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Investigation of Charging Technologies for Electric Vehicles

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Abstract: In today's world, internal combustion engine vehicles are widely used. These vehicles cause harmful emissions as they use fossil fuels for engine propulsion and vehicle movement. To address this issue, electric vehicles have been considered as a solution. In electric vehicles, electric motors are used instead of traditional internal combustion engines and the necessary electrical energy is supplied from battery packs. In this way, electric vehicles do not cause harmful emissions to the environment. If the energy required for electric vehicle charging stations is obtained from renewable energy systems, electric vehicles will be zero-emission vehicles. Battery packs, that provide energy for electric vehicles, typically consist of rechargeable Lithium-ion battery groups and they can be charged using fast charging technology. In this study, the future of transportation, electric vehicles and the standards and technologies used in electric vehicle charging stations have been examined. Additionally, an electric vehicle system has been designed using MATLAB/Simscape.

Key words: Electric vehicles, charging stations, charging technologies.

Elektrikli Araçlar İçin Şarj Teknolojilerinin İncelenmesi

Öz: Günümüzde, içten yanmalı motorlu araçlar yaygın olarak kullanılmaktadır. Bu araçlar, motor tahriki ve araç hareketi için fosil yakıt kullandıkları için zararlı emisyonlara sebep olurlar. Elektrikli araçlar bu soruna bir çözüm olarak düşünülmüştür. Elektrikli araçlarda, geleneksel içten yanmalı motorlar yerine elektrikli motorlar kullanılır. Elektrikli motorların çalışması için gerekli olan enerji ise batarya paketlerinden sağlanmaktadır. Bu sayede, elektrikli araçlar zararlı emisyonlara sebep olmazlar. Elektrikli araç şarj istasyonları için gerekli enerji yenilenebilir enerji sistemlerinden sağlanırsa, elektrikli araçlar sıfır emisyona sahip araçlar olacaktır. Elektrikli araçlara enerji sağlayan batarya paketleri, yenilenebilir Lithium-ion batarya gruplarından oluşmaktadır. Bu bataryalar hızlı şarj teknolojisi kullanılarak şarj edilebilirler. Bu çalışmada; geleceğin ulaşım tercihi olan elektrikli araçlar, şarj istasyonlarında kullanılan standartlar ve teknolojiler incelenmiştir. Ayrıca, MATLAB/Simscape yardımıyla bir elektrikli araç sistemi tasarlanmıştır.

Anahtar kelimeler: Elektrikli araçlar, şarj istasyonları, şarj teknolojileri.

1. Introduction

With the increase in the population, the use of vehicles is also on the rise. The use of internal combustion engines contributes to CO2 emissions. The significant share of the transportation sector in CO2 emissions is a crucial issue that needs attention [1]. A common idea around the world as a solution to this issue has developed in the form of electric vehicles (EVs). EVs provides quieter, greener and more economical transportation by using electrical energy as fuel. It is obvious that electric cars will have a significant impact on the automotive industry in the future. It is thought that EVs will not only save fuel but also reduce environmental pollution and carbon emissions [2].

At the outset, the limited proliferation of EVs was attributed to elevated production costs. Nevertheless, the resurgence of interest in EVs can be attributed to advancements in battery technology and charging infrastructure. However, persistent challenges impede the ubiquitous adoption of EVs and their full displacement of conventional internal combustion vehicles. The progress of this technology is hindered by factors such as battery costs, full charge range, charging time, the unavailability of the existing grid infrastructure and both the environmental and economic impacts of EVs. Consequently, the majority of studies related to EVs focus on battery packs and charging technologies.

Through studies focused on charging technologies, the charging management systems of EVs are continually advancing. Novel charging management systems offer innovative solutions in areas such as grid integration, smart charging, energy storage, and user experience. These systems can be categorized as Smart Grid Integration, Vehicle-to-Grid (V2G), Adaptive Charging Algorithms, Energy Storage Integration, Advanced Remote

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Management, Payment Integration, and Pricing. These developments aim to provide electric vehicle owners with a more flexible, efficient, and user-friendly charging experience [3,4].

The charging technologies of EVs are continually evolving. Presently, various charging technologies such as Home Charging, Public Alternating Current (AC) Charging Stations, Fast Direct Current (DC) Charging Stations, Inductive and Capacitive Wireless Charging Technologies, and High-Power Density and Lightweight Charging Cables are available. This study examines the existing charging technologies [5].

This study investigates the operational principles, impacts and charging technologies of EVs. Furthermore, the adequacy of the existing charging station infrastructure in the countries and the adverse effects of EVs on the distribution grid are discussed. Standards for EV charging stations and information regarding vehicle charging technologies are provided. A sample EV is designed and relevant parameters are calculated. The EV is modeled using reference project in the MATLAB/Simscape environment.

2. Electric Vehicles

EV is a type of vehicle in which the traditional internal combustion engine and electric motor are not used together, but only the electric motor is used. Vehicle movement is provided only by the electric motor. An EV system consists of an electric motor, high-capacity battery, power electronics and charger. Vehicle movement is provided by electrical energy taken from high-capacity batteries.

EV battery packs consist of Lithium-ion batteries. With today's technology, the battery type with the highest cell voltage per unit cell and the highest energy density per unit mass is Lithium-ion batteries. These batteries; It is more preferred than other battery types due to its lack of memory effect, very low self-discharge and high cycle life [6]. Due to these advantages, Lithium-ion batteries are also widely used in EVs [7]. In Figure 1, an electric vehicle system is presented.

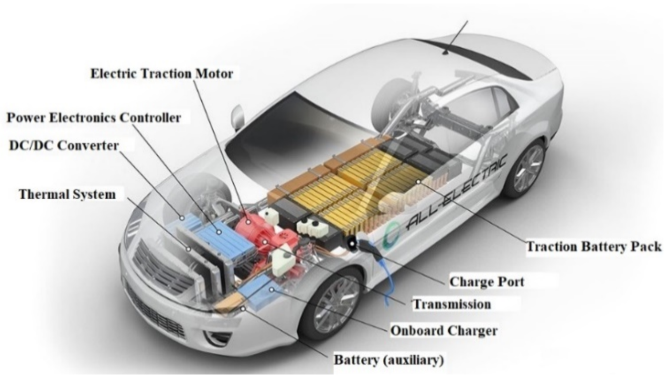

Figure 1. Electric vehicle system [8].

The advantages of EVs can be enumerated; encompassing a reduced frequency of breakdowns and maintenance requirements due to a lower number of mechanical components, quiet operation, the electric motor being comparatively more economical and having a simpler structure in contrast to traditional internal combustion engines. Furthermore, EVs can be powered by renewable energy sources and they possess the capability for hybrid operation.

In addition to these advantages, there are also some disadvantages of EVs that hinder the widespread adoption of these vehicles. Furthermore, similar to internal combustion engine vehicles, the proliferation of EVs is accompanied by various effects. These effects can be considered under three main categories: economic, environmental and grid-related impacts.

Undoubtedly, one of the most significant impacts of EVs will be on the grid. One of the major challenges preventing the widespread adoption of EVs is perhaps the unpreparedness of grid infrastructure for the extensive use of EVs. As the demand for EVs increases, the need for charging stations will also grow. With the increase in demand, the charging of EV will have a negative impact on the grid [9].

This situation can give rise to issues such as sudden and localized loading, grid harmonics, phase imbalances, overloading of equipment, voltage drops and so on. Additionally, the non-compliance of existing regulations with new developments will pose a problem [10]. The control of new-generation loads like EVs can be achieved using smart grid management algorithms. In this way, the charging load of the EV can be managed intelligently and negative effects can be reduced [11].

The selection of areas for the installation of EV charging stations is crucial in terms of distribution grid reliability and energy efficiency [12]. In addition, the balance of the electrical distribution network is also very important and all components must work together. An integrated grid system should be used to balance the load from EV charging stations [13]. Charging stations integrated into the grid system must be designed appropriately for grid reliability and balance [14]. Smart grid systems, grid management software and energy storage systems should be utilized to enhance grid stability and reliability [15]. At this point, all these solutions are of critical importance for the spread of EVs.

3. Electric Vehicle Charging Standards

In this section, charging station standards for EVs for only wired charging technologies are mentioned. Charging stations provide the infrastructure necessary for EVs to charge their batteries from external sources [16]. The charging process is carried out through charging equipment or charging stations. Factors such as the way batteries are charged, charging speed and charging frequency affect the reliability, durability and performance of the battery. There are two charging technologies in terms of charging speed: AC and DC charging. Therefore, the selection of the correct charging device and charging method is crucial for the accurate charging of batteries [1].

The increasing using of EVs leads to a growing demand for charging among EV owners. Consequently, the installation of more charging stations becomes necessary. The installation of charging stations and the use of EVs are interdependent systems. Therefore, countries and companies need to invest in the charging infrastructure required for the expanded use of EVs [16].

Since the voltage and frequency values of the electrical networks of different regions are different, the structures of the charging stations will also be different. Accordingly, leading countries in EVs technology have established EVs charging standards.

These standards include:

- SAE (Society of Automotive Engineers) Standards
- IEC (International Electromechanical Commission) Standards
- CHAdeMO Standards

In Europe, charging stations adhere to IEC standards. In addition, some companies include CHAdeMO standard sockets in their charging stations. However, different countries have charging stations adhering to various standards, including SAE, IEC and CHAdeMO.

3.1. SAE standards

Although established in the United States, it operates globally in the automotive sector. Numerous standards have been developed by the SAE. However, the SAE J1772 standard stands out for EVs [17]. According to this standard, charging speed is expressed in specific levels. Each level has a specified charging speed limit and vehicle charging ports are designed in accordance with this standard [16]. Table 1 shows the electrical parameters of the SAE J1772 standard.

Table 1. Electrical parameters of the SAE J1772 standard [18].

Source	Level	Voltage (V)	Max. Current (A)	Max. Power (kW)
AC	Level 1	120	12	1,44
		120	16	1,92
	Level 2	208-240	>20 ≤80	19,2
DC	Level 1	200-500	80	40
	Level 2	200-500	200	100

3.2. IEC standards

IEC is an organization that develops standards in the field of electric, electronic and related technologies [13]. For EVs, the IEC 61851 standard stands out. This standard, which is used in Europe and China, has similar requirements to the J1772 standard. Instead of the term “levels” used in the SAE standard, “modes” are used in the IEC standard. [16]. Table 2 shows the electrical parameters of the IEC 61851 standard.

Table 2. Electrical parameters of the IEC 61851 standard [18].

<table>
<tr><th>Source</th><th>Mode</th><th>Phase</th><th>Max. Voltage (V)</th><th>Max. Current (A)</th></tr>
<tr><td rowspan="6">AC</td><td rowspan="2">Mode 1</td><td>1</td><td>≤250</td><td rowspan="2">≤16</td></tr>
<tr><td>3</td><td>≤480</td></tr>
<tr><td rowspan="2">Mode 2</td><td>1</td><td>≤250</td><td rowspan="2">≤32</td></tr>
<tr><td>3</td><td>≤480</td></tr>
<tr><td rowspan="2">Mode 3</td><td>1</td><td>≤250</td><td rowspan="2">≤32</td></tr>
<tr><td>3</td><td>≤480</td></tr>
<tr><td>DC</td><td>Mode 4</td><td>-</td><td>≤1000</td><td>≤400</td></tr>
</table>

3.3. CHAdeMO standards

CHAdeMO is a fast-charging standard developed by Japanese automotive companies and is primarily used in Japan [19]. The CHAdeMO standard is used for DC fast charging and many fast-charging stations worldwide support this standard [16]. Table 3 shows the electrical parameters of the CHAdeMO standard.

Table 3. Electrical parameters of the CHAdeMO standard [18].

Standard	Voltage (V)	Max. Current (A)	Max. Power (kW)
CHAdeMO	500	125	62,5

4. Charging Technologies for Electric Vehicles

In this section, the charging technologies of EVs, both wired and wireless, have been examined.

4.1. Wired charging technologies

AC charging charges the battery more slowly. On the other hand, DC charging can charge at higher power and is generally used on highways and in areas with heavy traffic. DC charging is faster than AC charging and can charge 80% of the battery in about 30-45 minutes. However, DC charging stations cost more than AC charging stations [20].

The DC charging method is carried out using an off-board charger and this method enables the power received from the AC network to be directly converted to DC. In this way, AC power is converted to DC power without using any extra equipment. However, since DC charging stations have high voltage and current values, their investment costs are higher [1].

Different charging technologies are employed at each station depending on the structure of the charging station. EV manufacturers need to adapt their vehicles to different countries and markets. Therefore, there are charging station standards. The purpose of establishing these standards is to prevent potential damage to batteries during charging and enable manufacturers to make their vehicles suitable for use in different countries.

There are three types of EVs charging station structures used worldwide. The structure of the station, where an EV will be charged, determines the type of connector to be used. When the structure of the charging station changes, the equipment used also changes. The essential equipment used during EV charging includes the plug, connector (on the cable from the source to the vehicle), inlet (on the vehicle) and socket [21]. In Figure 2, charging cable connector types used in EVs are presented [22].

Type-1: It is an AC charging connection point designed according to the SAE J1772 standard, commonly used in the United States and Japan. These connectors typically support 120 V and 240 V AC charging levels. Type 1 connectors are used for AC Level 1 charging and are designed for slow charging processes [16].

Type-2: These types of charging cable connectors are also known as Mennekes connectors and are widely used in AC charging stations in Europe. This charging port is designed in accordance with the IEC standard and is commonly used by most AC Level 2 charging devices. Unlike the Type 1 socket, this connector features control and safety pins that enable communication between the EV and the charging device [16].

GB/T: It is the connector type defined by GB/T 20234 standards created in China and used only in China. The GB connector type is similar to the Type 2 connector mentioned in the IEC standard. It supports single-phase charging with 16/32 A current and 250 V output voltage. It is similar to Type 2 connectors in appearance and structure. However, these two connectors do not overlap functionally [16].

Combo Connector: The first DC fast charging standard is the CHAdeMO standard introduced by Japan. However, eight major automotive manufacturers (Audi, BMW, Chrysler, Daimler, Ford, General Motors, Porsche and Volkswagen) have decided to support the combo socket, which combines AC and DC charging defined in IEC and SAE standards in a single connector/input duo. CHAdeMO standard sockets only support DC charging. For this reason, vehicles using the CHAdeMO standard will always need two connector input pairs, separate for AC and DC charging. This is a negative situation that increases the production cost of the vehicle. CHAdeMO standard connectors will be replaced by combo connectors in countries other than Japan in the future, as they are not combo compatible [16]. The combo connector is an improved version of the type 2 connector with a fast-charging attachment. It also supports AC and DC charging up to 170 kW [23].

Tesla Supercharger: This technology is exclusively used in Tesla EVs. Thanks to this technology, the vehicle can be charged up to 80% within 30 minutes [24].

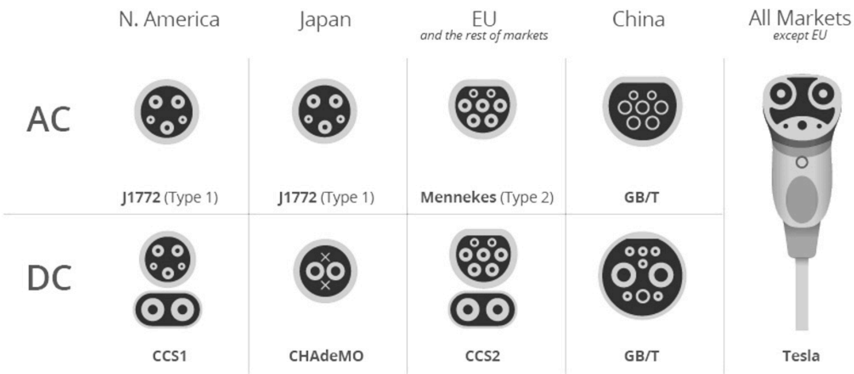

Figure 2. Connector types [22].

The large differences in the standards of charging stations and the types of sockets used reduce the accessibility of EV charging stations. Therefore, in parallel with the development of EV technology, the number of current socket types should be reduced to a single connector type [16].

4.2. Wireless charging technologies

Wireless charging includes a set of technologies used to charge electrical devices or vehicles without using a cable. Wireless charging technologies are supported by many electrical device and automobile manufacturers. These technologies provide the user with the advantage of getting rid of cable clutter and providing a more convenient charging experience. Capacitive Power Transfer (CPT) and Inductive Power Transfer (IPT) technologies are widely used. There are also Mixed Wireless Power Transfer (MWPT) and Magnetic Gear Wireless Power Transfer (MGWPT) technologies [25]. But CPT and IPT are detailed in this study.

CPT: Capacitive wireless charging is a technology that transfers energy using electrostatic capacity instead of electromagnetic induction. A capacitive coupling is created between the device and the capacitors on the charging plate. This system is a wireless charging method that transmits energy using the change of electric field between two capacitor plates. CPT transfers energy using the change of electrostatic capacitance. Energy transfer is achieved through capacitance changes between the capacitors in the charging tray and the capacitors in the vehicle. In this process, the electric field shows low loss. That's why they are suitable for charging EVs [26].

IPT: Inductive wireless charging is based on the principle of magnetic induction. A magnetic field is created between the device and the coils on the charging plate. Energy transfer occurs through the magnetic field. Thanks to the IPT magnetic induction principle, a magnetic connection is established between the coils on the charging tray and the coils in the vehicle to ensure energy transfer between magnetic fields. Inductive charging generally allows for high energy transfer rates because it transfers energy through magnetic fields. This provides faster charging times. That's why they are suitable for charging EVs [27].

Both technologies (CPT and IPT) enable wireless charging of EVs, but the preferred technology may vary depending on the situation in which it will be used and user needs. For example, CPT can be used in situations with low power needs or over shorter distances, while IPT may generally be the more common choice due to its advantages such as wide availability and high energy transfer rates [28].

Wireless charging technologies allow users to charge their EVs in a more comfortable and convenient way. However, energy transfer efficiency and speed can often be lower than wired charging systems. Therefore, it is currently used mostly in home and office environments and is still considered an area under development.

5. Method

In this article, a modeling study has been conducted in order to examine the charging mechanism and performance parameters of EV. The parameters of EV were calculated and found to be used in modeling. In order to apply these calculated values to the EV, an exemplary project runnable in the MATLAB/Simscape environment was utilized. This reference model encompasses the motor, generator, battery, drive system, transmission and other transmission components, providing a comprehensive representation of an EV [29]. In Figure 3, MATLAB/Simscape model is presented.

The performance parameters of an electric vehicle can be classified as Range, Charging Speed, Acceleration and Top Speed, Battery Capacity, Energy Efficiency, Suspension and Handling. In this study, Acceleration and Maximum Speed parameters will be initially examined. Subsequently, Range, Charging Speed, and Battery Capacity parameters will be scrutinized. The performance parameters will be analyzed by comparing them with the average data of an electric vehicle.

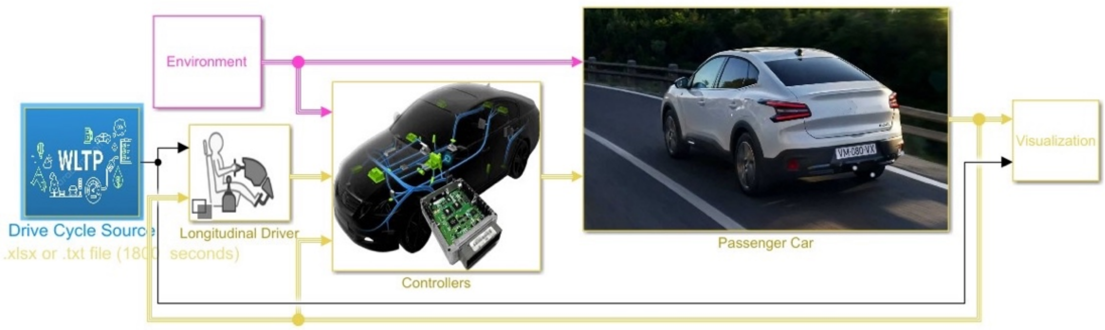

Figure 3. MATLAB/Simscape model.

Firstly, to examine the acceleration parameter, the time for the vehicle to reach a speed of 100 km/h will be considered. An average electric vehicle is expected to reach this speed in approximately 10 seconds. To achieve this speed within this time frame, the motor power should be 100 kW, and the torque should be 265 Nm. In the design process, an Internal Permanent-Magnet Synchronous Motor (IPMSM)with these values was selected. This chosen motor provides its maximum torque in the range of 0-3600 RPM. It can deliver its maximum power (100 kW) up to 10,000 RPM. Utilizing these characteristics, the maximum speed was found to be approximately 149 km/h from Equation 1 [30]. The power requirement at this speed is approximately 42 kW. With these motor values, the gradeability of the vehicle is a maximum of 37.6%, decreasing to 8.1% at the maximum speed. The power and torque of the electric motor are crucial for achieving the desired acceleration and gradeability of the vehicle. The motor power was calculated using Equation 2, and Equation 3 was used to analyze the acceleration parameter [30]. The parameters used in these calculations and the results are provided in Table 5.

According to these values, when creating the MATLAB/Simscape model, the energy consumption was found to be approximately 160 Wh/km in the WLTP (Worldwide Harmonized Light Vehicles Test Procedure) Class 3 cycle. To achieve an approximate range of 300 km, the battery capacity needs to be 50 kWh. For the design of a battery pack with these specifications, a total of 4,428 batteries were used, configured as 108 series and 41 parallel, as specified in Table 6. Additionally, the modeling was done with reference to CCS (Combined Charging System) technology because a vehicle with fast charging capabilities, capable of charging in approximately 30 minutes, is desired. The designed vehicle achieved a fast-charging power of approximately 100 kW. CCS is an appropriate standard for many EVs to utilize fast charging infrastructure. It is widely used in both Europe and North America, providing fast charging capabilities at various power levels.

While modeling the battery pack, the Lithium-ion NCA type battery coded NCR18650BD, which is currently on the market, was used as a reference. This battery, which finds its place in many application areas today, is widely preferred especially in EVs and power units [31]. Modeling has been carried out, taking into account the features of EVs that are commonly used and accessible across the world [32]. Table 5 and Table 6 shows the calculated values for the designed EV. The following equations (1) to (10) were used to obtain these values.

$$V_{max} = \frac{n_{max}.\pi.r}{30.i} \times \frac{1km}{1000m} \times \frac{3600s}{1h} \tag{1}$$

$$P_{mot} = \left[\left(\tfrac{1}{2}\rho A_f C_d v^2 + mgf_r \cos\alpha + mg\sin\alpha\right) \times v/\eta_{drv}\right] \tag{2}$$

$$t = \int \frac{m.1{,}03}{T_m \frac{i}{\eta_{drv}} - \left(mgf_r + \frac{1}{2}gC_d A_f v^2\right)} dV \tag{3}$$

The block uses these equations (4-10) to determine the combined voltage of the battery network [29]. Table 4 shows the variables that used in equations 4-10.

$$V_T = E_m - I_{batt}R_o - \sum_1^n V_n \tag{4}$$

$$V_n = \int_0^t \left[\frac{I_{batt}}{C_n} - \frac{V_n}{R_n C_n}\right] dt \tag{5}$$

$$SOC = \frac{-1}{C_{batt}} \int_0^t I_{batt} dt \tag{6}$$

$$I_{batt} = \frac{I_{in}}{N_p} \tag{7}$$

$$V_{out} = N_s V_T \tag{8}$$

$$P_{BattLoss} = {I_{batt}}^2 R_0 + \sum_1^n \frac{{V_n}^2}{R_n} \tag{9}$$

$$Ld_{Ah} = \int_0^t I_{batt} dt \tag{10}$$

Table 4. Variables used in equations 4-10 [29].

Variables	
SOC	State of Charge
E_m	Battery Open-Circuit Voltage
I_{batt}	Per Module Battery Current
I_{in}	Combined Current Flowing From the Battery Network
R_o	Series Resistance
N_p	Number Parallel Branches
N_s	Number of RC Pairs in Series
V_{out}, V_T	Combined Voltage of the Battery Network
V_n	Voltage for *n*-th RC Pair
R_n	Resistance for *n*-th RC Pair
C_n	Capacitance for *n*-th RC Pair
C_{batt}	Battery Capacity
$P_{BattLoss}$	Battery Network Power Loss

Table 5. Calculated values for the general parameters of designed EV.

Parameters	**Values**
Motor Power (P_{mot})	100 kW
Max. Torque (3600 RPM) (T_m)	265 Nm
Max. Power RPM (n_{max})	10000 RPM
Reduction Gear Ratio (i)	8
Max. Speed (V_{max})	~149 km/h
Mass (m)	1750 kg
Drag Coefficient (C_d)	0,27
Frontal Area (A_f)	2,464 m^2
Driveline Efficieny ($\boldsymbol{\eta_{drv}}$)	0,88
Tire Radius (r)	0,316 m
Rolling Friction (f_r)	0,01

Table 6. Calculated values for the battery packs of designed EV.

Parameters	**Values**
Per Module Battery Voltage	3,73 V
Per Module Battery Capacity	3037,3 mAh
Number of Cells in Series and Parallel (108 series x 41 parallel)	4428
Battery Voltage (25 °C, %60 SOC)	402,84 V
Battery Capacity (25 °C)	124,53 Ah
Battery Energy	~50 kWh
Continuous Discharge Current	125 A
Max. Discharge Current (5C - 10 sec)	625 A
Charge Current (Nominal 1C - Max. 2C)	125 A – 250 A

The individually calculated parameters for the designed vehicle were entered as data into the Workspaces in MATLAB/Simscape blocks. Both the accuracy of these calculated values was tested and the use of applications in the MATLAB/Simscape environment served as a reference for subsequent studies. Comments regarding the design are presented in the conclusion section.

6. Conclusion

EVs are considered the future choice of transportation due to their advantages over internal combustion engine vehicles. However, unresolved issues have prevented EVs from fully replacing traditional vehicles. In order for the existing distribution network to handle the EV charging load, it needs to be prepared using smart grid systems. Increasing the number of stations with fast-charging technologies is essential for both short and long-distance journeys to be easily achievable. Thus, the charging duration problem can be resolved. The abundance of diverse charging technologies diminishes the accessibility of charging stations. Therefore, charging technologies should be reduced to a single type. Additionally, it is crucial for EV charging stations to be powered exclusively by renewable energy sources to ensure the zero-emission nature of EVs. Significant investment costs are required to address these challenges.

When examining the studies related to EVs, it is observed that emphasis is placed on battery and charging technologies. This is because the most significant obstacles to the widespread adoption of EVs are associated with these parameters. Particularly, the unpreparedness of grid infrastructure for the charging load introduced by EVs makes this issue a crucial matter to address. If these problems, which are briefly mentioned in this study, are resolved, the obstacles to EV replacing traditional vehicles will be eliminated.

In this study, the values of the vehicles taken as reference were tried to be reached while designing an EV. These reference vehicles are readily accessible in the world and represent EV of average level. A vehicle with an average range of 300 kilometers and the ability to be charged in approximately 30 minutes using fast-charging technology has been designed. The Simscape model used incorporates the WLTP Class 3 driving cycle, where the kilometer-based consumption is approximately 160 Wh [32]. When the energy value of our vehicle's battery pack is compared to this value, it is observed that the designed vehicle has an approximate range of 300 kilometers. Additionally, considering the nominal charging current value, a fast-charging power value of approximately 100 kW is obtained. This value is suitable for fast charging and an EV with this capacity can be charged in approximately 30 minutes with the fast-charging option.

Simulation and modeling studies facilitate the design of all systems. This enables predictions to be made regarding the performance and status of EVs. Moreover, modeling studies are crucial in terms of cost and time. In this study, the parameters related to the designed vehicle and the existing projects in the MATLAB/Simscape environment can serve as references for future studies.

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