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# The Structure of Advanced Converters in Rechargeable Hybrid Electric Vehicles

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**Abstract**

The main goal of this article was to compare advanced converters in plug-in hybrid electric vehicles. In this article, there are two examples of integrated chargers, the first charger integrates two DC/DC converters and uses the obtained converter in the structure of the charger, and the second charger integrates two power converters and inverters. It introduces a second integrated charger. These two chargers were simulated using valid references and compared with each other and finally the results showed that the second structure is better in the car. The second structure reduced the volume, consumption, charging cost, and losses by reducing the power of electronic elements. This structure also had a better and higher capacity than the first structure. When it comes to getting the battery voltage to a high enough level to power the motor, the performance of the two structures was not much different, but in all other cases, the second structure performed better than its counterpart. Therefore, it is better and more economical to use this converter in rechargeable hybrid cars.

**Keywords:** Power Converters, Inverters, Rechargeable Hybrid Vehicles.

## 1. INTRODUCTION

The limitation and finite nature of some available resources, such as fossil fuels, inevitably lead us to the correct and optimal use of this national wealth. On the other hand, the air pollution crisis in recent years has gone beyond a local problem and has become a global problem. Air pollution can cause many problems (reduced visibility, destruction of landscapes, etc.) and various diseases, including respiratory and cardiovascular diseases. That is why it is important to try to reduce these problems [1].

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According to the available fossil energy consumption statistics, the transportation sector is one of the most important sectors that consume fossil fuels and, as a result, produce the resulting pollutants [2, 3]. This led researchers to use electricity instead of these types of fuels. Plug-in hybrid electric vehicles are basically hybrid gasoline-electric vehicles, which have a large battery and a wire to connect to the mains in order to charge [4]. The increase in battery size has increased the energy storage capacity, and as a result, plug-in hybrid electric vehicles can travel tens of miles, usually more than twenty miles, on electric power alone. Due to the increased battery energy storage capacity, the batteries are no longer charged using engine fuel, and vehicle braking is similar to standard hybrid vehicles. Therefore, cars must be plugged in to charge the battery system [5, 6].

Rechargeable hybrid electric vehicles have many advantages compared to old vehicles, some of which are:

- Most city driving can be done by these cars (for example, in America, the average daily driving is 40 miles [7].
- Significant savings in fuel consumption is one of the results of reducing the use of gasoline [8].
- Reducing primary energy consumption,
- Significant reduction in carbon dioxide emissions [9],
- Reducing dependence on foreign oil suppliers [10].

Some European Union countries have major plans for the use of hybrid and electric vehicles, as well as the technologies and infrastructure facilities required for these devices [11]. France, Germany, and Sweden are among these countries. International cooperation in the development of these technologies between suppliers of parts and car manufacturers has reached a significant level. Automobile manufacturers in the European Union have increased their cooperative activities in the field of research and development related to advanced technologies, which has been done in part in response to the activities of American companies under USCAR and programs such as PNGV [12]. In this regard, the European Union developed the European Council for Research and Development of the Automotive Industry (EUCAR), which is actually a consortium of 9 European car manufacturers, including the European Ford and Apple AG, which is a subsidiary of the German General Motors. The European Council for Research and Development of the Automotive Industry facilitates research projects based on cooperation (especially in the case of shrink batteries) and gives manufacturers a single strategy in matters related to research and development [13].

The continuous development of advanced batteries, especially lithium-ion technologies, has made the design of plug-in hybrid electric vehicles possible. To provide the power and energy needed to drive a vehicle using only electric energy, a heavy and large battery system must be installed in the vehicle. Lithium-ion technologies are much lighter than old metal and nickel hybrid electric battery systems [10].

Optimum use of the charging capacity of these cars has posed a great challenge to researchers. The car charging system is the essential part and the heart of these cars, and for this reason, researchers' research and reviews focus on this part. Regulation of consumption and its reduction is a very important issue that many articles have been published in recent years , this research is also in the same direction and based on the investigation of the car charger system to reduce consumption and actually minimize the internal losses of the car charging system using techniques special (in this article integration method) is established [14]. Today, maintaining the charge and reducing the consumption of cars has become a field for the competition of large automobile companies, and the integration technique, in addition to reducing consumption, which is the demand of consumers and manufacturers, also reduces the volume and production costs. Figure 1 shows the general system of a charger. The overall system has a rectifier and two DC/DC converters. The first converter is used to charge the battery and the second converter provides power to the motor by increasing the voltage [15].

Research related to rechargeable hybrid electric vehicles has a history of more than a decade, this research has been carried out in two general categories, including power electronics and systems; This research was related to electronic power converters in rechargeable hybrid electric vehicles, which this branch itself is divided into different parts. Charging systems have always been a problem for car manufacturers due to their high volume.

Today's charger systems are rapidly evolving and are now moving toward increased efficiency and have become the arena of competition for the world's automotive giants [16]. Currently, researchers are working on this sample of chargers to achieve an optimal charger by reducing the power electronic elements or reducing the number of converters and tools used. Innovation in this matter is very difficult and requires teamwork and a lot of time, however, in this research, we have achieved the results of prominent researchers and compared them [17]. In general, the purpose of this article is to review the charger system of rechargeable hybrid cars. Integration is one of the most important discussions in this case. The general purpose of this article is to review the types of integrated charger systems and choose the best ones through simulation and using the results of valid references [18].

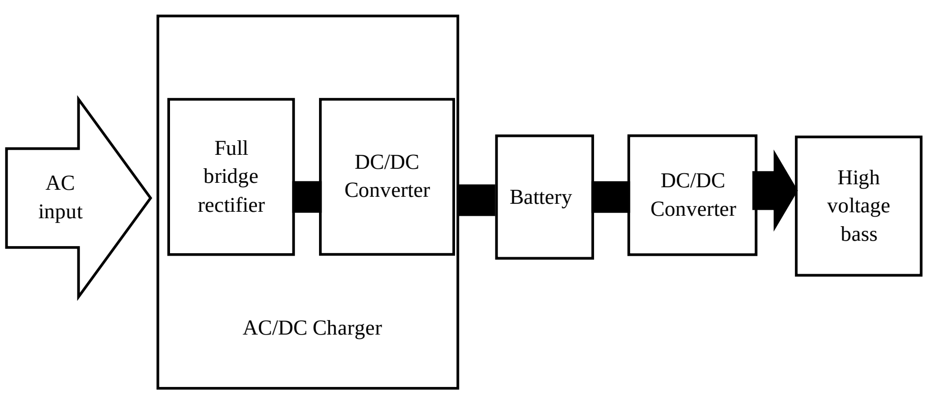


***Fig.1. Charger system for rechargeable hybrid electric vehicles [15].***

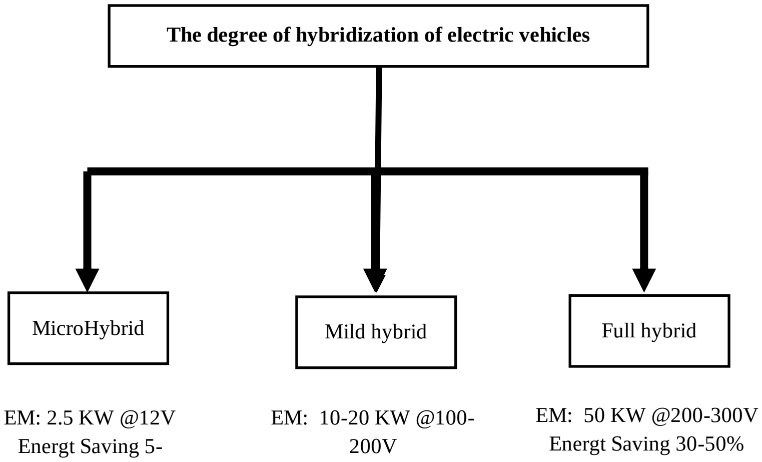


***Fig. 2. Division of three car samples based on the degree of hybridization [19].***

One of the biggest concerns of the world's people and statesmen was and is air pollution, which was partially eliminated with the invention of electric cars, but this invention created other concerns, such as the great challenge in power grids, the ability of batteries to maintain the charge, volume, and high cost. In order to solve these concerns, researchers always proposed new designs that, to solve the first challenge facing this science, increased its capacity by making the network smarter and introduced a new battery structure to solve the problem of maintaining the charge. The topic of this article is also based on reducing these concerns. This reduction of elements caused a reduction in internal losses as well as a reduction in volume, weight, and cost.

## 2. THE STRUCTURE OF ELECTRIC CARS WITH BATTERIES AND HYBRID ELECTRIC CARS

Hybrid cars have many divisions that will be mentioned below, an example of division can be seen in Figure 2, which is based on the degree of hybridization [19].

As the cars move towards electrification, new design methods of different topologies to optimize them based on criteria such as energy saving, types of energy sources, types of energy storage devices, hybridization rate, driving range, performance power, driver comfort, production cost, cost Ownership, etc. arise [20]. As the market has different demands in different regions of the world, it is natural that there are many battery electric vehicle and hybrid electric vehicle configurations, and these configurations are increasing. Car manufacturers are trying to create better car models that meet the needs of the market and at the same time maximize their income [21]. Hybrid cars are charged by the internal combustion engine, and during their movement, as long as the car has fuel and the internal combustion engine is turned on, it will never face a lack of charge, but battery-powered cars will not be able to move as soon as the battery is empty. Figure 3 shows one of the simplest structures for battery-electric vehicles. The energy stored in the battery (or in a battery pack) is used by a power converter using an electric motor drive [22].

The power converter unit may include a DC-DC converter and a drive motor. For maximum efficiency, the vehicle's kinetic energy must be converted into electrical energy by the motor/generator in the battery pack through a power converter, during downhill, or whenever the brake pedal is pressed, the resulting energy is converted into electrical energy and stored in the battery. Of course, the electronic details of the power converter (eg, structure, control strategy) are a function of the type of motor employed. If the battery cannot be charged with fast kinetic energy, a supercapacitor or a flywheel may be used to store energy temporarily (when the battery is charged with kinetic energy) [19].

## 3. TYPES OF INTEGRATED SYSTEMS

There are various types of integrated chargers in the industry, some of which are listed below. A: Combined motor drive and battery recharging system, B: Integrated battery charger for four-wheeled electric vehicles [18], C: Integrated charger for lift vehicles, D: Integrated two-way AC/DC and DC/ DC for rechargeable hybrid electric vehicles [22].

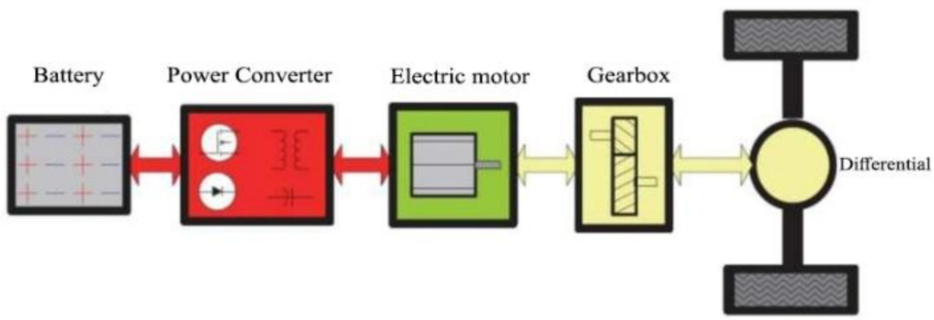


*Fig. 3. Electric vehicle with an engine battery [19].*

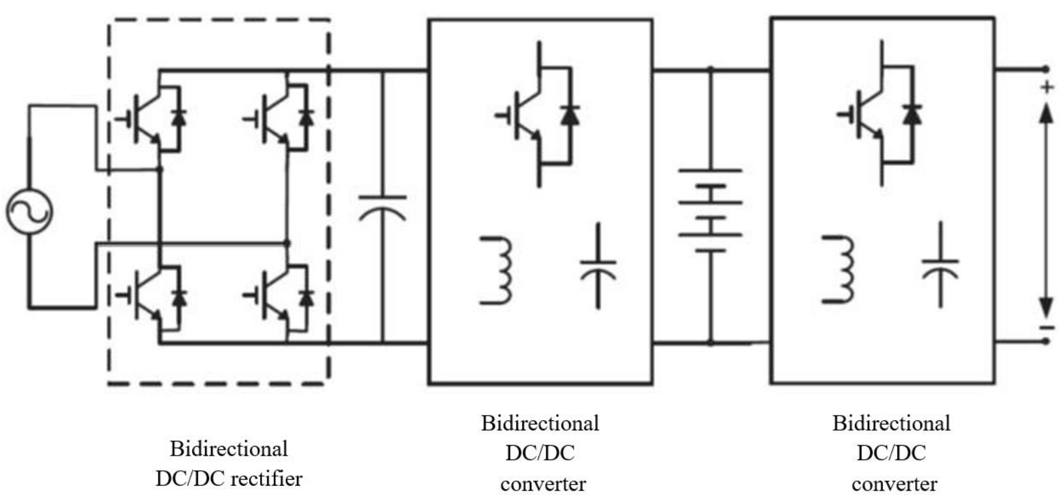


*Fig. 4. Charging method of rechargeable hybrid cars [18].*

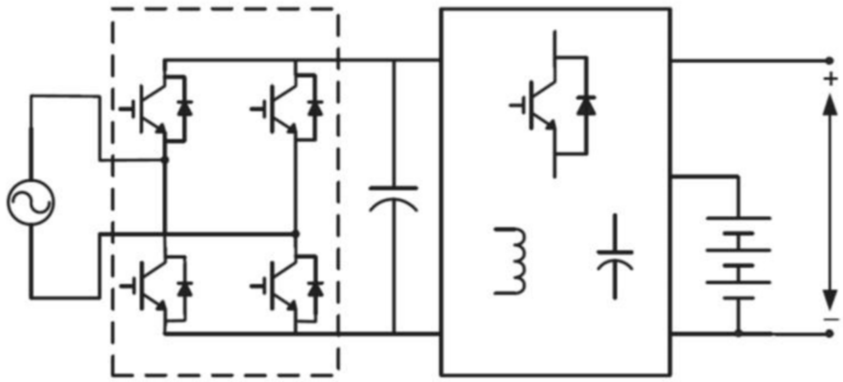


***Fig. 5. The structure of Lee et al. (2009) integrated charger [25].***

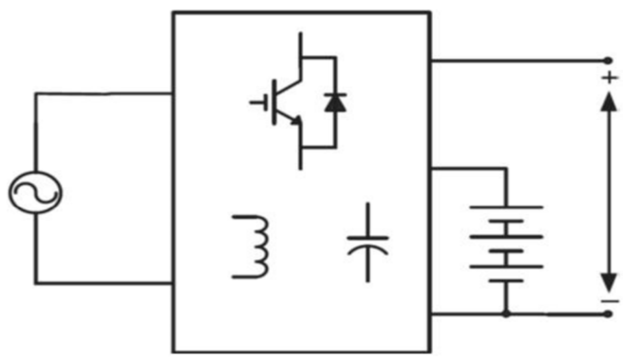


***Fig. 6. Another integrated converter proposed by Lee et al. (2009) [24].***

## 4. INTEGRATED TWO-WAY AC/DC AND DC/DC CONVERTERS FOR RECHARGEABLE HYBRID ELECTRIC VEHICLES

In this research, we focus on this example of integrated chargers, and our goal is to examine and compare two types of integrated chargers introduced by Lee et al., (2009) [24]. This example of integration by Lee et al (2009), was suggested in [24]. In this charger, high and low-voltage busses are connected to each other using a two-way DC/DC converter. Also, the DC/AC inverter is used to feed and control the AC drive system. Figure 4 shows the charging steps of a rechargeable hybrid car. Lee et al. (2009) proposed an integrated charger by combining two DC/DC converters and an AC/DC converter, which reduced the cost, the losses, and the volume of the charger system by eliminating additional electronic devices [24, 25].

By combining two DC/DC converters, the integrated charger proposed by Lee et al. (2009) (henceforth structure 1) was created. Figure 5 shows the structure of this charger.

Another proposed integrated charger system by this group can be seen in Figure 6 (hereafter Structure 2). This charger was obtained by combining two DC/DC converters and an AC/DC converter. This charge was called a single-stage integrated converter.

In the next section, we will examine and compare these two integrated converters (structures 1 and 2). These converters have 4 operation modes, we will examine these 4 modes in the next section. Finally, we will compare these two converters.

## 5. MODES OF OPERATION OF STRUCTURES 1 AND 2

This sample charger has 4 modes of operation:

- Mode 1 includes battery charging.
- Mode 2 is included in the same mode 1 in some references. This mode performs the charge return operation to the network G(2) V.
- Mode 3 increases the voltage from the battery to the high-voltage bus.
- Mode 4 is the battery recovery.

The internal circuit of the two structures shown in Figures 5 and 6 can be seen in Figures 7 and 8, respectively.

### 5.1. Mode 1 operation method in structures 1 and 2

In this case, as mentioned, the car is in charging mode. The charging path in this case and in structure 1 can be seen in Figure 9. In this case, 3 transistors (keys), a diode, and an inductor form the charging path. 1Q and 2Q in PWM switching mode and 3Q is still ON during operation. Input/output

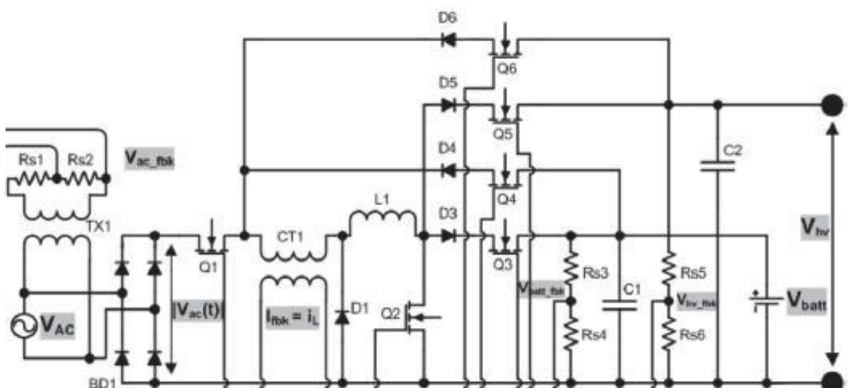


*Fig. 7. Internal circuit of structure 1 [25].*

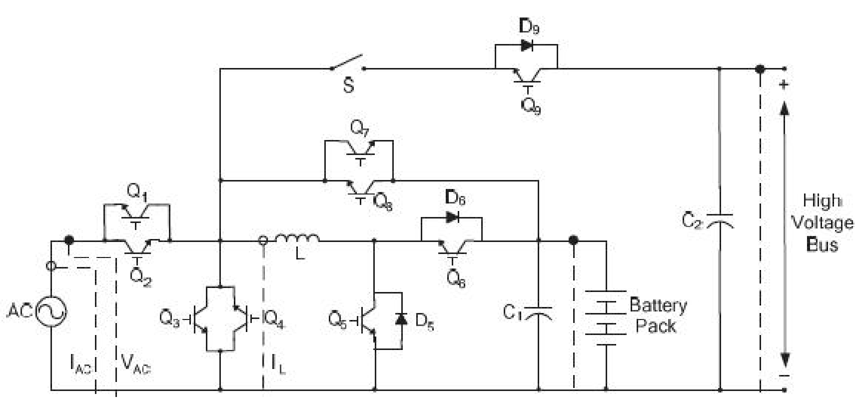


*Fig. 8. Internal circuit of structure 2 [18].*

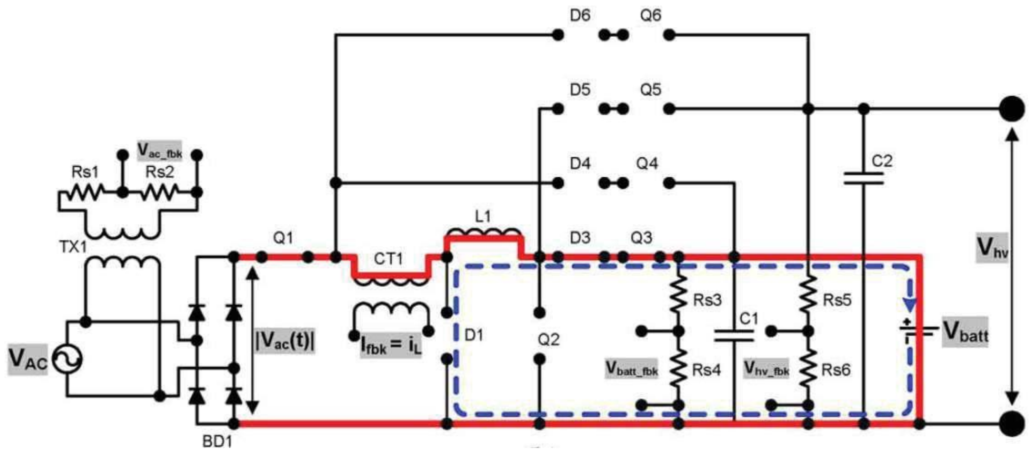


*Fig. 9. State 1 in structure 1 [9].*

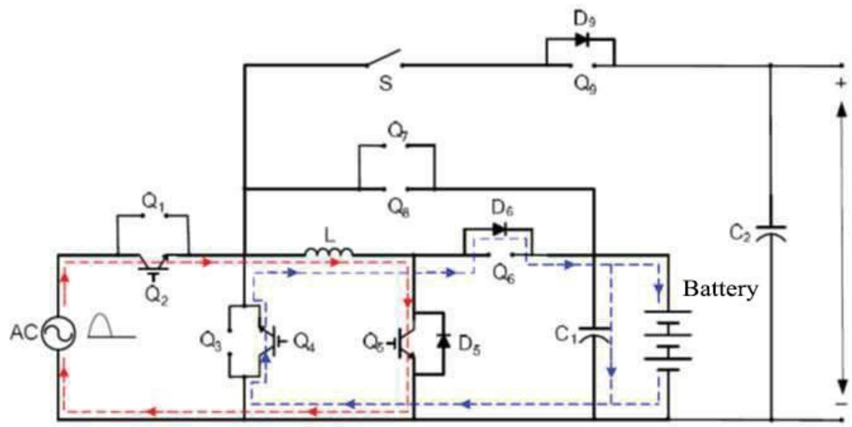


*Fig. 10. state 1 in structure 2 [9].*

and inductor current are obtained by measuring 1CT and 4RS, 3RS, 2RS, and 1RS. Diodes and other switches 6Q, 5Q, 4Q, 4, D, 5D, and 6D remain in the OFF state to disconnect the high voltage bus of hybrid electric vehicles from the battery and AC input.

In this case, the same number of diodes and switches form the charging path from structure 2. Figure 10 shows this path. 9Q, 8Q, 7Q, 6Q, 3Q, 1Q and S are off, 4Q is on, 2Q and 5Q are controlled by the same PWM signals.

In this case, both converters act as non-inverting buck-boost converters.

### 5.2. Mode 2 operation method in structures 1 and 2

This mode is actually the same as mode 1, but in the reverse direction, the number of keys and diodes does not change, and only the path changes a little. In fact, the use of this mode rarely happens because returning energy to the grid causes damage to the battery, and therefore the owners of these cars do not want to do this, of course, this is not the only problem and there are many challenges in this energy transfer.

### 5.3. Mode 3 operation method in structures 1 and 2

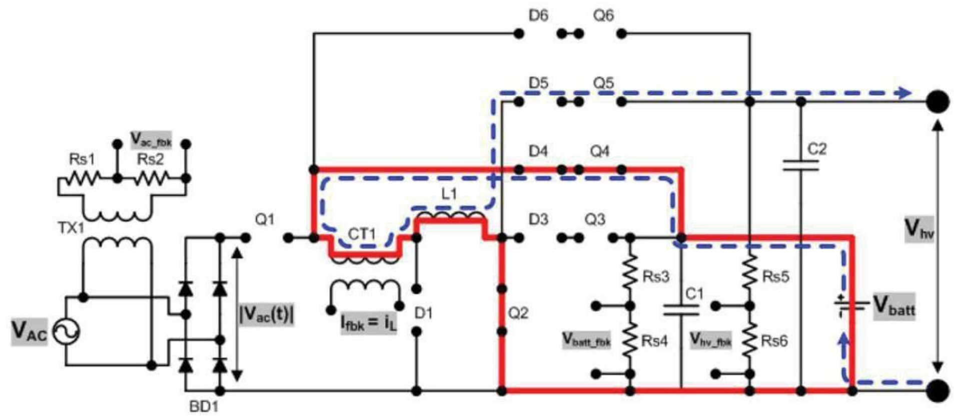


*Fig. 11. mode 3 in structure 1 [12].*

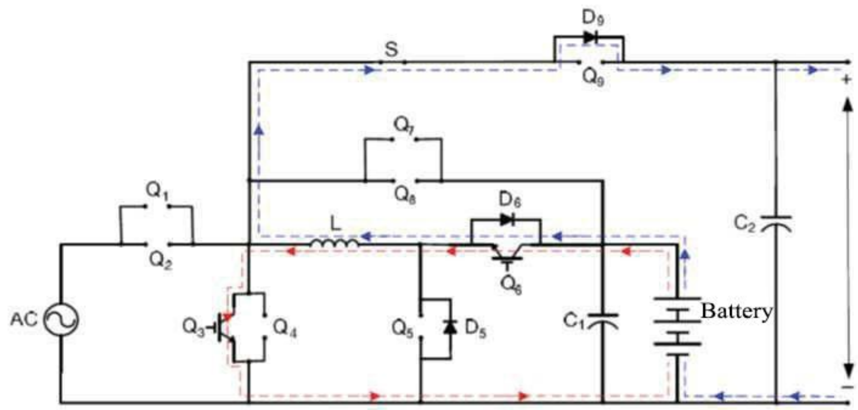


*Fig. 12. mode 3 in structure 2 [9].*

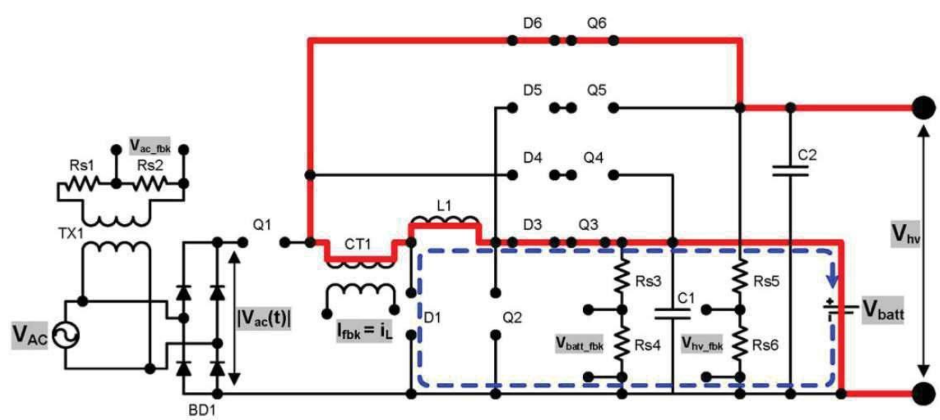


*Fig. 13. Function of structure 1 in mode 4 [18].*

In this case (in structure 1), battery voltage and high voltage bus voltage are the input and output voltage respectively. 2Q is in PWM switching mode, 4Q and 5Q are not in any mode, so the current path can appear between the battery and the high-voltage bus. Figure 11 shows this state.

Figure 12 shows mode 3 of the structure or converter 2. In this case, keys 8, 7, 5, 4, 3, 2, 1, and 9 are off, but keys 6 and S are on, and key 3 is controlled by the PWM signal.

This mode, which increases the battery voltage for the high-voltage bus, is known as the boost function [12].

### 5.4. Mode 4 operation method in structures 1 and 2

The work of the charger in this mode is to reduce the voltage of the high-voltage bus and return it to the battery [24]. 6Q works in PWM switching mode, 3Q remains on and 1D provides the stray path. Keys and diodes 4, D5, Q4, Q2, Q1Q and 5D are off. Figure 13 shows the performance of this charger in mode 4.

In structure 2, in this mode, the operation of 4Q and S keys are on, 9Q is controlled by the PWM signal, and the rest of the keys and diodes are off. Figure 14 clearly illustrates this issue.

From the comparison of the performance modes of these two structures, it appears that they are practically not much different from each other (although structure 1 has a slight advantage over structure 2 in some situations), but the main difference between these two chargers is the number of power electronics and the size reduction. Table 1 shows this fact.

### 5.5. output power in each mode of operation

Calculations for each mode by Verma et al. (2021) and Lee et al. (2009) have been done, the values for each performance mode are given in Table 2. Table 2 shows the power of two structures for each performance mode [25,23].

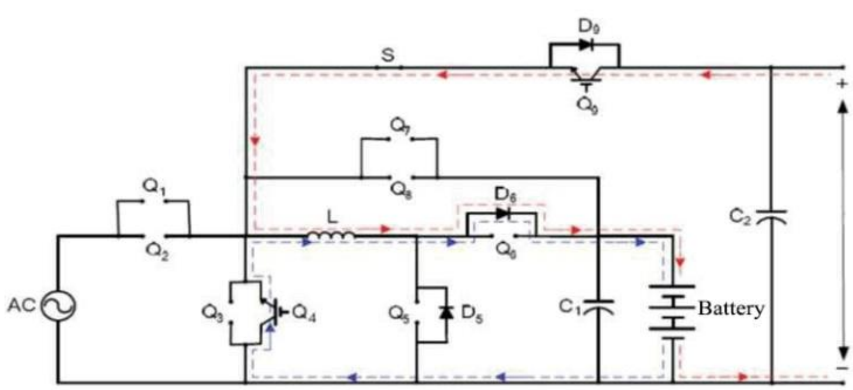


*Fig. 14. Function of structure 2 in state 4 [18].*

**Table 1.** ***The number of power electronic devices used in a normal charger and two integrated chargers.***

| Structure | Number of keys | Number of diodes | The number of Inductors |
|---|---|---|---|
| Normal charger | 11 | 11 | 2 |
| Integrated structure (1) | 10 | 9 | 1 |
| Integrated structure (2) | 9 | 2 | 1 |

**Table 2.** ***Output power of structures 1 and 2.***

| Structure Type | Modes of operation | Output Power |
|---|---|---|
| Structure (1) | 1 | 1/44 Kw |
| | 2 | 5 Kw |
| | 3 | 5 Kw |
| Structure (2) | 1 | 2/2 Kw |
| | 2 | 7 Kw |
| | 3 | 6 Kw |

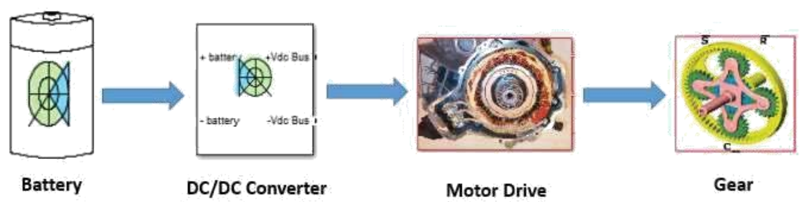


***Fig. 15. Structure model 1.***

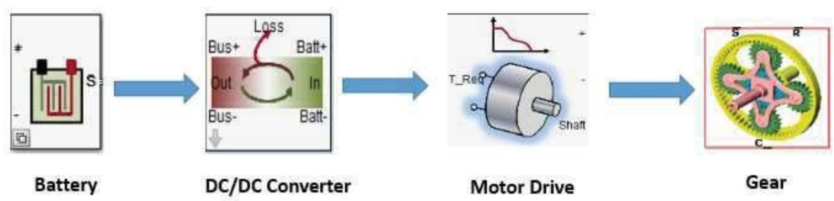


***Fig. 16. Structure model 2.***

By comparing the two structures and the values given in the table, it shows the superiority of structure 2 in producing output power. But the efficiency of two structures or chargers (according to the values given in two references) is equal to each other and something around 80 to 90 percent. Now we want to discuss the performance of two chargers according to the simulation results.

## 6. COMPARISON OF TWO STRUCTURES THROUGH SIMULATION RESULTS

The simulation in this part is done using MATLAB Simulink software. Two available chargers have been simulated and compared by this software.

By checking the current waveform and the output voltage, the DC voltage is the high voltage bus of the DC/DC converter. The figure simulated in MATLAB software (DC/DC converter part) can be seen in Figure 15 and Figure 16 for each of structures 1 and 2.

Figures 15 and 16 are only to show the difference in simulating the structure of the two chargers. Figures 17 and 18 are the output voltages of structures 1 and 2, respectively, and figures 19 and 20 show the output current of the two structures. Voltages are in volts and currents are in amperes, and the horizontal axis shows time in seconds in each figure. In this part of the simulations, two structures have been compared alone, so that the charged battery with a voltage of about 200 volts delivers its direct voltage to these converters, and then the current and voltage outputs have been compared separately. The voltage of the converters is around 500 volts. In fact, this part is the simulation of the electric part of the hybrid car.

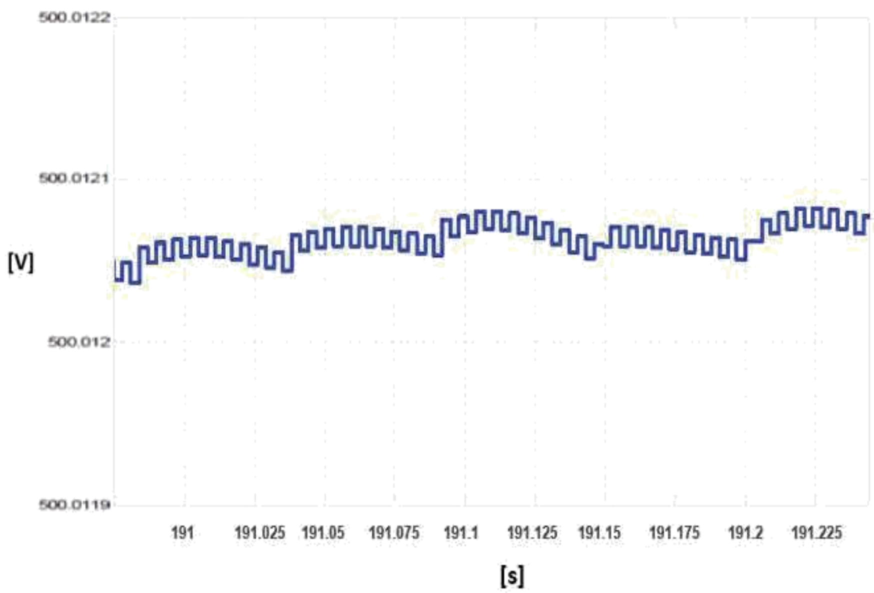


*Fig. 17. Output voltage of structure 1 in volts.*

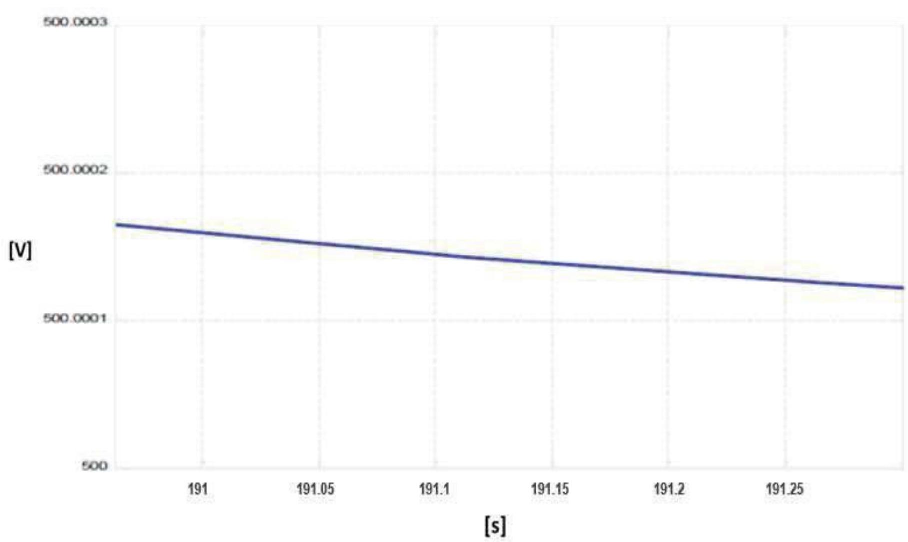


*Fig. 18. Output voltage of structure 2 in volts.*

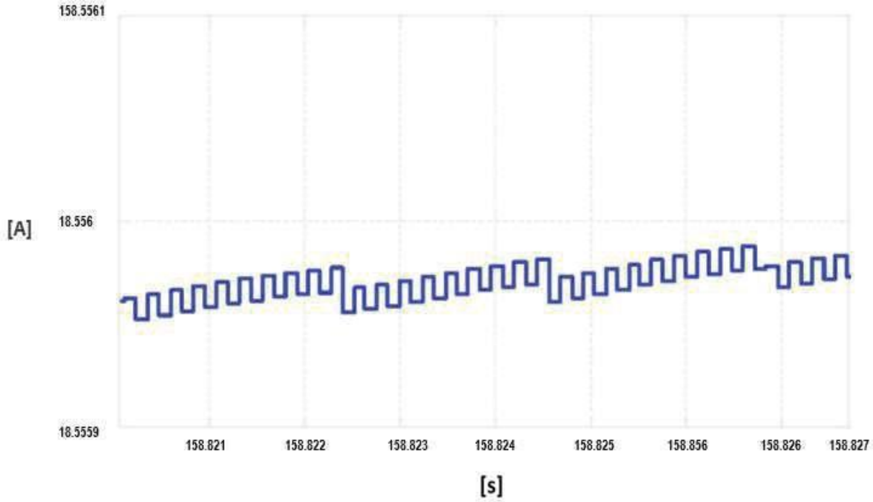


***Fig. 19. Output current of structure 1 in amperes.***

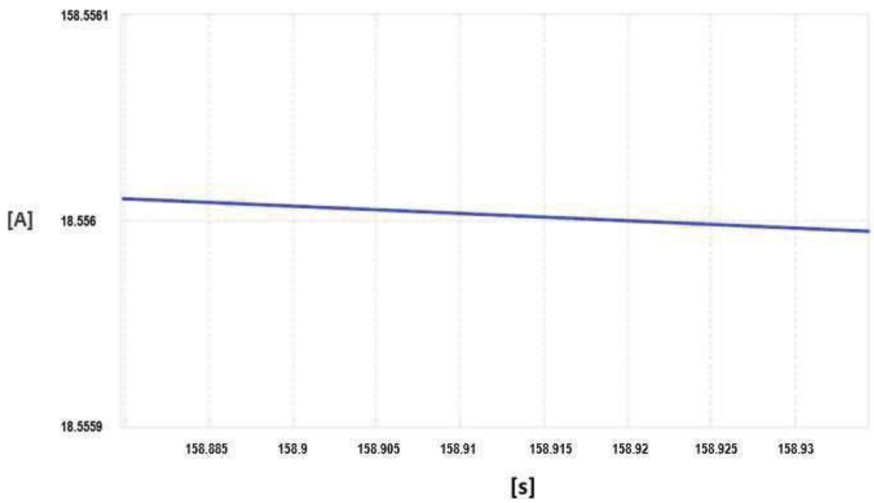


***Fig. 20. Output current of structure 2 in amperes.***

The output voltage in structure 1 has many jumps, but the output voltage in structure 2 is without any jumps, as seen in the figures of the last chapter, this voltage goes to the motor for consumption, which is why it is of great importance to us. It should be ready to transfer without any jump, which is done well in structure 2, so structure 2 has a good advantage over structure 1 from the point of view of output voltage.

Now let's check the output currents.

As shown in Figure 19, the output current of structure 1 is very bad and has a lot of fluctuation. This fluctuation is not present in Figure 20, which is related to Structure 2, so regarding the output current, Structure 2 is still superior to Structure 1.

The arguments of parts 1-3 and 3-2 and the simulations of part 3-3 prove the superiority of structure 2.

## 7. SIMULATION

In this section, we will use the two structures 1 and 2 that we compared in the previous section, in a rechargeable hybrid car and we will compare the results. The results have been obtained through simulation with MATLAB software.

### 7.1. Simulated Car Components

The simulated car has 5 parts:

A. The first part is the control part which has the battery controller, generator, and internal combustion engine.

B. The electrical part that includes the battery, DC/DC converter, engine, and synchronous generator,

C. This part includes the internal combustion engine,

D. The power transmission part that includes the gearbox,

E. Finally, the general characteristics of the car, including weight, type of tires, maximum load tolerance, etc.

Figure 21 shows the car designed in the software environment; the mentioned parts are identified by the number on the figure.

### 7.2. Description of Simulated Car Components

In this section, we will give a detailed description of the components of the simulated car.

- Control unit

This part of the rechargeable hybrid car, it is logically controlled by using conditional rules and using three variables (which are named as GEN-ENABLE, MOT-ENABLE, and ICE-ENABLE in this design) in each controller. Figure 22 shows the logical control unit.

This part is actually the brain of the car, as it was said, this part commands the two internal combustion engines and the electric motor when to turn on and enter the circuit, the other and very important task of this part is the control of power electronic converters (integrated converter here).

- Electric unit

According to our discussion, the most important part is this simulation. This part consists of a DC/DC converter, battery, motor, and synchronous generator. The specifications of the DC/DC converter were fully reviewed in the last chapter, but the specifications of the battery in this design can be seen in Table 3.

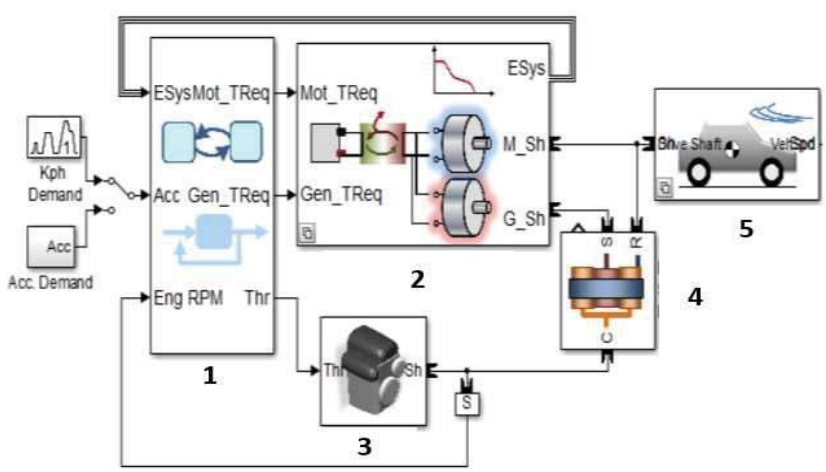


*Fig. 21. Simulated car components.*

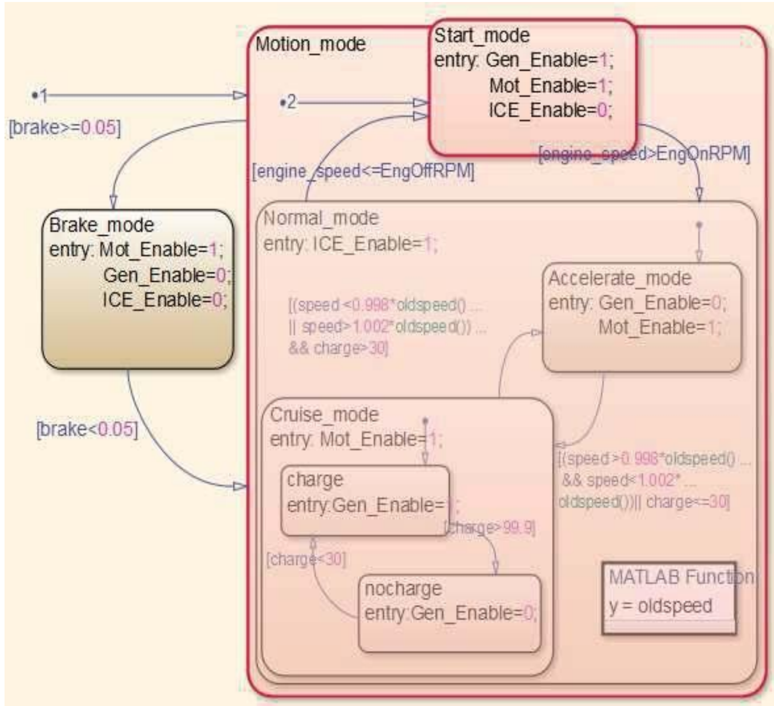


***Fig. 22. Logical control unit.***

**Table 3.** ***Battery parameters used in the simulation.***

| Battery Type | Lithium-ion |
|---|---|
| Maximum battery capacity | 8/7231 Ampere-hour |
| Voltage at full charge | 235/5932 V |
| Rated discharge current | 1/62 Ampere |
| Internal resistance | 0/24691 Ohms |
| Capacity at rated voltage | 7/7885 Ampere-hour |

-internal combustion engine

This engine works with fossil fuels. In hybrid electric cars that cannot connect to the network, this engine is responsible for charging the battery, but in rechargeable electric cars, these engines enter the circuit and charge the battery when the battery is empty, and when we do not have access to the power source. In this simulation, the power of this engine is considered between minimum and maximum [5700 to 5700]. The engine speed at maximum power is 5000 rpm, although the maximum engine speed is assumed to be 6000 rpm.

- Power transmission department

This section contains the gear wheel, the gear wheel used in this simulation is of the planetary type.

- Vehicle specifications

The weight of this car in this simulation is 1,325 kg and the tires have a load capacity of 3,500 newtons on the road.

### 7.3. Simulation Results

In this section, we compare the outputs of the simulated car. The simulation results can be compared in all 5 parts, but because this research is on integrated converters, we only compare the outputs of this part.

Figure 24 shows the percentage of battery charge maintenance in the appropriate range (%SOC) in two structures 1. As the name suggests, this percentage is a measure to measure whether the battery charge is within the appropriate limits or not. Figure 25 shows this criterion for structure 2.

As seen in Figure 24, the battery charge retention percentage fluctuates within a reasonable range in structure 1, but this measure is much better for structure 2 (Figure 25), this measure shows the better performance of structure 2, although the two structures They try to keep this criterion in a reasonable range (nearly 100 here), but structure 2 has better performance.

The task of converters in rechargeable hybrid cars is to deliver the battery voltage to the high-voltage bus and then to the engine to make the car move. In this simulation, the battery voltage is considered to be about 200 volts. The converter in this simulation increases the voltage level to 500 volts for the engine. Figures 26 and 27 show the battery voltage and the high voltage bus of the converter for structure 1, respectively.

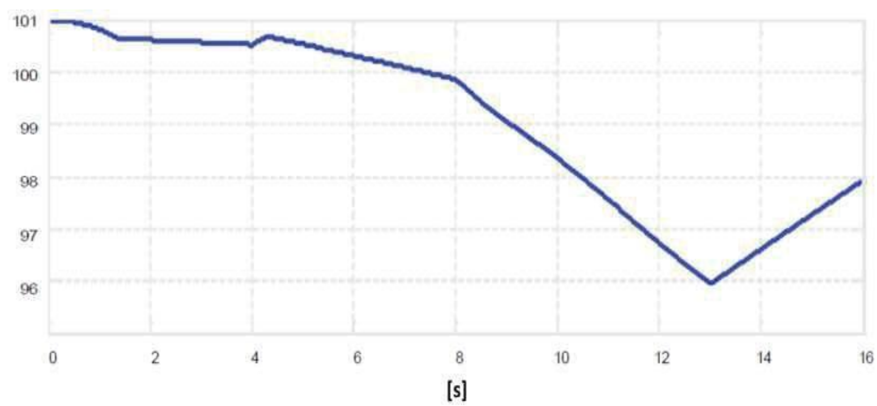


***Fig. 23. Battery charge maintenance percentage in the appropriate range (%SOC) for structure 1.***

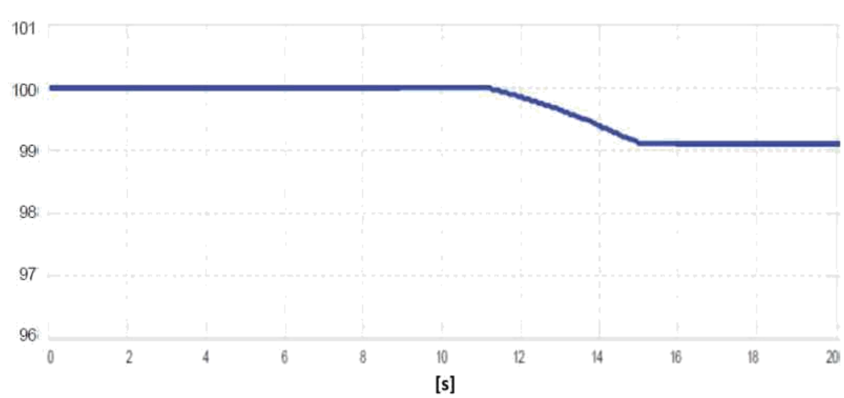


***Fig. 24. Percentage of maintaining the battery charge in the appropriate range (%SOC) for structure 2.***

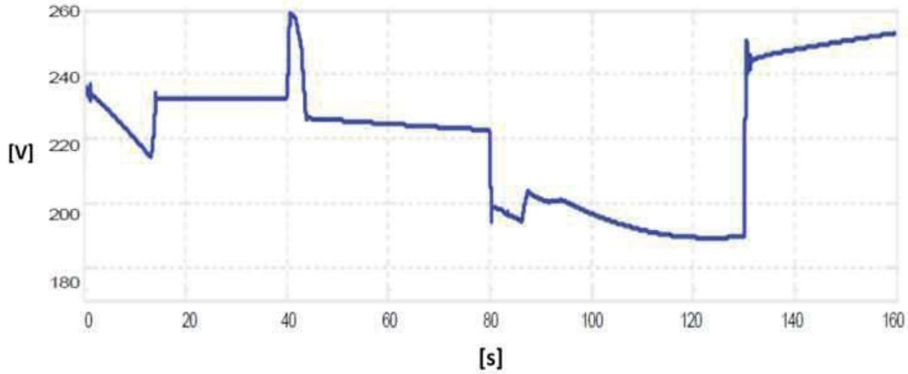


***Fig. 25. Battery voltage in structure 1 in volts.***

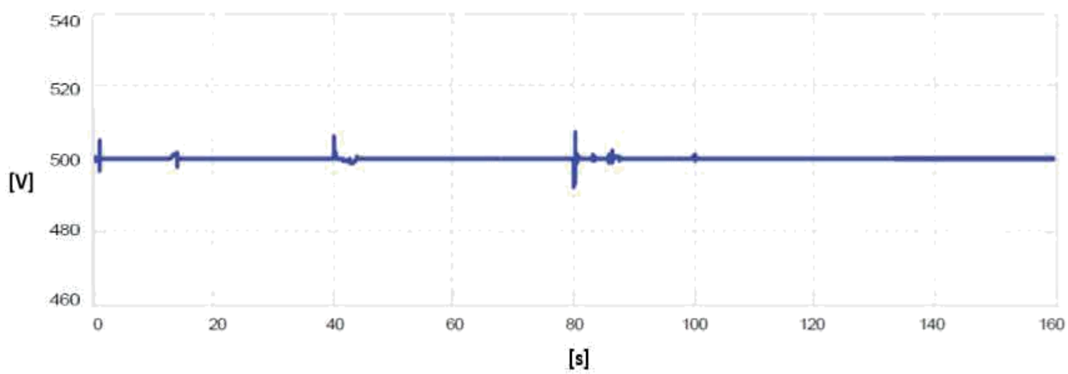


***Fig. 26. DC bus voltage in structure 1 in volts.***

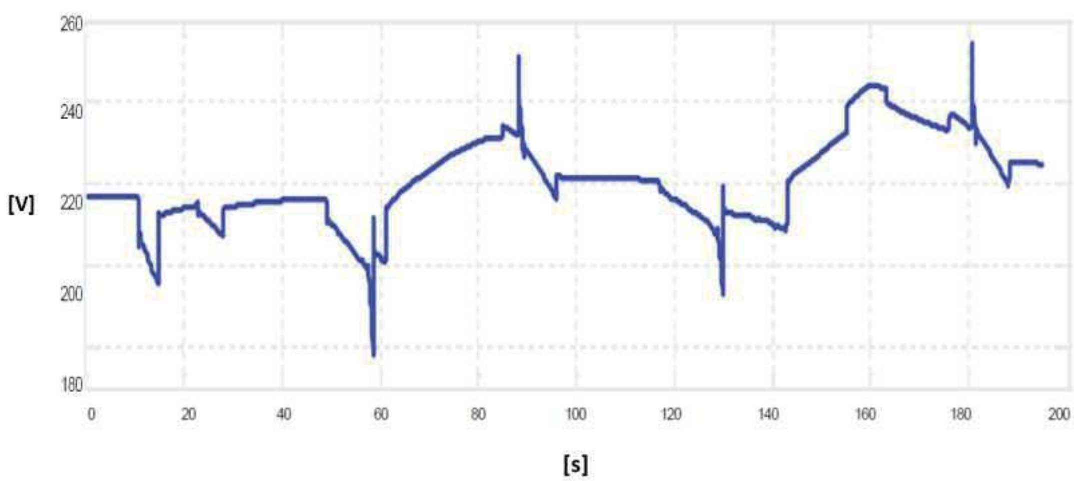


***Fig. 27. Battery voltage in structure 2 in volts.***

As we can see, the battery voltage has high distortion, but the DC bus voltage is a good waveform, although there is a jump at some points, which is caused by a large jump in the battery voltage.

Figures 27 and 28 also show the battery voltage and the high voltage bus of the converter for structure 2, respectively.

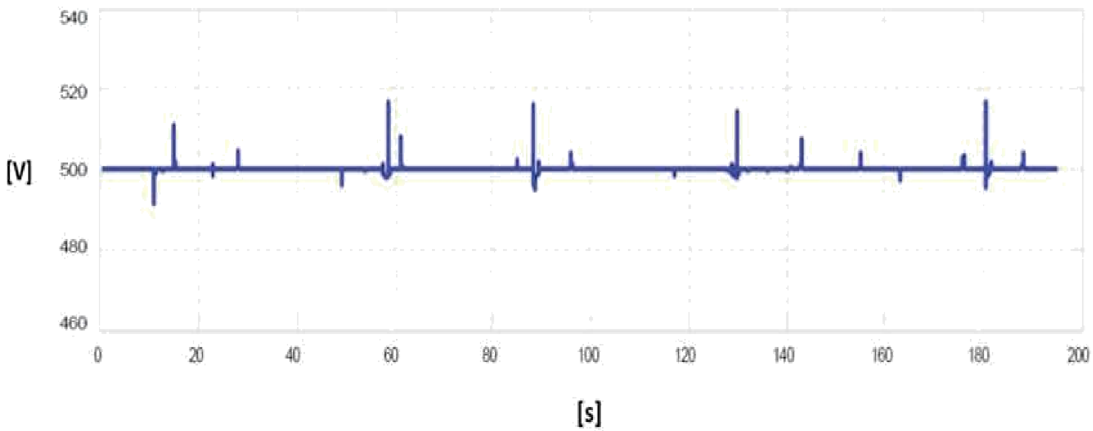


***Fig. 28. DC bus voltage in structure 2 in volts.***

Structure 2 also has a good response to battery voltage fluctuations, but in this part, structure 1 performs better, so in this comparison, the two structures perform well and are not superior to each other in this respect.

## 8. CONCLUSION

According to the results of the simulation, structure 2 is better in the car, as seen in the findings of the article, structure 2 reducing power electronic elements caused a reduction in volume, consumption, charger cost, and losses. This structure also had a better and higher capacity than structure 1.

In this article, both structures were used in a rechargeable hybrid car, the simulation results also acknowledge the superiority of structure 2, although the performance of the two structures did not differ much in terms of bringing the battery voltage to a high-level voltage for engine consumption, but in the rest structure 2 has a better performance than its counterpart. Therefore, it is better and more economical to use this converter in rechargeable hybrid cars.

This research was based on the two plans proposed by Lee et. al. (2009) and his colleagues, including Khaliq, and with scientific reasons, simulation, and help from reliable scientific authorities, one of the two plans that had better results was selected, using Simulink MATLAB vehicle using Two structures were simulated and the results were analyzed. The charger or the structure reduces the weight, volume, consumption, and cost in the car, the car manufacturers are always looking for the same results in the industry.

This research was to reduce this volume and, of course, reduce cost and consumption through integration, but a lot of research can be done on other parts as well, such as:

1. Integrated charger design by reducing additional power electronic elements,
2. The use of larger batteries as well as supercapacitors for chargers or a newer technology than today's lithium-ion technology can reduce the size of the battery and increase its capacity.
3. The integrated structure has other types and types that can be used in

research to achieve a better and optimal charger from these types of chargers and other integration types.

4. The source of energy used for cars is alternating current, it is possible to design chargers in charging stations with the direction of reducing power elements and alternating to direct converters inside the cars, which have the ability of this conversion to work in this direction and achieve the stated goals. In this research, it is a great help and a big step.

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