Journal of
Renewable Energy Research and Applications (RERA)

Published online

Reliability Modeling of Different Types of Electric Vehicles in Renewable Applications

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Received Date 01 March 2022; Revised Date 30 March 2022; Accepted Date 19 April 2022
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Abstract

The widespread growth of electric vehicles in distribution networks could be a variety of challenges and opportunities for the electricity network. This issue is important since the owners of electric vehicles are trying to maximize their profits, which, in turn, can cause many problems such as increased losses, congestion, and increase network costs. in distribution networks. Therefore, it is required to study different aspects of this new technology such as the reliability and the failure rate. For this purpose, the presented paper introduces a reliability model based on the Markov theory for different types of electric vehicles, and the main novelty is to determine the impact of the failure rate of the composed components of each electric vehicle on the overall failure of the vehicle. In the proposed reliability models for these electric vehicles, the failure of the main composed components is considered. In order to compare different types of electric vehicles from the reliability viewpoint, the numerical results associated with the reliability evaluation of these vehicles are given. It is deduced from the numerical results associated with the reliability evaluation of different types of electric vehicles, and the reliability of the compound plug-in hybrid electric vehicle is more than the other technologies.

Keywords: *Electric vehicle, failure rate assessment, reliability modeling, Markov model.*

1. Introduction

The problems arising from fossil fuels such as pollution of the environment, greenhouse gas emission, change of the climate, and global warming result in the development of electric vehicles. Replacement of automobiles based on the internal combustion engine by electric vehicles can reduce the environmental impacts of fossil fuels. So far, three types of electric vehicles including hybrid electric vehicles, plug-in hybrid electric vehicles and all-electric vehicles have been developed in the transportation system. In the hybrid and plug-in hybrid electric vehicles, the movement of the vehicle is done by the internal combustion engine and the electric motor. However, in the all-electric vehicles, the internal combustion engine is removed, and the vehicle is moved only by the electric motor [1]. In order to reduce the use of fossil fuels, the conventional power plants and the fossil fuel-based automobiles are replaced by renewable energy-based power plants and electric vehicles, respectively. In the countries with thriving economies, the electricity distribution networks play a very important role in supplying important and industrial electrical loads. It has changed, like scattered manufacturing technology and electric vehicles. Considering these two important events in the distribution networks can create various challenges and opportunities for the electricity network. Various studies have shown that the distribution networks will be severely damaged by the high intrusion of electric vehicles that are uncoordinatedly charged and discharged. These effects can include maximum load increase, loss, voltage drop, and system load factor change [2, 3].

So far, three types of electric vehicles including the hybrid electric vehicle, plug-in hybrid electric vehicles, and all-electric vehicles have been developed in the transportation system. In the hybrid electric vehicles, the internal combustion engine is used from the fossil fuels to drive the vehicle. In addition to the internal combustion engine, an electric motor supplied by a battery can be used for driving the hybrid electric vehicle. This battery can be charged by the electric power generation by the movement of the vehicle, and cannot be connected to the electric grid. In the plug-in electric vehicle, similar to the hybrid vehicle, the movement of the vehicle is done by both the internal combustion engine and the electric motor. However, in the plug-in electric vehicle, the battery can be connected to the power grid using the charging stations. In the all-electric vehicle, only the electric motor supplied by the battery is used to move the vehicle. The battery of the all-electric vehicle, similar to the plug-in electric vehicle, can be connected to the power grid through the charging stations [4, 5].

Numerous literatures have been published on the reliability of the electric and hybrid vehicles, some of the most important of which have been analyzed and evaluated below. Then the research gaps have also been discussed for each paper. In the last paragraph of this section, the proposed solution to check and study the reliability of these categories of vehicles will be presented. With the growth of the electric vehicles in the transportation system, different aspects of these vehicles such as reliability must be studied. For this purpose, in the past studies, the reliability evaluation of electric vehicles has been performed. In [4], the reliability assessment of a hybrid power system, including the generation and transmission parts, containing two types of electric vehicles has been performed. Among the electric vehicles, the plug-in hybrid and all-electric vehicles can be connected to the power grid, and affect the reliability of the power system. For this purpose, the probabilistic models of the plug-in hybrid electric vehicles, the full-electric vehicles, and the system load are used to calculate the loss of load probability index of the hybrid power system including the electric vehicles. It is deduced from the paper that the electric vehicles equipped with the vehicle to grid technology can improve the reliability of the hybrid power systems. Paper [5] studies the impact of the electric vehicles on the reliability performance of the power systems containing wind generation units. In this paper, the impact of the electric vehicles equipped with the vehicle to grid technology on the reliability indices of the power system including loss of load probability and expected energy not supplied indices are evaluated. Besides, the impact of the random charging state and the charge-discharge control strategy based on the particle swarm optimization method on the results is investigated. In [6-10], the reliability evaluation of the distribution network containing the electric vehicle is performed. The model presented in [6] studies the reliability of the distribution system taking into account the impact of the quasi-dynamic traffic flow and vehicle to grid technology of the electric vehicles. For this purpose, the Monte Carlo approach has been used to simulate the reliability performance of the modified IEEE-RBTS test system with six buses containing the electric vehicles. In [7], the reliability of the distribution network affected by the electric vehicle charging stations has been investigated. For this purpose, the impact of the electric vehicle charging stations on the IEEE 33-bus test system has been investigated, and the reliability indices including the system average interruption frequency, system average interruption duration, customer average interruption duration, average interruption time, and average energy not supplied are calculated. In [8], the impact of the charging and discharging loads associated with the electric vehicles on the reliability, economical efficiency, and environment and energy intermittency of the distribution system has been studied. For this purpose, five modes including the plug-in electric vehicle without logic control mode, unidirectional timed charging mode, plug-in electric vehicle with logic control regulated charging mode, plug-in electric vehicle without logic control regulated charge/discharge, and batteries to grid charging mode are taken into account. Paper [9] studies the impact of the penetrations of the aggregated plug-in electric vehicles in the charging stations on the reliability performance of the distribution system. The optimal power flow based on the backward-forward sweep method is used to calculate the current of each branch of the radial distribution network. In [10], the impact of the electric vehicles equipped with the vehicle to grid technology on the reliability of the distribution network has been analyzed. For this purpose, the reliability indices of the distribution system are calculated before and after the integration of electric vehicles. Based on the proposed method, the electric vehicles can be used to supply the power back to the grid in emergency conditions such as failures or outages. The model presented in [11] proposes the proper configurations to supply the electric vehicles based on the DC or AC microgrid using the optimal sizing procedure and system reliability evaluation. For this purpose, the Markov process, the block diagrams, and the supply priority approaches are suggested. In [12], the reliability performance of different structures of electric vehicles has been developed and compared. In this paper, the reliability models of different structures of electric vehicles including single-engine pure electric vehicle, pure electric vehicle with two or four engines, series hybrid electric vehicle, parallel hybrid electric vehicle, and combined hybrid electric vehicle have been developed. Paper [13] proposes a method based on the fault tree diagram to analyze the reliability, availability, and maintainability of the plug-in electric vehicle. Besides, the impact of the charging stations on the availability of plug-in electric vehicles has been studied. In [14], the reliability assessment of the main composed components of the electric vehicles including the lead acid battery, motor controller, and electric motor has been performed. This paper uses the simulation model of the understudied electric vehicle using the MATLAB-SIMULINK software to consider the variation of the driving cycle, thermal stress, thermal cycling, and fault analysis in the proposed reliability studies. Paper [15] evaluates the reliability performance of different charging systems including non-isolated low power systems, high-frequency isolated inductive systems, unidirectional chargers, and multi-phase interleaved charger used in the electric vehicles. For this purpose, the major influence factors affect the failure rate of the composed components of these chargers including temperature, rated voltage, power dissipation, and current are taken into account. In [16], the reliability modeling of the electric motors as the main component of electric vehicles has been performed using the fault tree and extended stochastic Petri nets. In the proposed reliability model of the electric motor, the impact of the failure of its main components including the stator core, the stator winding, the rotor core, the rotor winding, the bearing, the shaft, and the bond on the overall failure of the motor is considered. The model presented in [17] proposes a new technique to study the reliability performance of the integrated system containing the transportation system and the electrical power network considering the role of electric vehicles. For this purpose, a bidirectional charging control strategy for electric vehicles is suggested to model the interaction between the transportation system and the electrical power network. Paper [18] studies the reliability of the batteries used in the electric vehicles. In this paper, the failure types of the lead acid batteries including grid corrosion, grid growth, discharge of negative plate, dry-out, and sulfation are studied. Besides, the testing method, the life prediction technique, and the approaches for reliability improvement of these batteries including thermal protection, state of charge and state of health monitoring, cell equalization, and tolerance setting are discussed in the paper.

It is deduced from the reviewed papers that a comprehensive reliability model is not developed for all types of electric vehicles that considers failure of the composed components. Reliability is an important factor that can be used to compare different types of electric vehicles to select a suitable choice. Besides, the failure rate of different composed components is dependent on the speed of vehicle that is not studied in the last researches. In order to fill these research gaps, the present paper develops a comprehensive reliability model based on the Markov theory for all types of electric vehicles considering the impact of vehicle speed on the component failure rates.

Due to the growing application of the electric vehicles in the transportation system, the reliability evaluation of different types of them is necessary. For this purpose, the current paper develops a reliability model for different types of electric vehicles based on the Markov theory.

Thus the contributions and novelties of this paper would be as:

- Develop a comprehensive reliability model based on the Markov theory for all types of electric vehicles including the hybrid electric vehicle, the plug-in hybrid electric vehicle, and the all-electric vehicle considering the failure of the composed components.
- Determine the impact of the failure of the composed components of the electric vehicle on the overall failure of the vehicle.
- Compare different types of electric vehicles from the reliability viewpoint.
- Determine the impact of vehicle speed on the failure rate of the composed components of electric vehicles.

Based on the aim of the paper, it is organized as what follows. In the 2nd Section, the structure of different types of electric vehicles is studied. Section 3 is devoted to the reliability modeling of these electric vehicles. In Section 4, the impact of the variable speed of the vehicle on the failure rate of the composed components of the electric vehicles is investigated. The numerical results are given in Section 5 to compare different types of electric vehicles from the reliability viewpoint. The last section is devoted to the conclusion of the paper.

2. Structure of different types of electric vehicles

In this work, three kinds of electric vehicles including the hybrid electric vehicle, the plug-in hybrid electric vehicle, and the all-electric vehicles are studied. In order to determine the reliability model of these vehicles, the structure and their composed components must be analyzed. In this section, the structure and the main composed components of these electric vehicles are introduced.

2.1. Hybrid electric vehicles

This type of electric vehicles is driven by a combination of the internal combustion engine and the electric motor [19]. The fossil fuels are used in the internal combustion engine in order to create the power required for driving the vehicle. This power is created by the combustion and expansion of the fossil fuels in the combustion chamber. In addition to the internal combustion engine, the vehicle can be driven by the electric motor. The power required for the electric motor is provided by the batteries or the generators. The batteries of the hybrid electric vehicle cannot be connected to the external electric grid, and thus in order to charge the batteries and generate the electricity required for driving the electric motor, the rotation of the vehicle by the internal combustion engine is required. The other main components of the electric vehicles are the chassis, the body, the control system such as brakes, and the transmission system including clutch, gearbox, differential, axle, and wheels. Based on the different combination of the electric motor and the internal combustion engine, three types of the hybrid electric vehicles including the series hybrid electric vehicle, parallel hybrid electric vehicle, and compound hybrid electric vehicle can be developed. The configuration of a series hybrid electric vehicle is presented in figure 1 [19]. As it can be seen in the figure, the fossil fuel enters the internal combustion engine. By the combustion and the expansion of the fossil fuel, the mechanical power is generated. A generator is used to convert the mechanical energy into the electrical energy. The generated electricity can be used for charging the battery or driving the electric motor by an electric converter. Different types of the power electronic converters such as the DC/DC and DC/AC converters, and also different kinds of the electric motors such as brushed DC motor, brushless DC motor, switched reluctance motor, axial flux ironless permanent magnet motor, and permanent synchronous motor can be used in the electric vehicles [19]. The mechanical power produced by the electric motor can move the wheels through the gearbox. The internal combustion system is composed of the fuel tank, fuel system, combustion engine, cooling system, exhaust system, and lubrication system. The configuration of a parallel hybrid electric vehicle is presented in figure 2 [16].

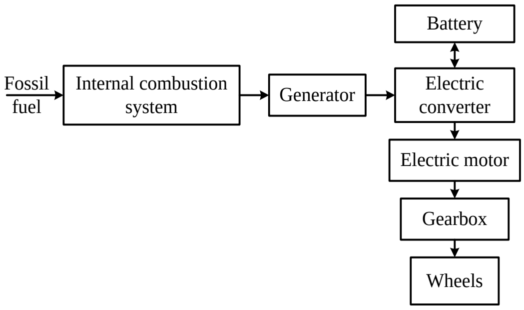

Figure 1. Structure of a series hybrid electric vehicle.

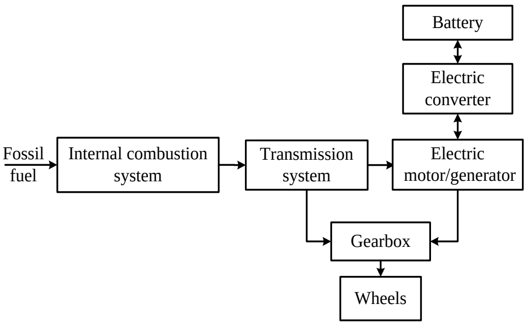

Figure 2. Structure of a parallel hybrid electric vehicle.

As it can be seen in the figures, in the series hybrid electric vehicle, the internal combustion engine is connected in series with the electric part of the motor. Thus in order to drive the vehicle, both parts must be perfect. However, in the parallel hybrid electric vehicle, the internal combustion engine and the electric part are connected in parallel. Thus in order to drive the vehicle, each part, i.e. the internal combustion system or the electric part, can be implemented. Similar to the series hybrid electric vehicle, in the parallel hybrid electric vehicle, the battery can be charged only through the generated power of the internal combustion engine. The configuration of the compound hybrid electric vehicle is presented in figure 3 [19]. As it can be seen in the figure, the compound hybrid electric vehicle is a combination of the series and parallel hybrid electric vehicle.

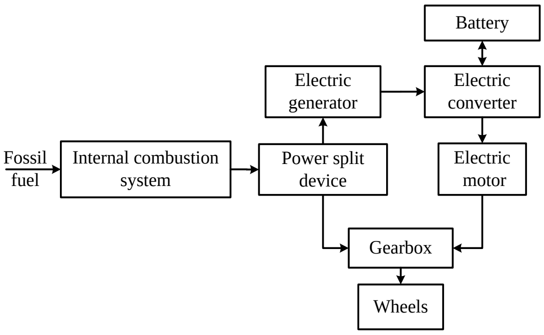

Figure 3. Structure of a compound hybrid electric vehicle.

2.2. Plug-in hybrid electric vehicle

In the plug-in hybrid electric vehicle, the battery can be connected to the electric grid using the charging stations. Thus in order to charge the battery of the vehicle, both the generated power by the internal combustion engine and the external grid can be used. Based on the different connections between the internal combustion engine and the electric part of the vehicle, three kinds of the plug-in hybrid vehicle including series, parallel, and compound plug-in hybrid electric vehicles can be developed. The structure of a series plug-in hybrid electric vehicle is presented in figure 4 [20].

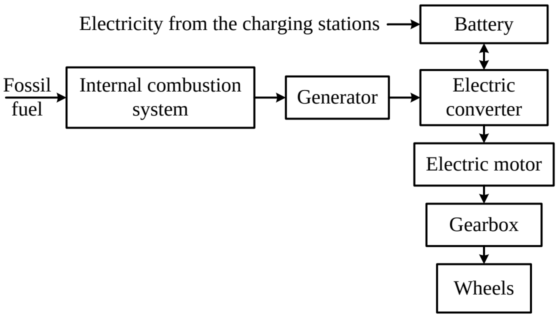

Figure 4. Structure of a series plug-in hybrid electric vehicle.

As it can be seen in the figure, the configuration of the series plug-in hybrid electric vehicle is approximately similar to the series hybrid electric vehicle. The only difference is the additional input of the vehicle, i.e. the electricity that can be used for charging the batteries through the charging stations. The structure of the parallel plug-in hybrid electric vehicle is presented in figure 5 [20]. As it can be seen in the figure, both the internal combustion engine and the electric motor can separately drive the vehicle. However, in the parallel plug-in hybrid electric vehicle, the battery can be charged only by the external electric grid using the charging stations. Thus the power produced by the internal combustion engine is used for driving the vehicle, and is not used for charging the batteries.

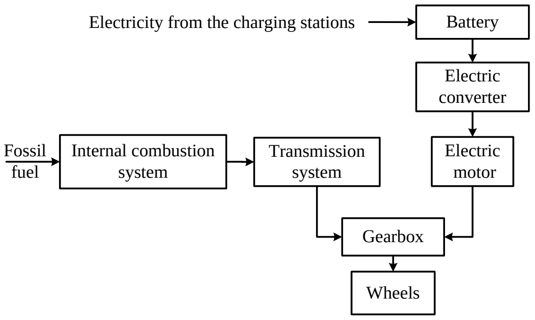

Figure 5. Structure of a parallel plug-in hybrid electric vehicle.

The structure of the compound plug-in hybrid electric vehicle is presented in figure 6 [20]. As it can be seen in the figure, the compound plug-in hybrid electric vehicle is a combination of the series and the parallel plug-in hybrid electric vehicles. The battery can be charged by both the power produced by the internal combustion engine and the external grid through the charging stations. Besides, the vehicle can be driven by both the internal combustion engine and the electric motor.

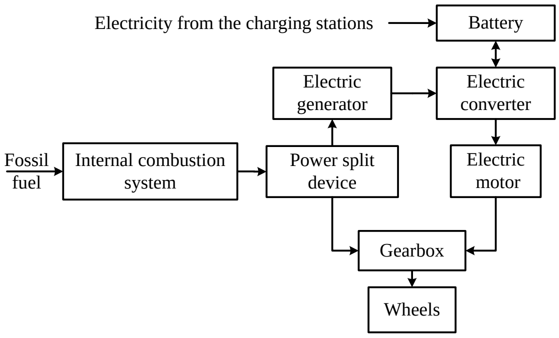

Figure 6. Structure of a compound plug-in hybrid electric vehicle.

2.3. All-electric vehicle

In the all-electric vehicle, the internal combustion engine is removed, and the vehicle is driven only by the electric motor. The fossil fuel is not used in this type of the electric vehicle, and from the environmental impact, it is the best electric vehicle [21]. The structure of this technology of electric vehicles is presented in figure 7.

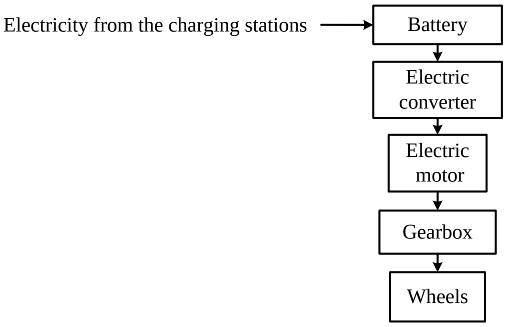

Figure 7. Structure of an all-electric vehicle.

3. Reliability modeling of electric vehicles

In this section, the reliability modeling of different types of electric vehicles, mentioned in the previous section, is performed. In order to develop the reliability model of each system, the following procedure must be followed [22]:

Step 1. Understand the system, the operation of the system, and the composed components.

Step 2. Identify different failures of the components.

Step 3. Determine the consequence of the failures and the impact of the component failure on the total failure of the system.

Step 4. Derive the suitable models to represent the results obtained in the previous steps.

The composed components and the operation principle of different types of electric vehicles are discussed in the second section. Thus in this section, in order to determine the reliability models of different types of electric vehicles, the impact of the failure of the composed components on the total failure of electric vehicles is evaluated. For the reliability evaluation of the electric vehicle, the following assumptions are considered:

- The reliability is the ability of a system to correctly perform its function. In this work, the function of an electric vehicle is considered to continue its movement and prevent it from stopping. Thus the other events such as turning off the lights are not studied.
- The reliability model is based on the Markov model. Based on the Markov model, only the failure of one component is considered, and the occurrence of the two or more components, simultaneously, is not taken into account.
- In the reliability model of the electric vehicles, the failure of the main components that results in the stopping of the vehicle is considered. Thus the failure of the other components such as lighting system is neglected.
- The impact of the fuel tank volume and the capacity of the battery on the reliability model are not considered.

In this work, the Markov model with up and down states is used to present each component of the electric vehicles. The state space diagram of a two-state Markov model is presented in figure 8 [23].

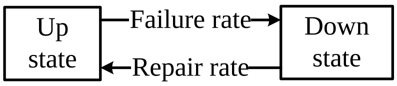

Figure 8. State space diagram of each component [23].

As it can be seen in the figure, the transition rate from the up state to the down state is the failure rate and the transition rate from the down state to the up state is the repair rate. The long-term availability of each component based on the two-state Markov model can be calculated as [23]:

$$\mathbf{A=R/(F+R)} \tag{1}$$

where *A*, *F*, and *R* are the availability, the failure rate, and the repair rate of the component. At this stage, the reliability model of each type of electric vehicles is determined. According to the operation principle and the composed components of the series hybrid electric vehicle presented in figure 1, the reliability model of this kind of electric vehicle is determined, and presented in figure 9. The reliability model of the internal combustion system and the common components are presented in figures 10 and 11, respectively. The internal combustion system is composed of the fuel tank, fuel system, internal combustion engine, cooling system, exhaust system and lubrication system. The common components placed in the reliability model of the vehicle are chassis, body, control system including different sensors and brake, wheels, and transmission system including the gearbox, clutch, differential, and axle.

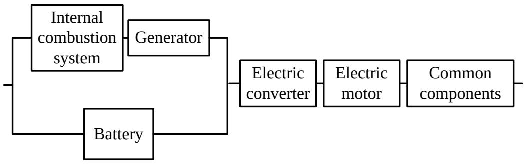

Figure 9. Reliability model of series hybrid electric vehicle.

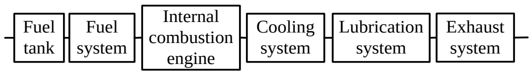

Figure 10. Reliability model of internal combustion system.

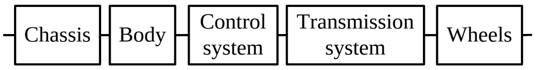

Figure 11. Reliability model of common components.

As it can be seen in the figures, the failure of each component of the internal combustion system results in the failure of this system, and so from the reliability viewpoint, all these components are series in the reliability model of the internal combustion system. The failure of the components placed in the reliability model of the common components results in the failure of the electric vehicle. Thus from the reliability viewpoint, these components are series. As it can be seen in the reliability model of the vehicle, the failure of electric converter, electric motor, and the common component results in the failure of the vehicle. Thus these components are series in the reliability model of the vehicle. However, in order to drive the electric vehicle, the electric motor can be supplied by the battery or the generator connected to the internal combustion engine. Thus from the reliability viewpoint, the battery is connected in parallel with the internal combustion system connected to the generator. In a reliability model composed of two series components, the equivalent failure rate (F), the equivalent repair rate (R), and the availability of the system (A) can be determined as [23]:

$$\mathbf{F = F_1 + F_2} \tag{2}$$

$$\mathbf{R = (F_1 + F_2)(R_1R_2)/(F_1R_2 + F_2R_1)} \tag{3}$$

$$\mathbf{A = A_1A_2} \tag{4}$$

where F_1 and F_2 are the failure rates of the series components, R_1 and R_2 are the repair rates of the series components, and A_1 and A_2 are the availabilities of the series components. The equivalent failure rate, repair rate, and unavailability (U) of a system composed of two parallel components can be calculated as [23]:

$$\mathbf{F = F_1F_2(R_1 + R_2)/(R_1R_2)} \tag{5}$$

$$\mathbf{R = R_1 + R_2} \tag{6}$$

$$\mathbf{U = U_1U_2} \tag{7}$$

where U_1 and U_2 are the unavailability of the components of the system. Thus based on the series or parallel connections of the composed components of the electric vehicles, the equivalent failure rate, repair rate, and availability of the electric vehicle can be determined by equations (2) to (7). Thus in order to determine the equivalent failure and repair rates of the series hybrid electric vehicle, the following procedure is followed:

Step 1: The equivalent failure and repair rate of the internal combustion system is determined by series the connection of the fuel tank, fuel system, internal combustion engine, cooling system, lubrication system, and exhaust system.

Step 2: The equivalent failure and repair rates of the common components that are series connections of chassis, body, control system, transmission system, and wheels are determined.

Step 3: The series connection of the internal combustion system and generator is determined.

Step 4: The parallel connection of the obtained system in step 3 and battery is determined.

Step 5: The equivalent failure and repair rates of the series hybrid electric vehicle is obtained by the series connection of the system obtained in step 4, common components, electric motor, and electric converter.

According to the procedure followed in this section, the reliability models of the parallel and compound hybrid electric vehicles are obtained and presented in figures 12 and 13, respectively. In figure 12, the transmission system for the internal combustion system (ICS) is composed of the required devices for connecting the internal combustion engine movement to the gearbox to drive the wheels of the vehicle.

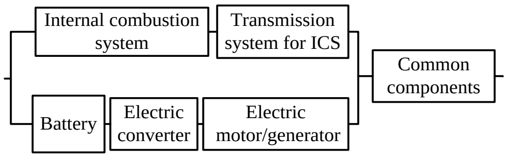

Figure 12. Reliability model of parallel hybrid electric vehicle.

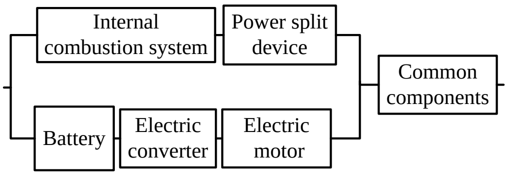

Figure 13. Reliability model of compound hybrid electric vehicle.

According to the procedure explained in this section, the reliability models of different types of plug-in electric vehicles including series, parallel and compound plug-in hybrid electric vehicles are determined. These models are similar to the reliability models of the hybrid electric vehicles presented in figures 9, 12, and 13. The only difference is the different value of the failure rate, repair rate, and availability of the batteries used in two types of the vehicles. The batteries used in the plug-in hybrid electric vehicles can be charged by both the charging stations and the internal combustion engine. Thus the utilization of the batteries used in the plug-in electric vehicle is more than the hybrid electric vehicle. For this purpose, the high-quality batteries are selected for use in the plug-in hybrid electric vehicles, and so the availability of these batteries is higher than the quality of the batteries used in the hybrid electric vehicles. In the all-electric vehicle, the internal combustion system is removed, and only the electric part is used to drive the vehicle. Thus the reliability model of this type of electric vehicle is as presented in figure 14.

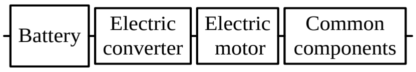

Figure 14. Reliability model of all-electric vehicle.

4. Impact of variable speed on component failure rate

In this section, the impact of variable speed of the electric vehicles on the failure rate of composed components is studied. Among the different components used in the electric vehicles, the failure rate of the semi-conductor devices such as diodes, thyristors, and power electronic switches is significantly affected by the temperature [24]. The mentioned devices are used in the power electronic converters used in all technologies of the electric vehicles including series, parallel and compound hybrid electric vehicles, series, parallel and compound plug-in hybrid electric vehicles, and all-electric vehicle. For determination of the failure rate of the semi-conductor devices, the temperature of their junctions must be calculated according to the power loss created in them. For this purpose, the current passing through the diodes or other semi-conductor devices should be determined. The failure of each semi-conductor device used in the power electronic converters, the overall operation of the converter is failed, and so from the reliability viewpoint, all semi-conductor devices used in the electrical converters are series. Thus the failure rate of an electrical converter containing six diodes and six IGBTs can be calculated as [24]:

$$\mathbf{F_C=6\times(F_{IGBT}+F_{diode})} \tag{8}$$

where, F_C, F_{IGBT}, and F_{diode} are the failure rate of the converter, IGBTs and diodes. In order to determine the failure rate of each semi-conductor device such as diode or IGBT, the following equation can be used [24].

$$F = F_u x_1 q_1 + F_v x_2 q_2 + F_w q_3 + F_x \tag{9}$$

where F, F_u, F_v, F_w, and F_x are the failure rate of each semi-conductor device, operation-mode base failure rate, non-operation-mode base failure rate, temperature cycle failure rate, and failure rate of junction electrical stress. The parameters x_1 and x_2 placed in equation (9) are, respectively, the operation-mode and non-operation-mode acceleration factors that are calculated based on the Arrhenius law as [24]:

$$x_1 \, or \, x_2 = e^{\frac{-E_a}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)} \tag{10}$$

where E_a is the activation energy associated with the operation or non-operation mode of device, k is the Boltzmann constant, T is the temperature of the device in Kelvin, and T_0 is the test temperature in Kelvin. The parameters q_1, q_2, and q_3 placed in (9) are the duty cycle factors associated with the operation-mode, non-operation-mode, and acceleration factor of the thermal cycle, respectively. These parameters can be calculated as [24]:

$$q_1 = \frac{1-P_{non}}{dc_{op}} \tag{11}$$

$$q_2 = \frac{P_{non}}{dc_{nonop}} \tag{12}$$

$$q_3 = \left(\frac{T-T_a}{dT}\right)^2 \tag{13}$$

where, the constant parameters placed in the equations including dc_{op}, dc_{nonop}, and dT can be collected from the manufacturers of the devices. Besides, P_{non} is the probability of the non-operation mode of the power supply used as the input of the electrical converter. The thermal loss of each semi-conductor device can be calculated as [24]:

$$\begin{aligned} loss = \frac{1}{2}\left[U_0\frac{I_m}{\pi} + r\frac{I_m^2}{4}\right] \pm \\ m\cos\phi\left[U_0\frac{I_m}{8} + r\frac{I_m^2}{3\pi}\right] + \frac{U_{dc}}{U_{nom}}P_{sw} \end{aligned} \tag{14}$$

where $loss$, I_m, U_0, r, m, ϕ, U_{dc}, U_{nom}, and P_{sw} are the thermal loss of each semi-conductor device, the peak value of the current passing through the semi-conductor device, the voltage drop on the diode or IGBT, the resistance of diode or IGBT, the modulation index, the angle between the voltage and the current, the DC link voltage, the reference voltage, and the switching power loss. In the inverters, the sign of the second term of (14) for IGBTs is positive, and for diodes is negative. The power loss of the electrical converter can be calculated by summing the power loss of all semi-conductor devices used in the converter. In order to determine the temperature of the devices put in (10), the following equation is used [24]:

$$T = T_a + P_L R_{th} + loss R_{ch} \tag{15}$$

where T_a is the ambient temperature, P_L is the power loss of the converter, R_{th} is the thermal resistance between the heat sink and the medium of semiconductor devices, and R_{ch} is the thermal resistance between the semi-conductor medium and the junction. According to equations (8)-(15), the failure rate of the electrical converters used in the electric vehicles in different vehicle speeds can be determined. Based on the electric motor used in the electric vehicle, the current I_m associated with the specified vehicle speed is determined, and accordingly, the vehicle failure rate is calculated. In this work, the average value for failure rate of electrical converter is used to place in equation (2) or (5).

5. Numerical results

In this section, the numerical results associated with the reliability evaluation of different types of electric vehicles are performed. Based on the calculated reliability indices, different types of electric vehicles can be compared from the reliability viewpoint. The reliability parameters of the composed components of the electric vehicles including the failure rate and their repair rate are presented in table 1 [11-12] and [14-15]. Based on the reliability models obtained for different types of electric vehicles, the equivalent failure rate, repair rate, and equivalent availability of these vehicles are calculated, and presented in table 2. In order to clearly compare the reliability performance of different types of electric vehicles, the equivalent failure rate and availability of different types of electric vehicles are presented in figures 15 and 16, respectively.

As it can be seen in table 2 and figures 15 and 16, the failure rate of the mechanical components is higher than the failure rate of the electrical components. Thus it is expected that the reliability of the electric vehicles is higher than the conventional vehicles based on the internal combustion engine. It is deduced from the numerical results that the order of electric vehicles in terms of reliability from greater to less would be as follows:

1. Compound plug-in hybrid electric vehicle
2. Parallel plug-in hybrid electric vehicle
3. Compound hybrid electric vehicle
4. Parallel hybrid electric vehicle
5. Series plug-in hybrid electric vehicle
6. Series hybrid electric vehicle
7. All-electric vehicle

Table 1. Failure rate and repair rate of composed components of electric vehicles [11-12], [14-15].

Components	Failure rate (occ./y)	Repair rate (occ./y)
Electric motor	0.01825	2500
Electric converter	0.00876	800
Electric generator	0.01111	2400
Internal combustion system	2.52802	350
Power split device	0.8	1000
Common components	1.85	600
Transmission system for ICS	0.2	1250
Electric motor/generator	0.022	2000
Battery used in hybrid electric vehicle	0.00746	273.75
Battery used in plug-in hybrid electric vehicle	0.00125	450
Battery used in all-electric vehicle	0.0006	876

Table 2. Equivalent failure rate and availability of different electric vehicles.

Types of electric vehicles	Failure rate (occ./y)	Repair rate (occ./y)	Availability
Series hybrid electric vehicle	1.8772	605.1901	0.99690776
Parallel hybrid electric vehicle	1.8504	600.0621	0.99692575
Compound hybrid electric vehicle	1.8504	600.0676	0.99692578
Series plug-in hybrid electric vehicle	1.8770	605.1715	0.99690799
Parallel plug-in hybrid electric vehicle	1.8503	600.0630	0.99692596
Compound plug-in hybrid electric vehicle	1.8503	600.0633	0.99692598
All-electric vehicle	1.8777	605.2503	0.99690724

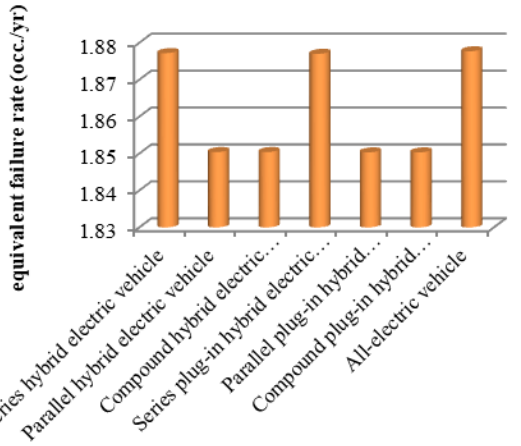

Figure 15. Equivalent failure rate of different types of electric vehicles.

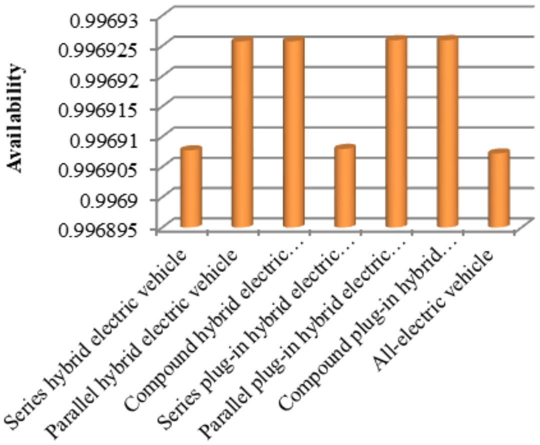

Figure 16. Availability of different types of electric vehicles.

It can be seen that the failure rate for all types of electric vehicles is shown in table 1, which indicates the adverse effect of the internal combustion system on the performance of the whole system. Given that the failure rate of the electric converter is lower than the other components of electric vehicles, it can be concluded that the reliability of the electrical parts is higher than the mechanical parts. Therefore, if access to the electrical components is not possible, assuming they are safe, the mechanical parts can be repaired. In addition, as shown in the right-hand column of table 1, the amount of electric generator repair rate per year is higher than the other vehicle parts, which indicates the importance of regular service for vehicles.

According to the case studies conducted out represented in table 2, the availability and failure rate for the six types of studied vehicles were evaluated. The results obtained show that the equivalent failure rate will be the highest for the all-electric vehicle type as1.8777 ooc/year, and the lowest for both the parallel plug-in hybrid electric vehicle and the compound plug-in hybrid electric vehicle types as 1.8504 ooc/year. In addition, the availability of the all-electric vehicle is as lowest as 0.99690724 and the maximum is for the parallel plug-in hybrid electric vehicle as 0.99692596.

6. Conclusion

In this work, the reliability modeling of different types of electric vehicles including the hybrid electric vehicle, the plug-in electric vehicle, and the all-electric vehicle was performed. In order to determine the reliability modeling of these vehicles, different combinations of the internal combustion engine of the vehicles and their electric part was considered, and so the reliability models of the series, parallel and compound structures of the hybrid electric vehicle, and plug-in hybrid electric vehicle were obtained. In order to develop the reliability modeling of the vehicles, the impact of the failure of the composed components on the total failure of the vehicle was considered, and based of the Markov theory, the series and parallel combinations of the components in the reliability model were determined. According to the developed reliability models of the different types of electric vehicles, the numerical results associated with the reliability performance of these vehicles were determined. For comparison between different types of electric vehicles from the reliability viewpoint, the reliability indices including the failure rate, repair rate, and availability of these vehicles were calculated. It was deduced from the numerical results that the reliability of the compound plug-in hybrid electric vehicle was more than the other vehicles. Besides, due to the removal of the internal combustion engine in the all-electric vehicle, the reliability of this type of electric vehicle was less than the other vehicles. In order to determine the reliability models of the electric vehicles, their function was considered to continue its movement. However, in the future works, the other functions of the electric vehicles can be considered to determine their reliability or it can be to determine the reliability model of different parts of electric vehicles. Besides, the impact of the capacity of the batteries used in the electric vehicles or the reliability of the charging stations on the reliability performance of electric vehicles can be taken into account in the future works.

7. Nomenclature

A: Availability
R: Repair rate
F: Failure rate
U: Unavailability
F_C: Failure rate of converter
F_{IGBT}: Failure rate IGBTs
F_{diode}: Failure rate of diodes
F_u: Failure rate of operation-mode base
F_v: Failure rate of non-operation-mode base
F_w: Failure rate of temperature cycles
F_x: Failure rate of junction electrical stress
x_1: Operation-mode acceleration factors
x_2: Non-operation-mode acceleration factors
E_a: Activation energy
T_a: Ambient temperature
R_{ch}: Thermal resistance between semi-conductor medium and junction.
k: Boltzmann constant
T: Temperature of a device in Kelvin
T_0: Test temperature in Kelvin
q_1: Duty cycle factors associated to operation-mode
q_2: Duty cycle factors associated to non-operation-mode
q_3: Acceleration factor of thermal cycle
P_{non}: Probability of non-operation mode of power supply
loss: Thermal loss of each semi-conductor device
I_m: Peak value of current passing through semi-conductor device
U_0: Voltage drop on diode or IGBT
r: Resistance of diode or IGBT
m: Modulation index
U_{dc}: DC link voltage
U_{nom}: Reference voltage
P_{sw}: Switching power loss
R_{th}: Thermal resistance between heat sink and medium of semiconductor devices
P_L: Power loss of converter

8. Abbreviations

IEEE-RTS: IEEE Reliability Test System
DC: Direct Current
AC: Alternative Current
ICS: Internal Combustion System
IGBT: Insulated-Gate Bipolar Transistor

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