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The Sustainable Road Transportation "Plug-In Hybrid Electric Vehicle": A Review

Amol V. Walvekar[1], Ashwini V. Kamble[2]

[1,2] *Visiting Lecturer*
[1,2] *Department of Mechanical Engineering*
[1,2] *Walchand collage of engineering, sangli, (MS), India*

Abstract:

The Plugin Hybrid Electric Vehicle (PHEV) is one of the recent advance technology in the field of road transportation. It becomes more popular, as it can be charge externally by plugging vehicle to grid and internally by ICE. The driver can run vehicle in pure Battery Electric Vehicle mode as well as he can run vehicle as Hybrid Electric Vehicle. The PHEV offer long travel range without stopping for charging vehicle externally and offer zero emission if it run as BEV only and it gives comparatively very low emissions when used as HEV. The PHEV offers benefits of BEV and HEV. The PHEV reduced emissions, enhance overall performance of vehicle and makes vehicle more fuel efficient. The paper is focused on the various key components of PHEVs and constructional difference between types of PHEV along with advantages. The abstract mostly focused on Series PHEV, parallel PHEV and Series-parallel PHEV. The paper also discusses various driving modes of PHEV. This paper highlights importance of regenerative braking, power split device in PHEV. Overall, this paper coves in depth review of types of PHEV.

Key Words: *Internal Combustion Engine (ICE), Hybrid Electrical Vehicle (HEV), Plugin Hybrid Electric vehicle (PHEV), Hybrid power unit (HPU), Energy Management System (EMS), Battery Electric vehicle (BEV), Charge Depleting (CD) Mode, Charge Sustaining (CS) Mode, All-Electric Range (AER) Mode, continuously variable transmission (CVT)*

1. Introduction

Electric vehicles were invented more than 100 years ago, today they comes in the form of hybrid, plug-in hybrid or all-electric types. [1] Nowadays, rising demand and depleting supply of fossil-fuels as well as various economic and environmental factors are motivating researchers to develop alternatives vehicle technologies for sustainable road transportation systems. [2,3] Moreover, increasing demand for fossil-fuels causes increased prices of commodity that has direct economic impact and uncontrolled use of fossil-fuels shows higher greenhouse gas (GHG) emissions shows long-term effects like climate change, global warming. [3] To overcome those problem, the recently developed Plugin Hybrid Electric Vehicle (PHEV) option can be a better alternative choice over the conventional internal combustion engine (ICE) vehicles in future.

The PHEVs are also known as Extended Range Electric Vehicles or (EREVs). [4] The PHEVs are simply combination of Battery Electric Vehicle (BEV) and a conventional ICE vehicle. Like current HEV's the PHEV's also have ICE, electric motor and battery, the battery pack can charge by external source, electric generator driven by ICE or by regenerative braking. [3]

The PHEV gives advantage as BEV to charge its battery pack by plugin vehicle to external power source i.e. grid at home or at commercial fast battery charging station and its battery can be charged by electric generator placed in vehicle. [5] The ICE gives power to the vehicle when battery is mostly depleted and also the ICE power vehicle for rapid acceleration, to gain high speeds or when air conditioning is required. [4]

Mostly the PHEVs are manufactured as passenger car, but nowadays, commercial vehicles, military vehicles, scooter, medical vehicles, etc. are also made as PHEVs. [5]

2. Components of Plug-In Hybrid Electric Vehicle

The PHEV has almost all components as conventional internal combustion engine ICE and Battery Electric Vehicle BEV. Following are the key components of PHEV. [11]

a. **Fuel Tank:** The PHEV use ICE to power vehicle and to charge the battery, like conventional ICE the fuel tank used to store fuel which is mostly the fossil-fuel.

b. **Internal Combustion Engine (ICE):** The engine is used to generate mechanical power which is further given to either transmission unit to drive vehicle directly or to electricity generator to generate electric power.

c. **Exhaust System:** the emissions of ICE are exhausted by tailpipe. To reduce pollution, the catalytic converter is also used.

d. **Cooling System:** The temperature of engine, electric motor and other electronic component directly affects the overall efficiency of vehicle, the cooling system used to maintain temperature of those components so that they will give maximum output.

e. **Transmission system:** The battery can be charged by external electric power source or by the mechanical power of ICE, the transmission system used to transfer mechanical power of ICE or electric motor to the vehicle.

f. **Auxiliary Battery:** In PHEV large rechargeable traction battery and auxiliary Battery is used. Like conventional ICE vehicle, in PHEV the auxiliary battery is used to start the vehicle and it also power other vehicle accessories.

g. **Battery Charging Port:** The PHEV's battery pack can charge by external electric power source; it may be domestic electric power source or commercial high speed electric charging station. The charging ports are designed to connect any type of charging facility either domestic or commercial.

h. **Electric Power Convertor:** Depending upon type of electric motor and power electronic accessories used in vehicle, the power convertor in vehicle used like DC to AC convertor or high voltage to low voltage DC convertor.

i. **Electricity Generator:** The generator used for generation of electric power to recharge battery pack or to run the motor directly, the mechanical input for generator given by ICE and regenerative braking. [11]

j. **Electric Motor:** The most important component of any electric vehicle is motor. The electric motor is responsible for converting electrical energy into mechanical energy to propel the vehicle. It takes power from the battery or from direct generator. The motor produce torque required to run the wheels. [6]

The variety of electric motors are used in electric vehicles, the most common types of motor are Permanent Magnet Synchronous Motor (PMSM), Induction Motor (IM), Brushless DC Motor (BLDC), Switched Reluctance Motor (SRM) and Direct Current Motor. [7]

k. **On-board Charger:** The frequent charging of battery pack is required. The on-board charger not only used to convert AC current to DC current to charge battery but also used to monitor battery status like voltage, current, temperature and percentage of charging etc.

l. **Energy Management System (EMS):** The basic function of Energy Management System (EMS) is to control drivetrain by plays very important role in HEV's. It minimizes the fuel consumption by controlling the drivetrain components by supervisory control algorithm.

The EMS controls the power flow between engine, generator, battery pack and electric motor. It selects the most appropriate power source for real-time driving conditions by considering battery charge condition, driver inputs and vehicle speed, it results in improved overall efficiency. [6][8]

m. **Battery Pack Unit:** The battery is energy storing device that consisting of electrochemical cells to convert chemical energy into electrical energy. [9] The PHEV may use Lithium Ion (Li-Ion), Molten Salt (Na-NiCl2), Nickel Metal Hydride (Ni-H) or Lithium Sulphur (Li-S) type batteries. [10]

3. Working of PHEV

The PHEV works similarly as HEV the only difference between them is the PHEV has large battery pack which can charge externally by grid and charge while running vehicle by on-board charger powered by ICE.

A) The battery pack of PHEV works mainly on following operating modes

i. **Charge Depleting (CD) Mode:**

In this mode battery charge allow to decreasing up to certain specified limit. In this mode the maximum power required to vehicle drawn through battery up to specified range. In certain conditions if the power requirement exceeds than battery capacity, the ICE provides additional required power.

The PHEV mostly run on charge depleting mode for short trips within battery power range and vehicle gives benefits like battery electric vehicle (BEV). To achieve longer range, generally the PHEV has comparatively larger battery pack than HEV. [12]

ii. **Charge Sustaining (CS) Mode:**

In this mode the battery charge level is maintain to certain level. To maintain constant level of battery charging, the vehicle powered by both ICE and battery. This mode is similar as HEV, in it the ICE run at its optimum fuel efficiency level. The ICE assets vehicle power as well it charges battery also, this gives better extended driving range. Usually Charge Sustaining Mode is used after Charge Depleting Range when battery charge is at its low level. [12]

iii. **All-Electric Range (AER) Mode:**

In this mode the vehicle run purely on electric power of battery pack and engine is remains off. This mode is much similar as Charge Depleting Mode, only difference is the engine does not assist the vehicle power, engine remains off. The range of this mode is depends on battery capacity. [12]

B) The PHEV has basically following driving modes

i. **Battery Electric Vehicle (BEV) mode:**

In this mode vehicle only run on battery power and sometime super-capacitor are also used. In this driving mode most of the operations carried out in Charge Depleting Mode when the vehicle range is less than All-Electric Range. [13]

ii. **Hybrid Electric Vehicle (HEV) mode with Optimal Engine operation:**

In this mode the ICE runs at its maximum efficiency level regardless of power required to drive vehicle. This driving mode is used at Charge Sustaining Mode near minimum battery charge condition. [13]

iii. **Hybrid Electric Vehicle (HEV) mode with normal engine operation:**

In this mode the engine speed varies, it gives power to run vehicle as conventional ICE vehicle and it also charge the battery pack. [13]

4. Types of PHEV

The PHEV uses both battery and ICE to run vehicle, the different arrangement of these power sources are possible and each arrangement has their own benefits. Depending on those arrangements the PHEV can further categorised as Series Hybrid, Parallel Hybrid and Combine Hybrid Plug-in vehicles. The types and constructional arrangements of all those types of vehicle are very similar to HEV's types, only major difference is that the PHEV has larger battery pack.

A. Series PHEV:

In this type of arrangement, the ICE, electric power generator, power converting device, electric motor, battery unit and power transmitting unit are connected in series, the battery are able to charge externally by means of charging socket provided in vehicle, ICE and the regenerative brakes are also used.

In this the small power rating engine is used, this ICE connected to electric generator. The electric generator not only powers the electric motor but also charge the battery. This ICE mostly operates at maximum fuel efficiency mode. The only electric motor drives wheels of vehicles. The electricity generated in generator is feed to convertor, the convertor supply power to motor which derives the vehicle.

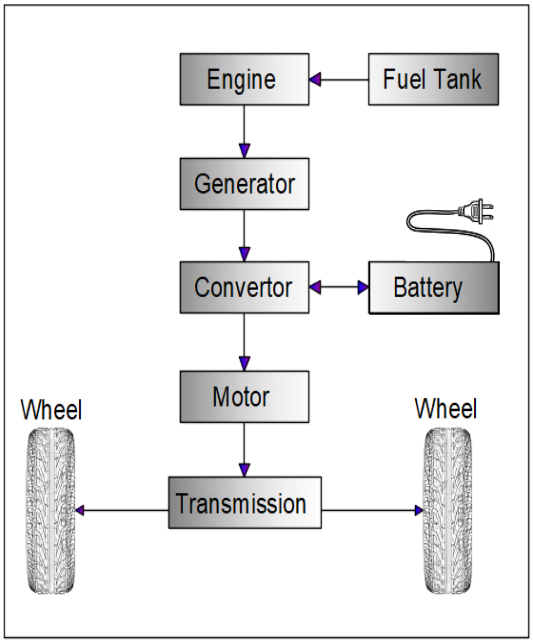

FIGURE NO 01. Series Plugin Hybrid Electric vehicle (series PHEV)

When ICE generates higher power than power demanded by vehicle, this excessive power used to charge battery pack. And when vehicle demanded higher power than generator power, the battery supply additional required power assist the motor. When vehicle decelerate or brakes are applied the regenerative braking system comes in action and charge the battery pack. In regenerative braking the motor acts as generator and it convert mechanical energy back into electric power, thus the overall range of vehicle is enhanced.

The facility to charge battery pack externally by plugging it to electric power supply and larger capacity battery pack, mostly allows vehicle to turn off ICE while running in short trips. Unlike HEV, the series PHEV run in pure electric mode till battery discharges to certain lower level at ICE shut off mode. Thus the less losses for power conversion are observed compared to HEV.

Series PHEV first run in All-Electric Range (ARE) mode until battery discharges to certain lower level, then ICE started and vehicle operates in Charge Depleting (CD) Mode which extend vehicle range and maintain the battery charging at constant level. [6][12]

B. Parallel PHEV:

In parallel PHEV the ICE and electric motor are arranged parallel, so they can power vehicle in combination or separately. In this type ICE and electric motor are connected directly to wheels through transmission unit. In it electric motor used can works as generator also, it generates electric power while vehicle decelerates or brakes are applied.

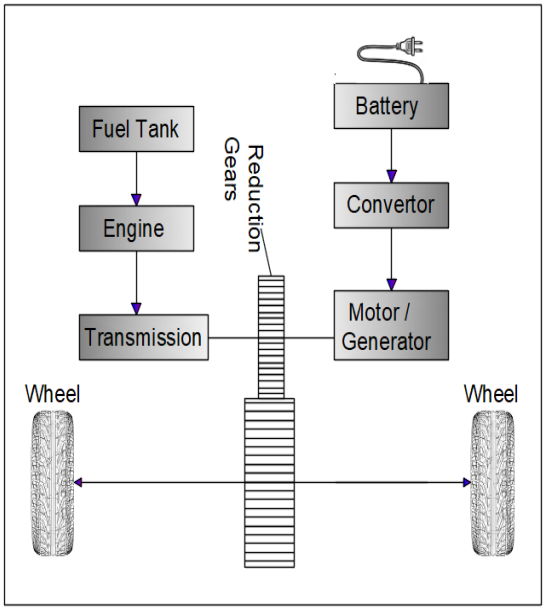

FIGURE NO 02. Parallel Plugin Hybrid Electric vehicle (Parallel PHEV)

In it the vehicle first run as BEV till the battery discharges to certain lower limit, then ICE starts and it used to power the vehicle and extra power of it used to charge battery pack. Whenever extra power required than power generated by ICE, the battery pack provides additional power along with ICE. The gear units allow vehicle to run at various speed and power, depends on driving conditions.

Though the engine and motor are directly coupled with gear unit, the engine detachment is done by clutch arrangement while vehicle running in AER mode. This allow ICE to turn off while vehicle is running and the overall efficiency is increased. [6][12]

C. Compound PHEV:

The combine or compound PHEV is Parallel-Series PHEV, it has advantages of both Series PHEV and Parallel PHEV. In it ICE and motor are coupled to power split device. The power split device is planetary gear set which allow ICE and motor to propel vehicle either in combination or separately. The power split device also allows ICE to power vehicle and/or power generator. The generator is connected to battery and electric motor through convertor.

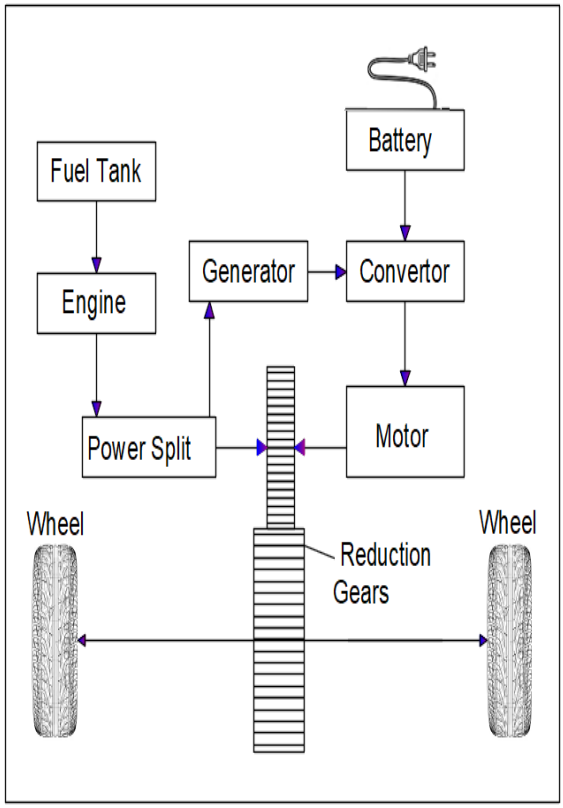

FIGURE NO 03. Compound (Parallel-Series) Plugin Hybrid Electric vehicle
(Compound PHEV)

The combine or compound PHEV is Parallel-Series PHEV, it has advantages of both Series PHEV and Parallel PHEV. In it ICE and motor are coupled to power split device. The power split device is planetary gear set which allow ICE and motor to propel vehicle either in combination or separately. The power split device also allows ICE to power vehicle and/or power generator. The generator is connected to battery and electric motor through convertor.

The power split device act as continuously variable transmission (CVT) which eliminates need of manual transmission or automatic transmission. The ring gear is connected to motor, ICE is connected to planetary gears and, ring gear and sun gear are coupled to generator through planetary gears.

In it also, first the vehicle run as BEV till the battery discharges to certain lower limit, then ICE starts and it used to power the vehicle and extra power of it used to charge battery pack. The power split uses the power from electric motor when vehicle moving at low speed, at moderate speed it uses power from ICE and when higher power is required it uses power of both IEC and electric motor. [6][12][14]

5. Advantages of PHEV over ICE and HEV

a) The PHEV reduces running cost of vehicle and also reduces harmful emission.

b) Compare to HEV the larger battery pack is used in PHEV which can charge either by external electric power at stationary condition like BEV or by ICE while running condition like HEV.

c) The larger battery pack allow vehicle to first run like pure BEV and ICE is remains in off condition, this reduces fuel consumption and ultimately reduces pollution, greenhouse gas emission.

d) Zero emission while running only on battery power i.e. AER mode

e) Compare to conventional ICE vehicle, the PHEV consume lesser fossil-fuel and it has comparatively lower emissions.

f) If battery pack never charged by external electric power and run only on engine power, the PHEV gives same fuel economy as HEV.

g) If battery charge fully and vehicle used for short trips, it will give similar output like BEV.

h) Like HEV, when extra power required than ICE, both engine and motor can operate together and gives required excessive power for vehicle rapid acceleration.

i) In series PHEV no mechanical links are required between engine and power transmission unit, so very less mechanical transmission losses.

j) In series PHEV, the ICE can run at constant speed irrespective to vehicle speed, which makes ICE more fuel efficient

k) In series PHEV, allow designer to locate engine and generator at any suitable place in vehicle.

l) In parallel PHEV, the electric motor used is works like generator and it generates the electricity, this generated electricity is used to recharge the battery pack.

m) In compound PHEV, the power split device act as continuously variable transmission (CVT) which eliminates need of manual transmission or automatic transmission.

6. Disadvantage

a) The large externally chargeable battery pack increases weight, size and cost of vehicle.

b) The engine runs generator by mechanical power and generator generates electric power, this electric power used to charge battery, and again this electric energy of battery is used to run motor. It means the mechanical power is converted to electric power and again electric power converted to back in to mechanical power. This mechanical-electrical-mechanical power conversion has engine power loss.

7. Conclusion

The key components of all types of PHEV are similar as HEV. The PHEV gives combine advantages of both BEV and HEV, it can work efficiently on petroleum and electric energy. The PHEV can be use pure electric power to run vehicle in short distance like BEV and ICE for longer journey like HEV. The PHEV is reliable source for continually long distance traveling and it does not require extra battery charging time. The PHEV is future of sustainable road transportation in developing countries, where battery charging infrastructure development is not economical, feasible and suddenly possible. With technological advancements the PHEV will become cheaper and more popular.

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