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Optimal Design Strategies for Emerging Hybrid, Fuel Cell, and Electric Vehicles: Impact on Performance and Real-Time Management

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Abstract**—** Hybrid Electric Vehicles (HEV), Fuel Cell based vehicles and electric vehicles are the major trend in the automobile industry and they are becoming an alternative to the conventional vehicle systems. In near future, these technologies will completely change the entire perspective of the industry. As the technology is evolving there is an eventual need for the research and development of the technology. This paper is structured in a way to propose an optimal design strategy for the various configurations employed in it. The first section provides the brief introduction of the various technologies followed by the various configurations involved in the design of the vehicles. Third section gives a view on the impact of these configuration on the vehicle performance and how it is been managed in real time.

Index Terms**— *design strategies, component, HEVs*;**

I. INTRODUCTION

The population of the world is increasing and it is directly proportional to the mobility of people which means that the transportation is drastically increasing [1] day by day. At present there are numerous rules and regulations deployed and implemented by all the governments of the world in the automobile industry towards air pollution and fuel consumption. On the other hand, people are thriving for more comfort, performance, safety and luxury to be present in their vehicles. [1]

In order to meet both the ends, that is to reduce the air pollution without compromising the needs of the customers now a days automobile industry is moving towards electrical components in their vehicles like most of the mechanical and hydraulic components are replaced by the electrical components which in turn reduces the weight of the vehicle. Even the vehicles are lighter and more concentration is towards the aerodynamics of the vehicle to reduce the energy needed for the propulsion of the vehicle. [1]

As discussed, unlike the conventional vehicles in which fuel is the only power source which is readily available everywhere. But in electric vehicles battery is the power source which needs electricity for the battery to get charged but the problem is the feasibility of it. Thankfully this problem can be rectified by focusing more on the design of the vehicles in which the complete design is optimized to get the most desirable output of it.

Further moving on the engine model of the conventional vehicles has not much more altered for the last 100 years but it is completely different in the electric vehicles as their design features experience a boom as to meet the requirements of the customers. This paper discusses more about the design of main components which by means the type of battery to be used in the model, types of components and their architecture which includes the sizing of them [2]. Therefore, the system design of an electric vehicle has various considerations and each of them have their own results but the architecture remains same. The two main points to be considered in an optimized design is increasing the fuel economy and also the performance of the vehicle.

The main motivation of this paper is to review and analyze all the eminent work that has been carried out in the field of optimal design of hybrid electric vehicles and electric vehicles. This paper outlines and formulates a structural frame work for understanding optimality in the case of HEV's and EV's and together with highlighting the core of those technologies which reciprocates all researches conducted in the field of hybrid electric vehicles and electric vehicles respectively.

The primary idea is that what is this new electrical technology, let us take a deep look into this technology, this can be of either way like electric vehicles use only battery as a power source wherein the hybrid electric vehicles use both the internal combustion engine and a batter as its power source from which it optimizes the power displacement between them and providing linear operation of the vehicle.

II. CONFIGURATION

In this section, we analyze the various configurations, types of components, topologies adopted in a HEV, Battery vehicle and fuel cell vehicles in detail. Normally, a HEV is a combination of ICE and Electric motors, these two components are combined in four different configurations such as series, parallel, series-parallel and complex configurations, one of these are adopted based on the application. Similarly, battery electrical vehicles use only an electrical motor as a component with no configurations and electrical grids as a power source. Fuel cell vehicles are also same as that of battery electrical vehicles but it uses fuel cell as its power source. PHEV is same as that of HEV in configuration but it differs in the working operation model. Table 1explains the various configurations of all the vehicles in a nutshell.

Table 1: Configuration of the vehicles

Types	Components	Topologies	Power source
Hybrid Electric Vehicles	-Electric motors -Internal Combustion Engines	1)Series 2)Parallel 3)Series-Parallel 4)Complex hybrid	-Electrical Grid -Gasoline stations
Battery Electrical vehicles	Electrical motors	None	Electrical grid
Fuel Cell vehicles	Fuel Cell	None	Hydrogen
PHEV	-Electric motors -Internal Combustion Engines	None	-Electric motors -Internal Combustion Engines

A. *Series Configuration*

- Conversion of mechanical energy to electrical energy.
- This configuration comprises of a battery as main power source and an Internal combustion Engine (ICE) as an optimal power source which works as a generator [3].
- In this only Electric motor is coupled with the wheels and the ICE acts as a power generator.
- The converted electrical energy can either be used to charge the battery or it can directly transfer to the wheels by circumnavigating the battery [3].
- The ICE is turned on when the state of charge of the battery falls below the minimum contained value as proposed by the manufacturers [3].
- The sizing of the series HEVs are difficult as these systems involve three types of systems for propulsion such as the electrical motor, the ICE and the generator [3].

B. *Parallel Configuration*

- Conversion of mechanical energy to electrical energy.
- This configuration comprises of both battery and ICE as their main power source [3].
- In this both the electric motor and ICE are connected to the wheel directly for the propulsion.
- The sizing of parallel HEVs is simple because they require only two propulsion systems – the electrical motor and the ICE [3].

C. *Series – Parallel Configuration*

- Combination of both series and parallel HEVs configuration.
- In this there is a separate mechanical connection between the ICE and the wheels as that of for series configuration and a separate generator as that of for the parallel configuration [3], [4].
- The sizing of series – parallel HEVs are quite complicated because it involves various propulsion systems [4].
- There are two compound types of operations such as electric intensive configuration in which electrical motor acts as a major power source and the other one is engine intensive configuration in which ICE acts as a major power source [4].

D. *Complex Configuration*

- Complex HEVs are same as that of series – parallel configuration.
- The distinct feature of complex HEV is that it allows bidirectional flow of power which is different in case of series – parallel configuration as it is of unidirectional in nature [3].
- The sizing of the complex HEVs is way more complicated as of series – parallel configuration.

E. *Fuel Cell Technologies*

DMFC – Direct Methanol Fuel Cell [4]

- Storage of liquid fuel.
- High energy density but low power density.

AFC – Alkaline Fuel Cell [4]

- Mainly used in Fork lift trucks and niche components for transportation.
- Costs of the equipment are less expensive as compared to other technologies.
- But the man problem pure hydrogen has to be used because we need to use pure hydrogen because of carbon dioxide poisoning which reduces the efficiency of the fuel cell.

SOFC – Solid Oxide Fuel Cell [4]

- Mainly used as a secondary power unit as air conditioning in cars and heaters.
- The disadvantage is that it has large starting time but they have a high operating temperature of about 800 to 1000 degrees.

PEMFC – Proton Exchange Membrane Fuel Cell [4]

- Compact design.
- Quick output demand can be achieved.
- The main disadvantage is there is more carbon monoxide impurities which in turn reduces the efficiency of the vehicle.

The above mentioned are the various fuel cell technologies which are being employed in recent automobile industries. All these technologies have their own advantages and disadvantages, thereby according to the required application these techniques can be implemented along with the other power source. As discussed now we will look into how the various combinations in which the above-mentioned fuel cell technologies have be employed and all these have their own advantages and disadvantages.

F. Fuel Cell and Battery configuration

- The most popular configuration in HEV.
- The demand from the battery and the electric motor is low and the SOC of the battery can be maintained constantly [4].
- Battery maintenance is expensive.

G. Fuel Cell with Battery and Super Capacitor configuration

- Same as that of the above model but here super capacitors are used as the range extenders [5].
- As the combination of super capacitors having high power density and the batteries having high energy density, we achieve high charging/ discharging capacity and thereby we get a good battery life.

In fuel cell-based vehicles [5] there are certain unique features which make them different from the HEVs such as they have flexibility towards the fuel and the energy conversion is completely direct and low air pollution.

H. Plug in HEV Configuration

Plug in Hybrid Electric Vehicles (PHEV) are the recent development in the HEV market and it has become a prominent boom in the entire automobile industry.

The main reason behind this is because of its notable mode of operation, a typical PHEVs operation is same as that of a HEV but there is an additional feature which is added above the HEV, that is known as the All-Electric Range (AER) [6].

As the name suggests, there is an Electric Motor on top of the HEVs configuration and instead of a mechanical power train which is normally employed in a typical HEV, this PHEV uses an electrical power train which acts as a primary energy source. So, the user can get completely fuel and emission free operation for few kilometers before the State of Charge (SOC) [6] of the battery falls below the required level. After that the PHEV switches to HEV mode of operation. But this All-Electric Range (AER) depends completely on the size of the electric storage system.

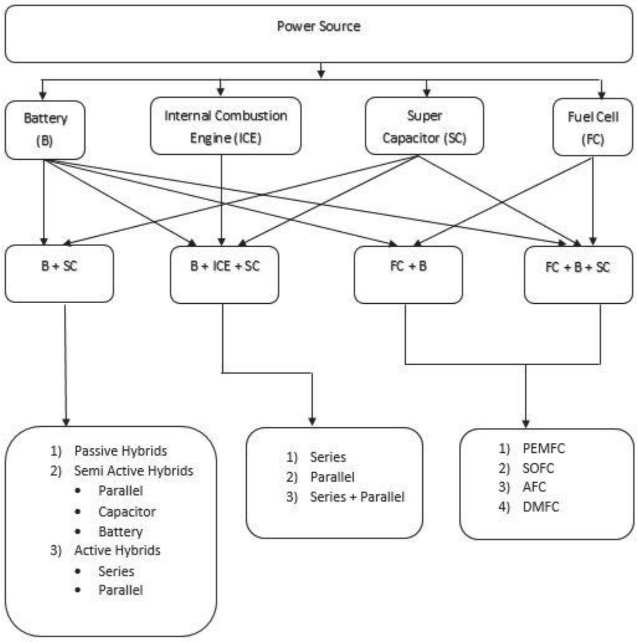

Fig 1: Configuration of HEVs, FCVs and BEVs

Figure 1, represents the various power sources of a typical electric and hybrid electric vehicle in the automobile industry, followed by the various combinations of the power sources and their specifications.

III. IMPACT ON VEHICLE PERFORMANCE

The main objective of Hybrid electric Vehicles is to increase the fuel efficiency and to reduce the emission of the vehicle. But the above factors are completely useless if we ignore the major attributes of the vehicles – performance and drivability of the vehicle. At this point a notable working Energy Management System (EMS) [7] is required in order to maintain the performance of the vehicle throughout its working life cycle. But how this EMS is more influential in an optimal design of the HEV and it is because the entire flow of energy is controlled by the EMS before it reaches the wheels of the vehicle. In a typical HEV [7], which follows various above-mentioned configurations will have their own fluctuations in the energy flow and that is where the EMS comes into action and various strategies are inbuilt in the EMS according to the configuration employed in the vehicle. Many research papers have been published on those control strategies used in the EMS and they are being tested in real time and improvements are made day by day. In simple terms EMS controls the operating modes of the vehicle in real time and also when the vehicle is in idle state.

As discussed, there are two types of control strategies employed in a HEV such as Rule based control strategy and Optimization based control strategies [7].

Rule based control strategy is further divided into two 1) Fuzzy rule-based strategy where nonlinear and fuzzy logic properties are used to make the decisions based on the performance. 2) Deterministic rule-based control strategy, where a heuristic function containing the attributes such as fuel consumption, emission level and even human expertise are generally considered to make a lookup table from which the performance of the vehicle is measured.

Optimization based control strategy [7] is further divided into two 1) Global optimization which is mainly employed in fuel cell based HEVs and Bellman's optimality principle is used to measure the performance of the vehicle. 2) Real time optimization is same as that of global optimization but the main difference is that the cost function employed is used to measure the real time fuel consumption and the sustainability of the electrical energy stored in the storage system.

A. Optimization of Hybrid Electric Vehicles Design

In [2], single mode and multi-mode design problems of HEV architecture were addressed. Hybrid vehicle architecture with entire battery configuration has considered. The impact of gear ratios on fuel consumption was analyzed. Initially, the architecture was varied keeping the sizes fixed, then both the architecture and sizing problems were simultaneously optimized. Generic algorithm was used for design optimization.

In [8] the engine, battery hybrid, different configurations were considered for fuel efficiency and drivability. With the help of dynamic program and ECMS and design requirements including feasibility, drivability, sizing and transmission efficiency, only 2 out of 1152 design candidates were selected. Optimization of design parameters for hybrid vehicles is considered in [14]-[20].

B. Optimization of Electric Vehicle Design

Optimization of design parameters of electric vehicles is considered in [21]-[27] where in [9] a battery super capacitor ESS is considered. Maximization is based on the choice of weight and degree of hybridization (DH) between super capacitor and the battery power. In [10] design variables of the motor, power electronics and vehicle propulsion models are optimized to achieve desired performance of the Battery Electric Vehicle (BEV). In [11], battery size and type are optimized with minimum cost as a figure merit. In [12] design optimization of FCHV is considered. Design challenges of fuel cell stack ie, number of cells, active cell area are considered. Stack voltage and current levels are noted along with the hydrogen fuel consumption. The results indicate that downsizing of the fuel cell system and increasing the degree of hybridization increases the overall system efficiency.

As compared to conventional engine-based vehicles, HEVs have emerged as a viable solution as they are capable of reducing the emission without compromising on mileage. It offers better mileage than EVs and more flexibility in sizing of components [6]. PHEVs are a step further than HEVs, in the sense that here, the storage is considered as the primary source instead of the engine. This they can give lower fuel consumption and emission than HEVs. However, since PHEVs and HEVs rely partly on Internal Combustion Engines, in future they are expected to be completely replaced by EVs. The low operating range of the EVS can be addressed by hybridizing them with other storage units or reinforcing them with range extenders. Two options can be considered [13] adding a renewable energy unit such as a super capacitor or a fuel-based unit such as a fuel cell. In both the cases with the appropriate EMS, energy sources can be optimally utilized and vehicle performance maximized.

CONCLUSION

As it is evident that there is a crisis for the fossil fuels, due to which the alternative technologies are being considered but these technologies have certain drawbacks such cases have been introduced. In this paper, we have discussed the various configurations, topologies and design parameters of HEVs, BEVs, FCVs, EVs and PHEVs, moreover how these technologies can be utilized based up on the applications in which they have been adopted and how the various topologies are used to optimize the performance of the vehicle compared to the conventional vehicles. However, further research and development is required to eradicate all these problems in real time and make the system much more stable.

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