Chapter 1

Introduction

The road transport sector is mainly governed by an internal combustion engine (ICE) based vehicles. These vehicles consume fossil fuel to propel the vehicle and release the noxious gases which pollute the environment. Fossil fuel-based power is limited, and its rapid use is increasing its cost. Therefore, the transport sector is looking for a replacement of these ICE based vehicles by battery-driven vehicles i.e., electric vehicles (EV) or using a combination of small ICE and battery-based vehicle i.e., hybrid electric vehicles (HEVs). The EVs can be a prominent solution to this problem but in developing nation like India, lack of charging infrastructure and short range of EVs are the major hindrances. Hence the HEVs could be a better solution to this issue.

In an HEV, the blend of both the forces i.e., from ICE and battery is used to propel the vehicle and has incredible advantages over pure gasoline-based vehicles. This vehicle offers improved fuel economy and overall efficiency and helps in maintaining the ecology as compared to gasoline-based vehicles.

The ICE efficiency used to be low hence in HEVs the size of the ICE is reduced generally. In HEVs the motor is operated in the region of low speed as the ICE during that period is least efficient. During acceleration, long highways, or hill climbing the electric motor provides additional power to assist the engine. These HEVs use regenerative braking to charge the battery which makes them more efficient therefore, HEV is best suited for the growing urban areas with high traffic.

1.1 Background

The invention of ICE was a great boon for the transportation industry. This engine runs on the fossil fuel and emits harmful gasses such as CO_2, NO_2, NO and CO which are hazardous to human health and the environment. Its rising demand has led to price hikes and the rapid depletion of fuel reservoirs.

In India, the transport division is one of the quickest developing sectors. As of now, the transport sector is one of the real patrons of CO_2 outflow and according to 2012– 13 information; the vehicles are responsible for 14% of India's vitality related CO_2 emanations. An evaluation completed by Central Pollution Control Board studied that 75% urban communities are at high danger with a PM10 level. Street transport, which is the primary method of transportation in India, has encountered expanded exercises regarding increment in the quantity of vehicles. The Indian automobile industry is one of the biggest on the planet with a yearly generation of 23.37 million vehicles in financial year (FY) 2014– 15 as shown in Fig 1.1, The vehicle production grew with a compound annual growth rate of 10.5% in last 10 years in India and is forecasted to develop at a similar rate in future too.

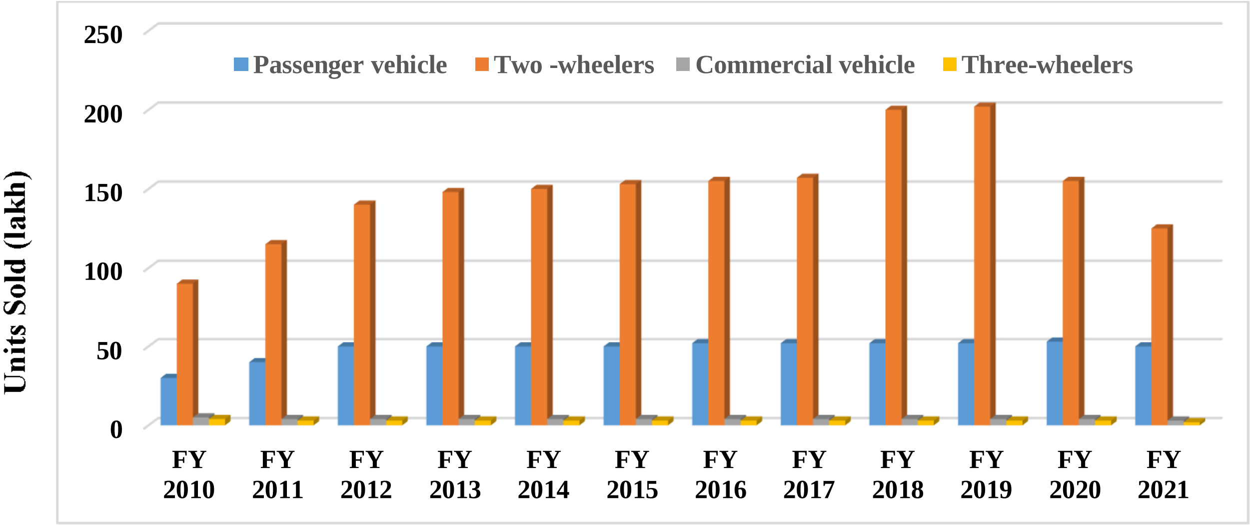

Fig. 1.1 Total production of automobiles in India [1], [2].

Note: FY in the above figure stands for finical years and units sold is in lakhs.

Ever since Lohner-Porsche, the first HEV, was developed in 1901, the automobile industry has come a long way. In recent years, HEV technology has gained tremendous boost in terms of research and development. There is a general sense of optimism in the industry regarding this new technology.

The requirements for the automobile market in the next decade need to be carefully investigated, because it is very important to identify and solve the correct problem. Contrary to some sources, the ICE does not need to be eliminated right away. It is important to recognize that reducing air pollution and fuel dependence are the two key goals. A hybrid-electric drivetrain can effectively meet these goals for the near to middle future. Eliminating the ICE is not a stated goal and should not be the sole focus of research. Improving the efficiency and performance of the complete vehicle as a system is the critical goal that should be closely investigated.

At first glance, the hybrid drivetrain seems inherently inefficient because two different, and presumably capable systems are being employed in the vehicle. The redundancy increases weight, complexity, and cost. The advantages lie in the fact that neither of the drive systems is completely acceptable for the entire range of vehicle power needs. While the electric drivetrain is extremely flexible and allows regenerative braking, it cannot store sufficient energy for extended operation. On the other hand, the ICE can be quickly refueled, but emits pollution and is likely to perform best when operated at a constant speed. Combining both systems into a "hybrid" vehicle allows each to be optimized to take full advantage of its strengths.

Current automobiles use their combustion engines to meet all the power needs of the vehicle. The engine must be large in order to meet peak demands and provide acceptable acceleration despite the fact that the full capacity of the engine is only occasionally used. This discussion leads us to think that the vehicle performs well by using a large or a small engine, should be used to fetch the good fuel economy and less emission. It is very difficult to achieve both objectives using current automobiles. The decoupling the ICE from the peak power demands allows it to operate at constant load and steady speed while providing the relatively low average power of the vehicle. This allows the displacement of the ICE to be smaller than current engines, and therefore return better fuel economy.

The ICE also gets the benefits from the elimination of engine idling. Current vehicles operate at engine idle about 19% of the time [3]. Their large engines are running and polluting but are producing virtually no useable work. This is extremely inefficient and leads to poor environmental performance. In a hybrid vehicle, the ICE is always producing useful work during the time that it is running. If the ICE is not needed to move the vehicle or to store electrical energy against future demand, then it is shut down. This keeps the overall efficiency of the vehicle higher and plays a large part in the fuel economy improvements of hybrid vehicles over conventional vehicles.

A few factors, which are responsible for moving towards the alternative of the ICE based transport, are described below.

1.1.1 GHG emission in the world by various sectors

There are various sources by which the emission of greenhouses gases (GHG) emission can occur. The GHG emission involves the gasses like CO_2, NO_x and CO etc. [4]. The industrial and electric producing utilities are responsible for the production of all most 50% of the GHG emission. Whereas the transport, agriculture and commercial & residential are responsible for the production of 28%, 10% and 12% respectively. Fig 1.2 shows the various sector with their GHG production capacity.

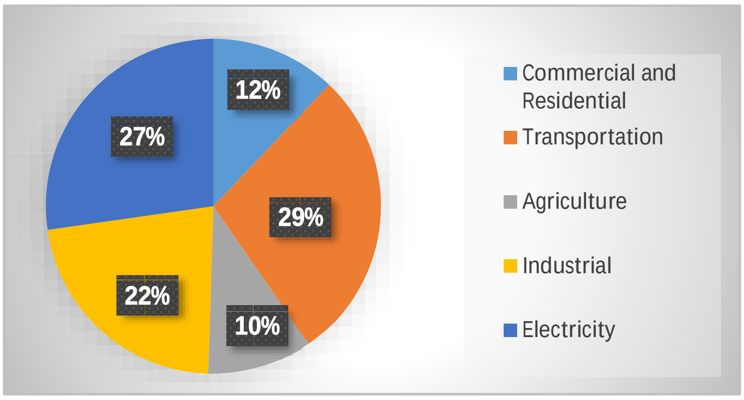

Fig. 1.2 GHG production by various sector

1.1.2 Oil price and its consumption

The oil consumption by various sector has been shown in Fig 1.3. It can be easily predicted from the provided pie-chart that road transportation is the greatest oil demanding sector in organization for economic co-operation and development (OECD) member states. In 2019, 35.23% of all oil consumed in the OECD was related to ICE based vehicle. Hence this is a matter of great concern for the governments of various countries.

1.1.3 Costs involved.

Ever since its inception, the cost of HEVs has always been much higher than its traditional counterparts in the same segment. Studying just its model price would be misleading so it is necessary to realize the various costs, such as maintenance, repair, depreciation, and fuel to get the complete picture. Comparisons between various costs involved in vehicle are as follows:

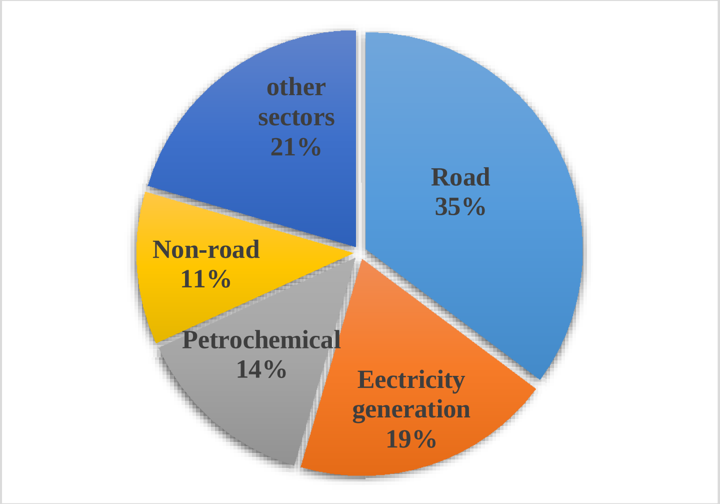

Fig. 1.3 Oil consumption by various sector [5].

1. Fuel costs: The main difference between EVs and ICEs is their fuel source, ICE run on gasoline while EVs run on electricity. According to a study of the University of Michigan's Transportation Research Institute, the operating cost of EV is less than half of gas-powered cars. The average operating cost of an EV is $485/year as against to $1,117 for gasoline-powered vehicles in the United States. This figure is subject to the rates of gas and electricity.
2. Purchase cost: The base price for an EV in general is seen to be higher in comparison to traditional alternatives. Higher costs can be attributed to increased complexity and number of components in a HEV and specialized parts.
3. Maintenance costs: In ICE, vehicle maintenance costs can be very high due to engine maintenance, which is a huge money sink, which further increases as the car ages. Changing the engine oil, coolant, transmission fluid, and belts can add up in value over time. Since an EV doesn’t have these parts, such repair costs are averted. The universal vehicle expenses i.e., tire and brake changes, insurance, and structural repair are part of owning any vehicle. EVs are also not free of expenses. The highest maintenance cost associated with EVs is due to its battery which is unlike normal batteries. It has large complex rechargeable batteries, which are quite resistant to any defect but degrade with time and their replacement is quite expensive.

4. Depreciation Cost: HEVs have seen a higher rate of depreciation compared to IC driven vehicles. Deprecation is judged by its resale ability. One possible reason for the higher depreciation cost could be linked to the rapid advancement in HEV technology. A HEV which was once state of the art could become much inferior within a short period due to the recent stress in research in this field.
5. Electric car rebates and incentives: A great reason which attracts consumers to go for EVs, is the country and state incentives available in the form of various subsidies and policies. These rebates help offset the typically higher cost of an electric car to make "going electric" more financially feasible [6].

EVs are not for every lifestyle, but when compared to the myriad costs surrounding ICE purchase and maintenance, choosing an EV can be an intelligent fiscal decision. Table 1 summarizes total costs of ownership (TCO) of the selected drivetrain architectures. This has been derived assuming the average German holding period of 4 years and an average yearly driving distance of 10,000 km. The cost break-down for a midsize conventional car with a gasoline engine versus different hybrid architectures, a full battery electric car, and a fuel cell vehicle are summarized in. The TCO assessment covers all types of expenses accruing for a vehicle owner including one-time cost (e.g., purchase price, expected resale value) as well as operating cost (e.g., fuel/energy, vehicle tax, general/exhaust inspection, maintenance, and repair) [7], [8]. It can immediately be inferred that HEVs are economical.

Table 1.1 Cost break-down for different powertrain options [8]

Costs type (in EUR, year 2020)	**ICE**	**HEV**	**PHEV 15**	**PHEV 30**	**EREV**	**BEV**	**FCEV**
Purchase price (excluding Co$_2$ penalties)	27,946	29,963	30,805	31,941	37,093	36,390	46,456
Resale value	-9,503	-11,916	-12,252	-12,704	-14,756	-10,335	-15,809
Net depreciation	18,443	18,047	18,554	19,237	22,337	26,054	30,647
Energy cost	4,016	2,142	1,739	1,564	1,637	1,235	2,587
Maintenance & repair cost	2,892	2,720	2,704	2,692	2,124	2,348	2,548
Other operation cost (e.g. motor tax, inspection)	330	160	160	160	160	53	53
Total cost of ownership	25,680	23,069	23,157	23,653	26,257	29,690	35,835

In above table: Plug-in series HEV (EREV), plug-in hybrid with two different battery sizes (PHEV15 and PHEV30).

1.1.4 Affordability

While discussing about HEVs, a natural question that arises is affordability. The government of every country is taking interest to search for an alternative method of transportation which is accessible to the public. As such, there is a rapid deployment of well managed infrastructure to supplement electric technology. Since the production of the batteries has increased, its cost was shaved by approximately 50% and is expected to be lesser than $200/kWh. Improvement in battery technology will reduce the cost of the hybrid vehicle and make it accessible to more people [9]. It is expected that EVs can be made affordable by 2022 even if the conventional cars improve their fuel efficiency by 3.5% a year. The analysis uses the US government's projected oil price of $50-$70 (£36-£50) a barrel in the 2020s. If the price is $20, the tipping point is pushed back between three to nine years. Fig 1.4 depicts the battery pricings over the next 12 years and it can be inferred that by 2022, EVs are likely to cost the same as ICE vehicle equivalent.

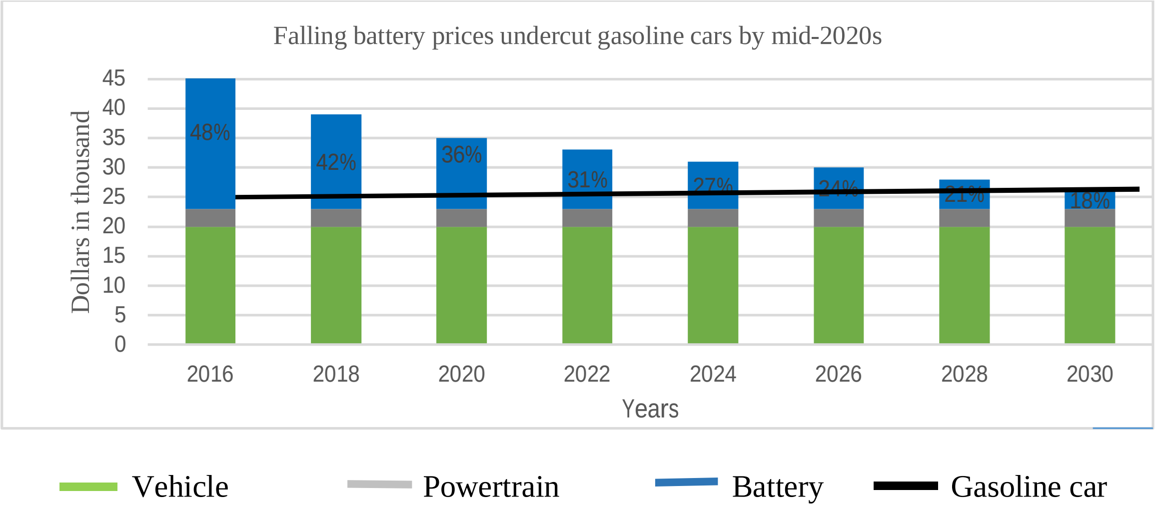

Fig. 1.4 Price fall status of hybrid vehicles [10]

Consequently, EVs will reduce the revenue from ICE vehicle but it will compensate via the revenue generated from this new window of opportunity for car manufacturers, for charging infrastructure companies and for battery manufacturers. Solid-state batteries will be the key to the enhancement in battery performance as they are 2.5 times denser than lithium-ion batteries.

The government has put forward many plans for launching EV from varied automakers. Based on these plans it is expected, that about 25 million units would on the road by 2025. Tesla Gigafactory is currently 35% operational and aims to produce 50 GWh of batteries in 2018. The EV charging station is a big hindrance which has yet not been focused and needs global attention. Currently, charging stations are present in limited areas where EVs sale is higher.

According to 2018 statistics, the total cost of ownership of a Ford Fusion Hybrid would amount to ~ \$35,606. This HEV lies comfortably in the midsize market range. In contrast to this, a Honda Accord, which is a traditional vehicle, would cost ~ \$35,709. By comparing other car models, it is evident that HEVs are now as price competitive as ICE vehicles. When looking into the compact market, it is seen that a HEV would be about ~\$9,000 - \$10,000 more expensive. The difference of the pricing in the two segments can be understood due to the higher maintenance and fuel consumption of a midsize IC driven vehicle compensating for a more expensive battery and base price. In a compact vehicle, the fuel consumption is also lower. Apart from that, the depreciation seen in a compact HEV is surprisingly higher which could be due to its lesser demand and product and rapid technology changes in the field. It is evident that HEVs in the midsize market are already price competitive and are affordable choices [11]–[14].

Table 1.2 Comparison chart for various existing hybrid vehicles

Vehicle	**Driving range**	**Efficiency**	**Fuel type**	**Overall Cost**	**Structure**	**Advantage**	**Disadvantage**	**ESS**	**Driving Mode**
ICE	high	low	Gasoline	High	Simple	1.Matured technology 2.Better performance 3.Simple and reliable 4.commerciAllized	1.Haramful emission 2. Fuel economy is poor	Fuel tank	City & highway
BEV	low	high	Electric	Low	Simple	1.Pollution free 2.Efficient	1. Poor dynamic response 2.Recharge time is high	Battery and Ultracapacitor	City
HEV	medium	low	Gasoline + Electric	medium	medium	1.Low emission 2. High fuel economy 3.Reliable and durable	1.Bulky 2. More number of components	Fuel tank, Battery and Ultracapacitor	Highway

From the above table it can be concluded that the ICE based vehicle has high driving range but lot of emission whereas the BEV has no pollution but short driving range whereas the HEV seems to be an in-between solution with medium driving range and low pollution compared to ICE based vehicle.

1.2 Motivation and Scope of Research

There are many fronts where HEV technology can grow in, be it in the adaptation, dissemination, or penetration of HEV in the market.

As we know that India is a developing country the charging infrastructure facility is not well developed and for BEVs charging infrastructure needs to be built at regular intervals so that these vehicles can be used for long journeys. HEVs can be used to extend the driving range an also to charge the vehicle using regenerative braking method. The scope of the research is summarized as below:

1. The HEV works on two sources i.e., ICE and battery powered electric motor. Hence, there is need of such EMS, which can make both of them to work at their highest efficiency. There is need of such optimization strategies, which can handle this crucial situation smartly. Hence, it calls for employing some machine learning techniques to address this problem.
2. The battery is a very costly and important component in a HEV., Firstly, there is a need to estimate the exact SoC. Moreover, the battery model needs to be tested with multi-RC circuit in the equivalent circuit of the battery.
3. The battery life span need to enhance. Hence there is a need to develop a HESS which can increase the battery life and provides smoother operation.
4. The cell balancing is a critical issue. Which need to be addressed to increase the battery life span and its performance.

Based on the literature gap and scope of the research following objectives have been identified.

1.3 Objectives

I. Adaptive SoC estimation of lithium-ion battery for hybrid vehicle applications using ANFIS.
II. Power optimization strategy for a HEV using Fuzzy logic controller and its real-time implementation using FPGA based MicroLabBox.
III. Power optimization strategy for an HEV using ENN based controller and its real-time implementation using FPGA based MicroLabBox.
IV. Fuel economy improvement of an HEV using ANFIS tuned algorithm for a power split HEVs and its real-time implementation using FPGA based MicroLabBox.
V. Development of a Hybrid energy storage system (HESS) for hybrid vehicle application.

1.4 Contributions of Thesis

The main contributions of this thesis are as follows:

1. The battery SoC estimation by adding 3- RC pairs in series with its internal resistance has been carried out. The values of the RC pairs have been calculated mathematically by solving the circuit model, based on charging and discharging dynamics of the battery. The values of these parameters have also been optimized using a “lsqnonlin” function. The SoC of the battery is estimated using the combination of coulomb counting and open-circuit voltage methods to minimize the error in estimation. The obtained SoC is further corrected for errors using ANFIS based algorithms. The effect of temperature has also been accounted for modelling the battery and in SoC estimation. These obtained SoCs for 3 cases, i.e. without RC/with RC pairs and then tuned with ANFIS based optimization are compared for the same load.

2. A hybrid electric vehicle is powered by the internal combustion engine and the battery-powered electric motor. These sources have specific operational characteristics, and it is necessary to match these characteristics for the efficient and smooth functioning of the vehicle. The nonlinearity and uncertainties in HEV model require an intelligent controller to control the energy sharing between battery and engine. In this work, a fuzzy logic-enabled energy management strategy (EMS) for the hybrid electric vehicle based on torque demand, battery state of charge and regenerative braking is designed and implemented.

The proposed EMS allows engine and motor to maneuver in their efficient operating regions. The designed hybrid electric vehicle and its control strategy follow the driver commands and regulations on vehicle performance and liquid fuel consumption.

3. A fuzzy logic and Elman neural network-based adaptive EMS in an HEV are designed and implemented. The input parameters to these EMS are torque demand, battery state of charge, and regenerative braking. The proposed strategy aims to maximize the fuel economy while maintaining the battery health. A power-split HEV along with EMS is designed, modelled and simulated in MATLAB/Simulink first and then the whole system is validated in real-time using controller hardware in the loop testing platform (CHIL). The FPGA based MicroLabBox CHIL has been employed to test the system behavior in real-time.

4. An adaptive control strategy to achieve higher fuel economy along with smooth operation and better performance of the vehicle has been investigated. An EMS control strategy is proposed for an HEV based on an adaptive network-based fuzzy inference system (ANFIS). The proposed adaptive equivalent consumption minimization strategy decides the power to be drawn from ICE and EM based on input parameters such as the speed of the vehicle, the state of charge of the battery, the EM torque and the ICE torque. The whole system is simulated in an advanced vehicle simulator tool. The proposed non-linear controller has also been tested for real-time behavior using a field programmable gate array–based MicroLabBox hardware controller to compare its performance against existing controllers.

5. The sizing of UC and battery based on the power- estimation for ESS hybridization has been carried out. The sizing method is based on the prescribed set of limiting values of current and voltages, tries to maintain the UC voltage and battery current within range. This method reduces the above-average peaks of the required current from the batteries. Similarly, while recharging due to the regenerative braking, the proposed method removes the above-average peaks of the charging current of UCs.

6. The performance of HEV in terms of the fuel economy, enhanced driving range, battery life improvement and SoC optimization has been tested in real-time using hardware in the

loop (HIL) by MicroLabBox hardware controller. The developed HIL system is investigated on an FPGA based engine with an appropriate time step. These devices mimic the real-world operations and provide appropriate control.

1.5 Structure of Thesis

The research work carried out in this thesis is organized as follows:

Chapter 1 introduces the need to reduce the ICE based vehicle by HEVs. The history of HEV, consumption of petroleum product by road transport, GHG enhancement in environment and its ill effect adoption, market status of HEVs, affordability is discussed here. The objectives and scope of the research are also identified in this chapter.

Chapter 2 review of hybrid electric vehicles based on their architectures and components.

Chapter 3 presents the modelling of a battery including multiple RC circuits and its parameters estimation. A combination of coulomb counting, and open-circuit voltage methods is used to estimate the SoC and then ANFIS algorithm is used to further tune the obtained SoC. This chapter also covers the effect of temperature variation on battery behaviour.

Chapter 4 investigates the real-time validation of fuzzy logic controller to improve the fuel economy, driving range and battery SoC. The MicroLabBox hardware controller is used for real-time validation.

Chapter 5 analyses the performance of fuzzy logic and Elman neural network-based adaptive EMS in an HEV. The proposed strategy aims to maximise the fuel economy of the vehicle and results in lesser degradation in the battery SoC. CHIL has been employed to test the system behaviour in real-time.

Chapter 6 examines the performance of ANFIS control technique and presents performance validation using real-time based HIL testing platform.

Chapter 7 focuses on the sizing, design and development of HESS for the hybrid electric application to increase the dependence on the on-board renewable source.

Chapter 8 draws the conclusion which summarizes the major findings. The thesis is concluded, stating the significance and future scope of the present research work.

The structure of the thesis has been shown in the form of flow chart.

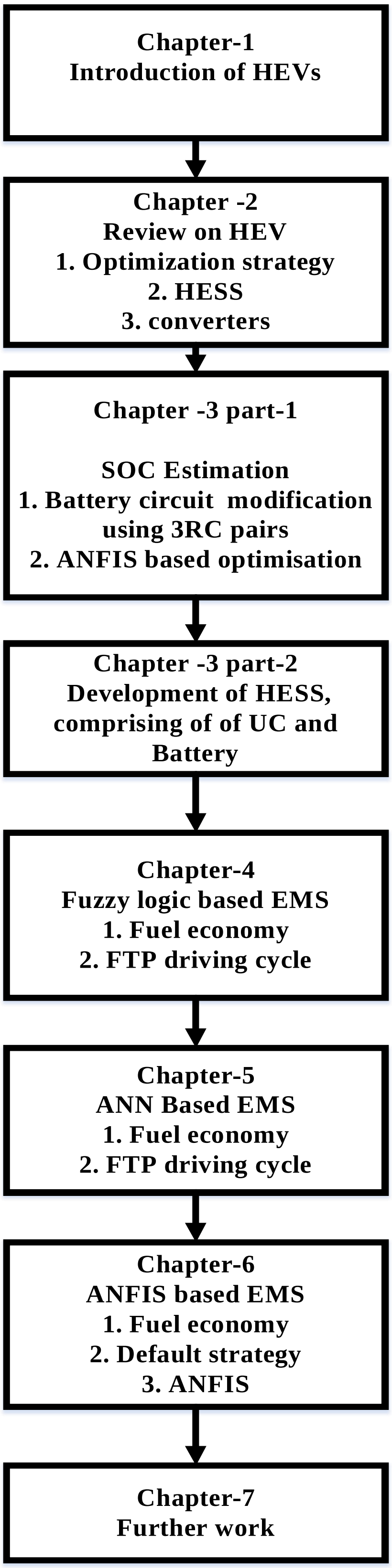

Fig. 1.5 Flow chart of research work