~8
Number of Sockets	800 (mall)	16	78207

Three different charging types were chosen for the mall, DC Fast Charging Stations, and household usages. Charging at the mall takes 4 hours using AC Mode 3, the mall contains 800 parking lots. 4 hours is ideal for a mall as faster or slower charging would impact shopping experience rendering it too short or causing other shoppers unpleasant waiting. For household charging AC Mode 2 is chosen which takes 3 hours to charge. In Kırıkkale city, there are 78207 individual residential users. For fast-charging stations, high capacity of charging station allows up to 175kW of charging power which is considered to be the most effective solutions when CAPEX (Capital expenditures) and OPEX (Operating expenses) are considered [25].

Battery State of Charge: For charging at residential locations, Table 1 was considered for various battery SOC (State of Charge). In [13] distances that EVs travel daily between nearby Ankara and Kırıkkale is summarized at Table 2.

According to Table 2, there is an incremental correlation between the SOC, traveling distance, and charge duration. Charging duration increases proportionally according to distance traveled [13].

Table 2. Charging Duration of an EV Regarding the Travelling Distance [13]

Travelling Distance (TD) (km)	**Battery State Of Charge (%)**	**Charging Duration (h)**
TD < 10	85-90	3
10 < TD < 20	70-80	4
20 < TD < 40	55-65	5
40 < TD < 60	40-50	6
60 < TD < 80	25-35	7
80 < TD < 100	10-20	8

Electric Grid and The Locations of Charging Stations: The electricity grid of Kırıkkale was modeled via Digsilent Powerfactory program as showed in Fig.1. Line characteristics, transformer, and load data were provided by the regional electricity distribution company [26]. For many considerations, optimum locations 1 and 2 for fast charging stations were chosen, these considerations are: the second busiest road of its category in Turkey, roundabout, intercity bus station (2) and a gas station with resting facilities and a mosque in addition to the nearby university (1). All these plus continuously obtained feed from different busbars right before low voltage transformers.

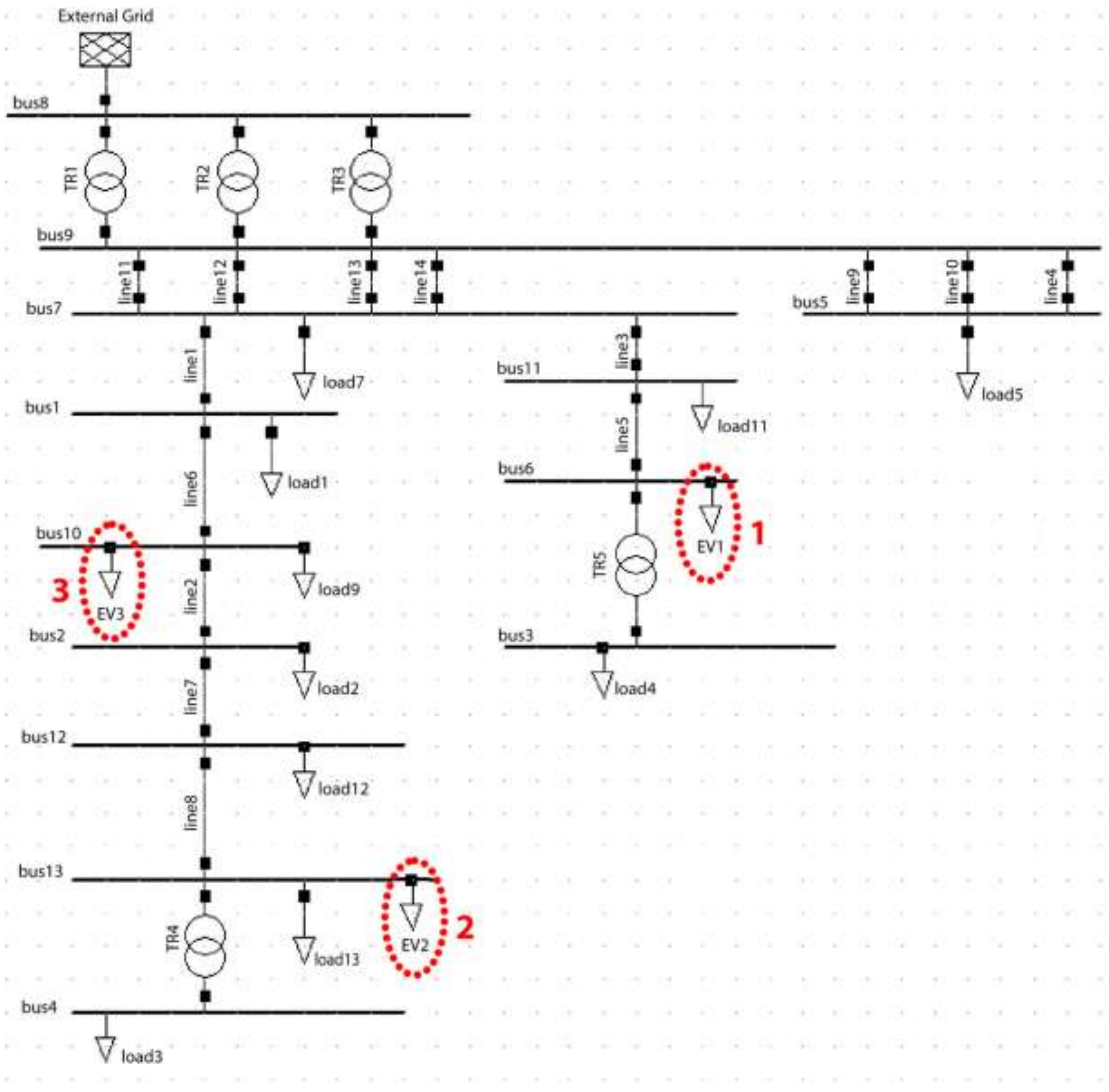


Figure 1. Single Line Scheme of Kırıkkale, Charging Stations (1-2) and Mall (3)

2.2. Raw Data

Loads without EVs: Peak day load has been chosen for simulations, for 2019, it is 15 March [27]. Within this day, loads were divided into intervals of half an hour and input to Digsilent Powerfactory program. Half an hour intervals loads are more useful because charging at DC charging stations takes no more than half an hour.

Charging Habit Data: In some countries, EV usage rates are high, sufficient data to form EV charging habits is accessible [6, 10, 12, 28-31]. Some data related to those countries represent the level of overall development, population density, number of EVs and their market share, incentives for the usage of EVs, number of charging points, average working hours per year, industrial and residential areas peak hours and charging habit data related to peak charging hours at residential, public and charging stations were analyzed by SPSS (Statistical Package for Social Sciences) program via Pearson Correlation-Two tailed feature to calculate the correlation between each data. A strong correlation (0.710 - 0.952) was found between the number of EVs and public charging points, and between population density and home charged hours. This indicates that having accessible charging points is also an incentive for buying EVs.

3. Estimated Time of Arrival Assigned Function

The time of EVs arrival is of the utmost importance for the prediction of the charging load given the limit of charging technology choices: AC at homes, AC at the mall, and DC at charging stations. Arrival times need to be estimated but charging information are random variables. For that, PDF as assigned. PDF is an integral calculated function that is used for finding the probability of random variables at statistical calculations. In other words, it is a list of all probable results corresponding to a random variable with its probable values in an event [32]. PDF doesn't calculate any value of the random variable but it defines the value of its probability within the defined interval. Charging at public AC (Fig.2b) finished at 20:00 because AC needs time to charge but DC is faster, so charging at public DC (Fig.2c) was extended until 22:00. So, for the EVs there are three different PDFs. So, PDF is used for estimating the time of arrival and the status at arrival.

4. Scenario Generation

To generate scenarios Monte-Carlo simulations were used. Monte-Carlo is a method that investigates the outcomes of a model generated from the inputs that are formed randomly, generally, it is made by using a process that has three steps; a scenario is nothing but input numbers "n" that is generated randomly, each input is fed to simulations and outputs are collected and evaluated.

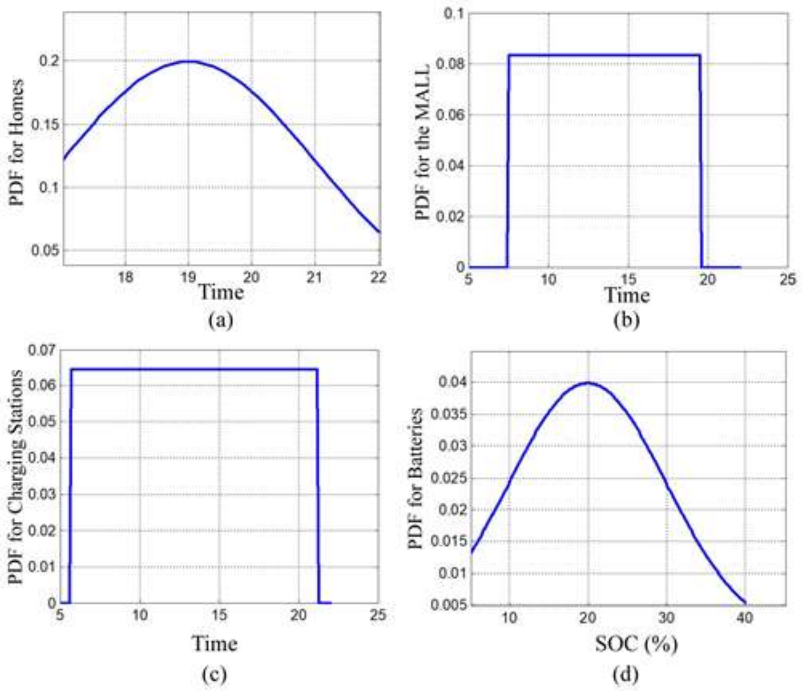


Figure 2. Assigned PDF Functions

Common criteria are averages and distributions of output values plus minimum or maximum output values [33]. In this study, to plan charging models of EVs around 100000 scenarios were formed by Monte-Carlo simulations. Then, these scenarios were reduced to the most probable five scenarios after determining the probabilities of each scenario by PDF. In Fig.2, every point on those PDFs is a form of these scenarios. For example, scenario 1 would be; home charging starts at 17:00, at the mall starts at 10:00 and charging at the charging station starts at 09:00, assigning 25% SOC, 10% SOC and 30% SOC for each of them respectively.

Multiplying probabilities happening simultaneously is one scenario, 100000 scenarios were made by MATLAB likewise.

5. Scenario Reduction

Each scenario is a probability of a state of charging. But 100000 scenarios cannot be evaluated and simulated at Digsilent Powerfactory. So, scenarios' numbers had to be reduced. Those scenarios were sorted by their relative probability. They were reduced to the 5 most probable scenarios. In the end, all probabilities accumulations are 1.

At Table3, most probable scenarios of charging at 3 different locations and different battery SOC can be seen.

Table 3. Scenario Reduction of Charging at 3 Different Locations

Scenario	Arrival Time			**SOC**	**Probability**
	AC3P (Mall)	**DC4P (Station)**	**AC2H (Home)**		
1	19	7	14	6.4	0.06967
2	22	7.5	7.5	5.9	0.00038
3	17	7.5	10	9.9	0.00146
4	17	16.5	11.5	6.1	0.05794
5	22	19	22.5	38.5	0.87093

6. Pattern

At every half an hour, load originated from EVs came from different scenarios and different probabilities. For example, the load of the EV of the first scenario and its probability were multiplied, likewise for the other scenarios and the summation of the results would be the load of that hour.

$$CP = \sum_{i=1}^{5} \pi_i \, x \, Load_i \tag{1}$$

To determine the charging pattern (CP) probabilities, 5 scenarios were multiplied by their charging load. This calculation was repeated for each load of each half an hour. The graph in Fig.3 illustrates this calculation for only 1 case and its 1 subcase.

At table 2, with changing the transformer loads, sensitivity analysis can be executed for any kind of EV load integration.

Charging pattern for each case can be seen in Table 4. Number of load types column indicates loads at Digsilent Powerfactory Program. For example, there is one mall so AC3P load is one, 2 fast-charging stations and 10 residential lumped loads from different busbars as can be seen in Fig.1. Share column indicates the total power of high voltage transformers which is 150 MVA, proportion amounts for three kinds of charging technologies. Loads for every subcase were calculated as follows:

$$Load = \Sigma HV \text{ Transformers Capacity } \times \text{Share} \times \text{Subcase Share} \tag{2}$$

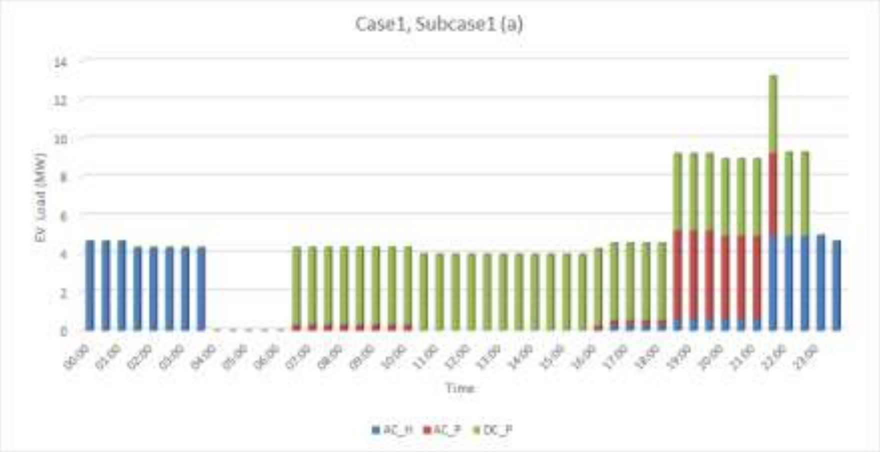
EV numbers for each subcase is calculated as:

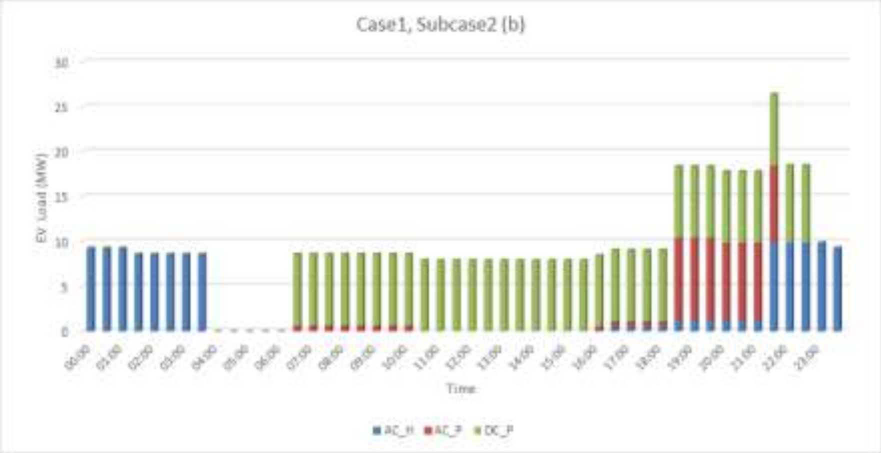
$$\text{EVN} = \frac{(\text{Charging Capacity} \times 100)}{\text{Load}} \tag{3}$$

This represents the number of vehicles (EVN) that were charged at the same time at those different locations. For each case, the loading level is different so the pattern peak is different. But patterns are almost the same everywhere as can be seen in Fig.3. The difference is the amplitude of the loads. Fig.3 is derived from Table 4.

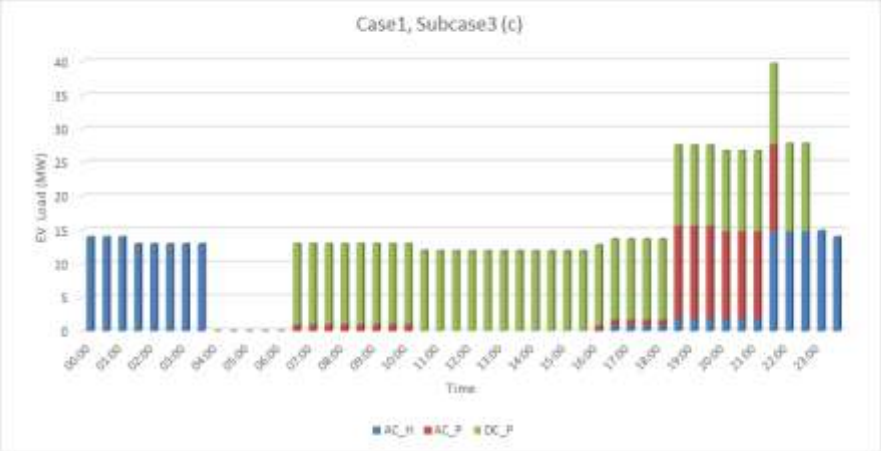
Table 4. Determining the Cases

Case	Tech.	Types of Load		10%		20%		30%	
				EV Number	Load (MW)	EV Number	Load (MW)	EV Number	Load (MW)
1	AC3P	1	33%	225	4.95	450	9.9	675	14.85
	DC4P	2	33%	29	4.95	57	9.9	85	14.85
	AC2H	10	33%	1650	4.95	3300	9.90	4950	14.85
2	AC3P	1	25%	171	3.75	341	7.5	512	11.25
	DC4P	2	25%	22	3.75	43	7.5	65	11.25
	AC2H	10	50%	2500	7.5	5000	15	7500	22.5
3	AC3P	1	17%	116	2.55	232	5.1	348	7.65
	DC4P	2	50%	43	7.5	86	15	129	22.5
	AC2H	10	33%	1650	4.95	3300	9.9	4950	14.85




Case1, Subcase2 (b)
EV Load (MW)
30
25
20
15
10
5
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time
AC_H
AC_P
DC_P

(Continued)


Case1, Subcase3 (c)
EV Load (MW)
40
35
30
25
20
15
10
5
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
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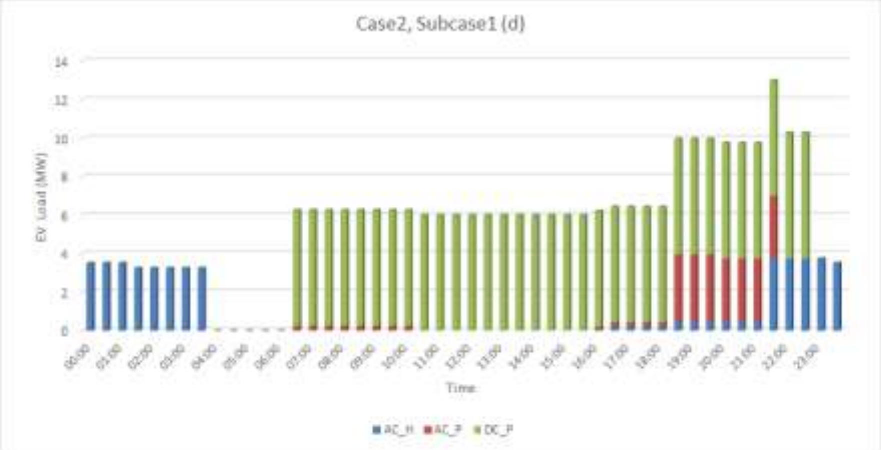
23:00
Time
AC_H
AC_P
DC_P


Case2, Subcase1 (d)
EV Load (MW)
14
12
10
8
6
4
2
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time
AC_H
AC_P
DC_P


Case2, Subcase2 (e)
EV Load (MW)
30
25
20
15
10
5
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
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Time
AC_H
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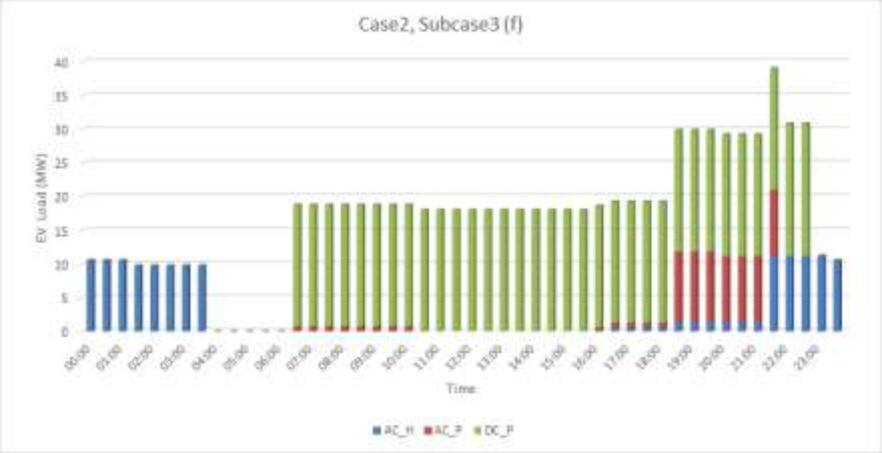

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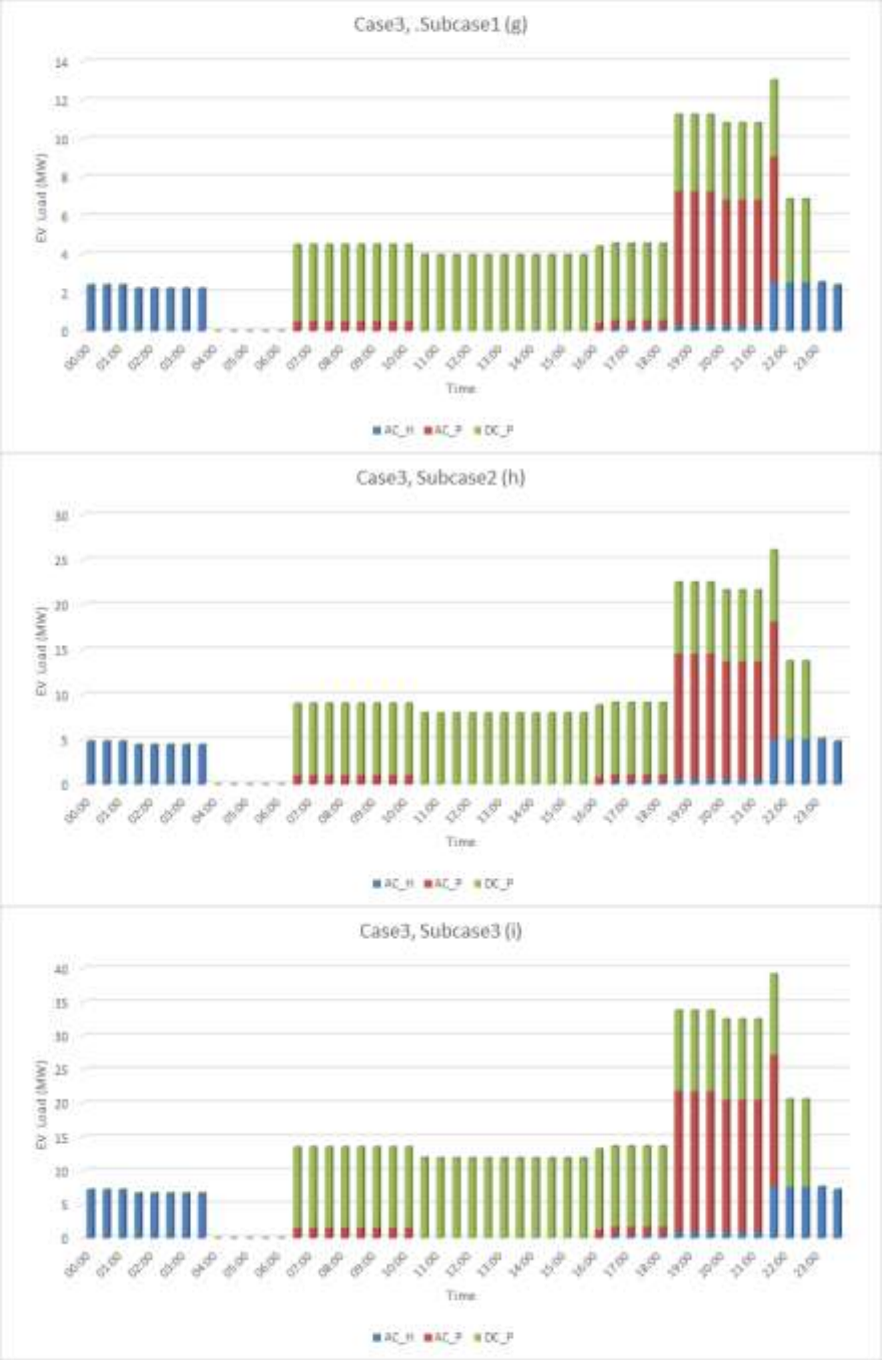

Figure 3. Same Pattern Different Amplitudes

Amongst all 3 cases and each of their 3 subcases just 2 of them can be seen in Fig.3. As a sum, for the charging model, scenarios that needed to be calculated by Monte-Carlo simulation were approaching 100000 scenarios. Then they were reduced to the 5 most probable scenarios using PDF. These steps were executed by MATLAB.

7. Index for EV Integration

7.1. Index of Voltage Violation

$$I\_VOV = \sum_{i=1}^{24} | \times \sum_{b=1}^{nbus} \frac{|v_{bus}| - V^{ref}|}{V^{ref}} \times 100 \tag{4}$$

At every hour (t=1 to 24) and for all busses (b=1 to nbus) index of voltage violation (I VOV) was calculated for non-EV case. Then the index of voltage violation for EV integrated case was also calculated. Then the difference (Δv) shows the degree of effect of EVs on the busses. For Turkey, according to Regulation concerning Supply Reliability and Quality of Electrical Transmission System tolerance of voltage changes interval is 10% [34].

7.2. Index of Line Loading Violation

$$I\_LLV = \sum_{i=1}^{24} \times \sum_{l=1}^{n_{line}} \frac{|LL_{line} - 100|}{100} \times 100 \tag{5}$$

At every hour (t=1 to 24) and for all lines (l=1 to nline) index of line loading violation (I LLV) were calculated for non-EV case afterward index of voltage violation for EV integrated case was also calculated. Then difference (Δl) shows the degree of effect of EVs on the lines.

7.3. Capacity Factor

Capacity factor measures how much of an element is being used at a given condition. Load increment at some special hours will increase the capacity factor of the transformers. This will reduce the life span and effects their aging.

$$\begin{aligned} CF &= \frac{\int_0^t Real\ dt}{C \times t} & &= \frac{1}{48}\sum_{t=1}^{48} Load \times 100 \\ &= \frac{\sum(C)}{C \times 48} & & \\ &= \frac{\sum(\frac{Load}{C})}{48} \times 100 & &= \frac{\sum(C \times 0.5)}{C \times 24} \times 100 \end{aligned} \tag{6}$$

At every hour (t=1 to 24) capacity factor were calculated for transformers present at the grid. The capacity factor of transformers was calculated both for EV cases and for non-EV cases. Then the difference (Δc) shows the EVs degree of effect on the transformers. This is the daily increment in capacity factor. When it comes to yearly usage it would be more tangible. In Fig.1 because of high voltage transformers shown as TR1, TR2 and TR3 have the same features, only transformer TR2 analyzed for capacity factor.

8. Simulations

Quasi-Dynamic simulation is a tool that enables the making of multiple power flow analyses on an electrical network with time step intervals defined by users. In Digsilent Powerfactory program, Quasi-Dynamic simulation tool allows medium to long term calculations. This tool is especially suitable for long term generation, load profiles, and investment studies conducted by network developers using variable variations and extended steps. Busbar voltages of the modeled grid with Digsilent Powerfactory Program using Quasi-Dynamic simulation can be seen at Fig.4. While charging at home, at charging stations and at the mall using charging pattern that is mentioned in chapter 2 while all cases and subcases that are mentioned in chapter 3 were considered, EVs increased voltage violation of busbars was (v) = 0.8%-2.7% within a day as it can be seen at Table 5. According to Turkish regulations on Supply Security and Quality of Electrical Transmission System, the voltage change range is 10%. This seems reasonable however considering EV numbers growth which will cause extra transformer loads, an eminent voltage violation increase seems inevitable.

Table 5. Grid Parameters Variations After Integration of EVs

Case	Subcase	Δ y	Δ l	Δ c
1	1	1.1803	20.1194	3.3379
	2	1.8971	39.9886	6.3958
	3	2.6627	58.4939	9.5263
2	1	1.3446	24.877	3.9256
	2	0.7667	9.0415	1.6286
	3	0.9209	12.4644	2.282
3	1	1.1465	19.238	3.1865
	2	1.8108	37.0938	6.0849
	3	2.5044	55.5282	9.049

After EVs were integrated into the grid, the index of line loading violation happened to be between (l) = 0.9%-58% within a day. And again, after EV integration of different scenarios, cases, and subcases capacity factor of each high voltage transformers were increased between (c) = 1.6% - 9.5% from the most to least optimistic cases.

According to the Electricity Grid Regulation, capacity increase is planned if the actual loads of the transformers reach 70% of the installed power [35].

The maximum increase of capacity factor is 9.5% per day for the transformers in the grid of Kırıkkale, which is taken as an example in this study, is not violating the terms of regulation because the current transformers operate with a capacity of 42%.

At Fig. 4, busbar voltage profiles of the grid can be seen. Bara 10 is the reference bara and highest voltage profile belongs to bara 9 which is around 0.98 pu. As it can be seen from the fig 4, the network is not highly loaded and the voltage drop is at an acceptable level. As the time goes (x axis, from 0 to 23th hour in a day, y axis shows the busbar voltages in p.u. quantities)

In this study, it has been observed that there is an increase in transformer capacity, line loads and busbar voltages at certain intervals as a result of integrating EVs with scenarios formed by using the charging time, battery charge rate and charging power values of various sizes. EVs increase the capacity factor between c =1.6%- 9.5%, line loading l=0.9%-58% and busbar voltages v= 0.8%-2.7% in one day. These changes do not increase in direct proportion to EV numbers. Because the factors such as charging type, battery SOC, and charge duration change the power drawn from the grid in addition to the charging hours effect. Considering that these increases are noticed within a day, changes seen in the grid will accumulate to higher levels within each passing day of a year interval.

A good voltage profile is important for three reasons; good supply quality, better safety, and lower transmission loss. Therefore, in all operating conditions, the busbar voltages must be kept within a narrow band of determined values. This has been identified as one of the most important operational challenge [36].

Increasing the capacity factor, which is a very important factor for transformers, has a negative impact on the life and aging of the transformer. Considering that these increases are only for one-day, the general changes to be noticed on the grid will be more negative. For example, transformer components such as AC winding, transformer oil, and maintenance will be adversely affected. Additionally, loads in the grid are increasing day by day. Considering that there is a tendency for users to charge their vehicles during peak hours of the grid, the capacity factor difference will increase gradually. Even if in the short-term there are no damages detected on the existing grid, it is obvious that the increase in the loads on the grid together with the growth of the number of EVs will cause damages to the transformers.

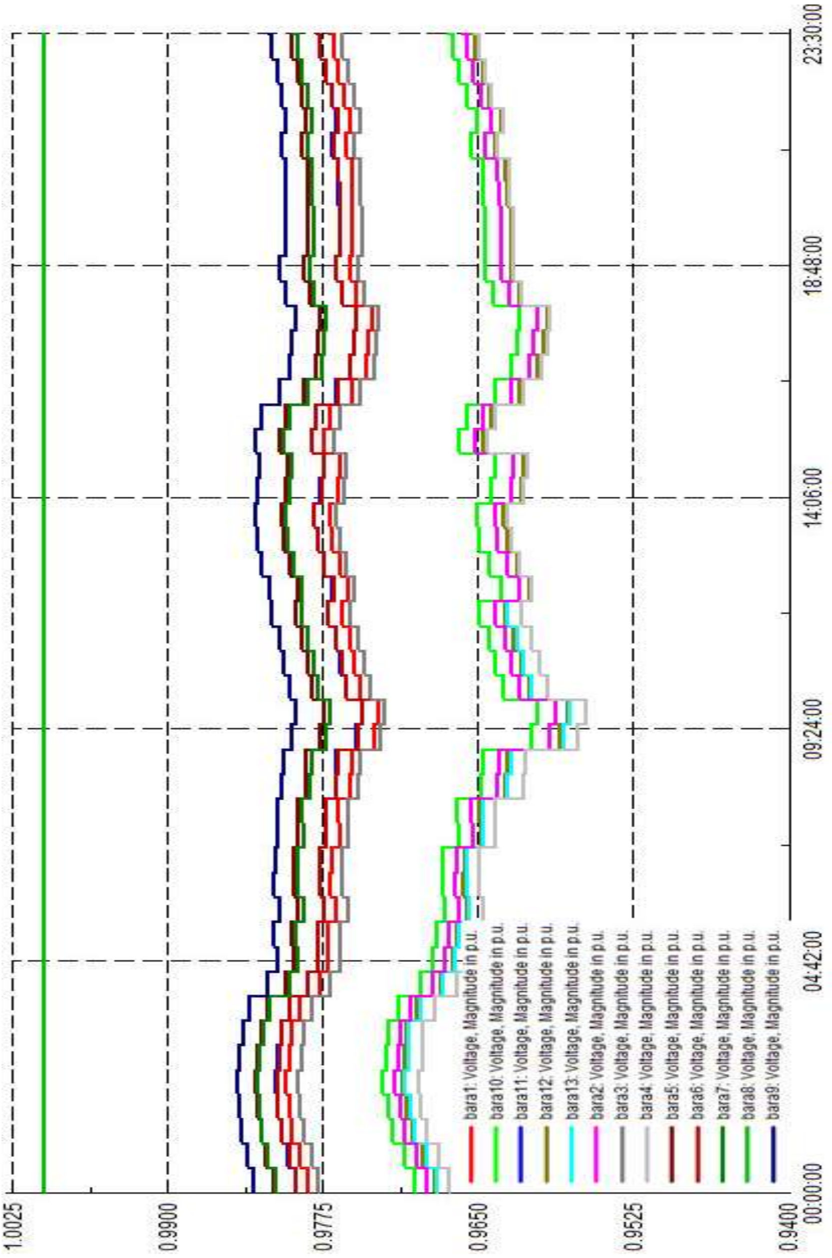

Figure 4. Busbar Voltages Profiles of The Grid

9. Conclusion

To simulate the effect of EVs on the distribution grid, a precise model of charging times is required in addition to charging technologies and charging loads. Charging status for EVs in homes, charging stations, and malls is different. Charging takes place in the afternoon at homes whereas charging in the charging stations and malls can often occur at midday and sometimes at other peak times of the week. Taking into consideration all these situations, the effects on the grid in Kırıkkale Province were examined, and also the locations of charging stations that could be established in Kırıkkale were determined. According to the results of this study, by 2025 electric vehicles will not have a significant impact on the city network and transformers. This data can be used by investors and the Energy Distribution Company operating in the city and it is a model that can also be used for the years that follow 2025. Moreover, the model created by this study is reliable and convenient, it can be applied to other cities all over the world. This is another important benefit of this study.

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