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Fuel efficiency optimization Techniques in Hybrid Vehicle

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***Abstract:** The hybrid electric vehicle (HEV) has the potential of sufficing drive needs with better fuel efficiency. The complex nature of hybrid vehicle provides multiple opportunities for obtaining better fuel efficiency. The mathematical modeling is a necessity for understanding the behavior of HEV. The fuel efficiency is obtained through various means including the design of energy management system, component sizing, emission control, and other methods. In the present paper, a mathematical model of HEV is presented for a parallel HEV with a review of various methods used for fuel efficiency optimization.*

***Index Terms**: Hybrid electric vehicle, fuel efficiency, optimization*

I. INTRODUCTION

The global warming, increased pollution and other environmental issues are demanding better alternative for the conventional automobile. The electric vehicle may be a better solution [1].On the other side, fossil fuel has limited resource, the automobile sector consumes about 49 % of global oil reserve which is predicted to be depleted by 2038 [2]. Controlled use of oil and other natural resources will provide more time to the researcher for exploring other possible opportunities of energy. An amalgamation of electric and conventional vehicle viz hybrid vehicle is becoming more popular as it may utilize the best of both the technologies. The hybrid vehicle provides an opportunity to increase fuel economy, optimized use of fossil fuel and extended drive range. The high initial cost of these vehicles may be compensated by long term saving in fuel expenses [3].

The hybrid vehicle has to operate with various constraints such as limited battery use, fuel efficiency, power and torque requirements, various driving conditions etc. The optimization techniques give the maximum output with the best possible fuel efficiency satisfying other given constraints. The different Energy and power management strategies would enhance the overall efficiency of the system[4, 5]. The hybrid electric vehicle (HEV) runs with battery backup in Charge depletion (CD) mode and with conventional fuel in Charge sustaining (CS) mode. During CD mode vehicle maximizes battery use while in CS mode it uses fuel to run the vehicle with sufficient battery charge state. If drive distance is equal to or less than the electric range it would be preferable to operate the vehicle in CD mode only when drive range is more than the electric range the best possible method should be chosen which will have maximum fuel efficiency. In comparison to a conventional vehicle, the hybrid vehicle has more complex operation as the demand power is to be distributed in available input power in most appropriate way to achieve better fuel economy. The choice of fuel converter, Electric matter, Battery System, Power electronic component and design of Energy management system has a vital role in improving fuel efficiency. [6]

II. MODELING OF HYBRID VEHICLE

The major component of hybrid vehicle includes IC Engine, Battery system, Electric Motor, Transmission system, Vehicle body, and wheel. The chemical energy of fuel is converted in mechanical energy by the IC Engine.

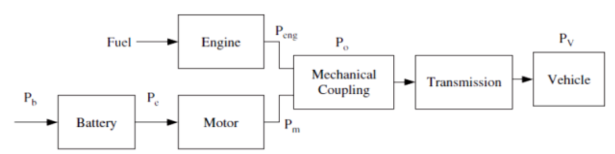

Fig 1: Hybrid Vehicle Architecture [6]

The IC Engine has four operating modes viz cranking, idle, engine-on and engine-off. In cranking mode, the engine produces negative torque which is overcome by a starter. The cranking torque in this mode is:

$$\tau_{crank} = J_{eng}\frac{d\omega_{eng}}{dt} + \tau_{access} + \tau_{cct} \qquad (1)$$

$$\omega_{eng} = \frac{1}{J_{eng}}\int_0^t (\tau_{crank} - \tau_{access} - \tau_{cct})\, dt \qquad (2)$$

J_{eng} is engine inertia, ω_{eng} is shaft angular velocity, τ_{access} is the constant lumped torque for mechanical accessory, τ_{cct} is closed throttle torque of engine given by :

$$\tau_{cct} = \alpha_1(T)\, d.\delta(t) + \alpha_2(T)\, sgn(\omega) + \alpha_3(T)\left(\frac{\omega}{\omega_{max\_eng}}\right) + \alpha_4(T)\left(\frac{\omega}{\omega_{max\_eng}}\right)^2 \qquad (3)$$

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d : engine displacement, δ (t) : Dirac delta function, ωmax_eng : maximum permissible angular velocity, T is temperature α1, α2 and α3 are static, Coulomb and Viscous friction respectively, α4 is Air compression torque coefficient.

During Engine off the breaks provide the negative torque, thus:

$$\tau_{ref} = \tau_{access} + \tau_{cct} \quad (4)$$

$$\tau^{*} = \tau_{ref} + f(\Delta\omega(t)) \quad (5)$$

$$\Delta\omega(t) = \omega_{idle\_desired} - \omega_{idle\_actual} \quad (6)$$

In the idle state, the clutch is disengaged, thus the desired speed is maintained by the governor:

$$\tau_{enf\_off} = \tau_{access} + \tau_{cct} + \frac{P_{acc}}{\omega_{eng}} \quad (7)$$

$$\omega_{eng} = \omega_{shaft} \quad (8)$$

In 'On' condition the engine provides propulsion torque provided by:

$$\tau_{generated} = \tau_{demand} + \tau_{access} + \tau_{cct} + \tau_a \quad (9)$$

where

$$\tau_a = J_{eng}\frac{d\omega}{dt} \quad (10)$$

And

$$\tau_{access} = \frac{P_{access}}{\omega_{eng}} \quad (11)$$

and maximum torque constraint would be:

$$\tau_{generated} \le \max(trq_{eng}) = f(\omega) \quad (12)$$

The interested readers may refer [7] for detailed modeling of HEV.

The emission may be calculated through the emission data as :

$$f_{fuel}(\tau,\omega,T) = \lambda_{fuel}(T)g_{fuel\_hot}(\tau,\omega) \quad (13)$$

$$f_{emi\_CO}(\tau,\omega,T) = \lambda_{CO}(T)g(\tau,\omega) \quad (14)$$

$$f_{emi\_HC}(\tau,\omega,T) = \lambda_{HC}(T)g(\tau,\omega) \quad (15)$$

$$f_{emi\_NOx}(\tau,\omega,T) = \lambda_{NOx}(T)g(\tau,\omega) \quad (16)$$

$$f_{emi\_PM}(\tau,\omega,T) = \lambda_{PM}(T)g(\tau,\omega) \quad (17)$$

g_x are the fuel consumption and emission factor and λ_x is temperature factor used for modulating hot temperature consumption of fuel and emission to given temperature.

The transmission model uses planetary gear in which the generator is coupled with sun gear and engine with carrier gear. Output of planetary gear is given to motor via torque coupler and motor output is given to the final drive. The generator speed and torque will be

$$\omega_g = k_1\omega_e - k_2\omega_r \quad (18)$$

$$\tau_g = k_3\tau_e \quad (19)$$

Where ki, i=1,2,3 are the gear ratio of planetary gear, e stands for engine and r stands for ring gear. The motor torque and speed will be:

$$\tau_m = \tau_r - (\beta_1\tau_g + \beta_2\tau_e)/\beta_3 \quad (20)$$

$$\omega_m = \omega_r \quad (21)$$

Where βi, i=1,2,3may be determined by dynamics of planetary gear [**]Torque (τr) and speed (ωr) required at ring gear depends on drive cycle and may be known by

$$\tau_r = \frac{e^{-\gamma t}}{\xi}(\tau_{req} + \tau_l) \quad (22)$$

$$\omega_r = \frac{\xi}{\mathcal{R}}\upsilon \quad (23)$$

Where

γ = driver model delay time, ξ = drive ratio, υ = vehicle speed and $\mathcal{R}$ is radius of wheels. τ_{req} may be calculated as

$$\tau_{req} = Kpa + Ki\upsilon \quad (24)$$

Kp, Ki being constant of PI controller. The τ_l may be known through

$$\tau_l = \mathcal{R}\,[mg\sin(\sigma)] + f_0 + f_1\upsilon + f_2\upsilon^2 \quad (25)$$

σ = grade, m = mass of vehicle, g = gravity and fi, i= 1,2,3 are vehicle curve fitting losses. Motor-generator losses and fuel consumption may be obtained by lookup table. The battery SOC is helpful in determining open-circuit voltage and source resistance of the battery using lookup table. The power requirement of motor and generator is supplied by battery (Pb) and is given by

$$P_b = V_0 - R_b i^2 \quad (26)$$

Vo is battery open-circuit voltage, Rb is battery source resistance and i is the current. The value of Rb and output voltage (V) may be obtained by solving Eqn 15 as:

$$V_0 = V_0 - R_b i \quad (27)$$

The SOC,(S) at every time interval (k) is

$$S_k = \frac{1}{C_{max}}\int_{t=k-1}^{t=k} i\,dt + S_{k-1} \quad (28)$$

Cmax is maximum capacity of battery in Ampere hour.

The optimization problem is to find best operating point of engine. The strategy is to increase fuel efficiency with satisfying fuel requirement constraint. The objective function would be:

$$\text{Min}:\ \vartheta(\tau_e,\omega_e) \quad (29)$$

Where ϑ is equivalent fuel consumption and may be obtained from

$$\vartheta(\tau_e,\omega_e) = \int_{t=k-1}^{t=k} m_e(\tau_e,\omega_e)dt + \sigma(S_k) \quad (30)$$

Energy consumed by battery is evaluated by SOC equivalent fuel (σ) and can be known by

$$\sigma(S_k) = -\mu V C_{max}(S_k - S_{k-1}) \quad (31)$$

The constraints for the energy management system are:

$$0 < \tau_e < \tau_{emax}(\omega_e) \quad (32)$$

$$\omega_{emin} < \omega_e < \omega_{emax} \quad (33)$$

$$-\omega_{gmax} < \omega_g < \omega_{gmax} \quad (34)$$

$$-\tau_{gmax}(\omega_g) < \tau_g < \tau_{gmax}(\omega_g) \quad (35)$$

$$-\omega_{mmax} < \omega_m < \omega_{mmax} \quad (36)$$

$$-\tau_{mmax}(\omega_m) < \tau_m < \tau_{mmax}(\omega_m) \quad (37)$$

$$S_{min} < S < 1 \quad (38)$$

$$-P_C(S) < P_b < -P_D(S) \quad (39)$$

PC is charge limit and PD is discharge limit.

Main issue in energy management optimization involves selection of correct objective function, information of future load based data and vehicle characteristics. [8]

III. FUEL EFFICIENCY OPTIMIZATION TECHNIQUES

The complex architecture of hybrid vehicle allows the multiple possibilities of obtaining better fuel efficiency. The possible methodologies include proper planning of energy management strategy, choice of proper Component size, control on emission etc.

i. Energy Management system (EMS):

In HEV, the IC Engine must run at optimum operating point for achieving better fuel efficiency.

The torque-speed performance curve of IC engine [Fig 2] shows that minimum fuel consumption will occur at operating point [ωe,τe]: [3200,55]:[rpm,N-m]

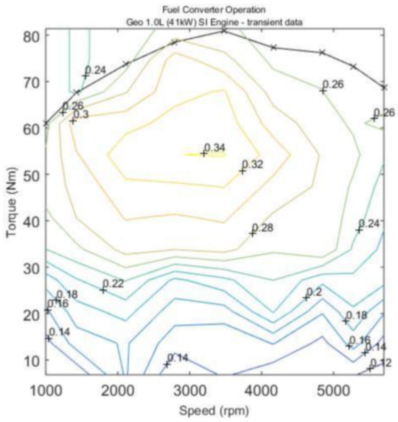

Fig 2: The Torque-speed characteristics for achieving optimal operating point of IC Engine.

The simulation results indicate the engine data for various types of emission.[fig 3 to fig 5]

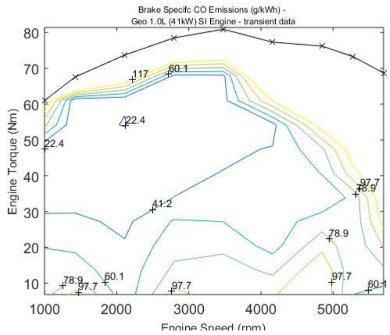

Fig: 3 engine data for CO emission

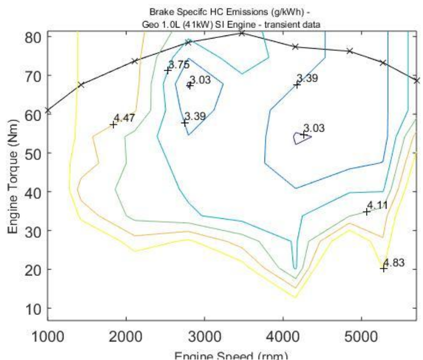

Fig: 4 engine data for HC emission

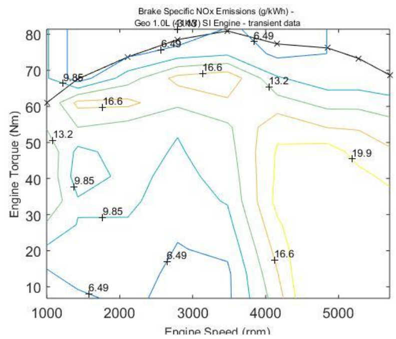

Fig: 5 engine data for NOx emission

The operating condition for lowest emission of various pollutants is:

Table 2 : Operating point for lowest emission

Pollutant	Speed (rpm)	Torque (N-m)
CO	2300	54
HC	2600	65
NOX	3200	64

The role of EMS is to make a trade-off for operating point between the lowest fuel efficiency and lowest emission.

In HEV the better flexibility is there for sufficing the power demands from the driver as power can be split in IC Engine and Electrical System. The suitable design of power split strategy can improve fuel efficiency. Such a scheme for optimizing design and control of a parallel hybrid vehicle was proposed in [9]. The model was formulated in state space and direct collocation method was used for solving the optimal control problem however exhaust emission analysis was not done. The instantaneous real-time optimization is a complex job. A strategy for the same was proposed in [10]. The instantaneous cost function was evaluated as minimum function by proper selection of variable for torque splitting. A fuel equivalent was determined in real-time as function of the existing system. Another method of power optimization was obtained by assessing the amount of engine torque required for generating propulsion power with a charge sustaining scheme for maintaining SOC of battery at sufficient level in [11]. Fuel optimization was obtained by minimizing the depth of discharge rate with non-linear constraints. The charge sustaining strategy was discussed for hybrid and stop mode of operation. Sensitivity analysis was done to know the range for which the variation will not make any impact on the optimal solution.

Neural network was applied for designing energy management system in [12]. The energy requirement was minimized and system was made compatible to work with various input sources like fuel cell, micro-turbine, Battery and other similar energy sources. A DSP (TMS320F241) was used for real-time implementation of proposed algorithm.

In [13], the hybridization of fuel cell was done with other energy sources like battery ultracapacitor. Optimization algorithm was proposed for effective splitting of power between fuel cell and energy storage system. Classical optimal control was used for the purpose. The global optimization of energy management problem was obtained by Lagrange formalism approach which is suitable for instantaneous control within a predictive control strategy. λ-predictive scheme is a instantaneous control scheme, The most complex part in such strategy is dependability on the predictions. The method given in [14] is not dependent on prediction of drive cycle as it approximates the future speed-torque as earlier one and thus can be considered as known. In [15] the classification of supervisory control scheme was presented. The difference of static and dynamic models was also explained. A brief of the simulation software ADvanced VehIcle Simulator was also given for a rule-based control strategy.

Various optimal control theories are not suitable for real time energy management as they require prior knowledge of the driving condition, which is not possible in most cases. In [16] the methodology concentrated on physical explanation of need of producing , consuming and storing electrical energy rather than solving mathematical expression. It depicted the vehicle characteristics immediately. The given concept is also useful for many existing and future HEVs. In [8] PSO was used for fuel economy of plugin hybrid vehicle. A simplified model of the power splitting in HEV was developed. The model was then used with PSO to obtain the optimum operating point of ICE while satisfying various physical and operational constraints. Resulting optimum operating point was then given as input to the PSAT model. The results were compared with PSAT default strategy and found that PSO strategy gives better fuel economy.

Fuzzy logic was applied in Energy Management system very effectively for obtaining better fuel efficiency [17]. It can schedule the power distribution between battery and engine. The possibility of fuzzy controller for torque distribution was successfully explored in [18]. The rule set of each mode of operation was designed for overall energy management strategy. The work is further extended in [19] in which real drive-cycle pattern analysis was incorporated within an overall planning for energy management. A new rule based energy management scheme was suggested in [20] in which a combination of rule base with equivalent combustion minimization strategy was used. The combination used one decision variable only without having tuning requirement of many parameters. The proposed scheme required less computation time in comparison to similar dynamic programming method. A hybrid dynamical system principle was used for formulating the HEV control system incorporating continuous as well as discrete dynamics. Sequential quadratic programming was used for battery and engine power, desired torque and SOC of the battery. It was based on quasi-static modeling of component without considering vehicle operating mode (VOM). The DP method was used for solving the complex VOM transmission problem. Using the results of these methods an online energy management system was developed . Fuzzy logic was applied for scheduling power sharing between battery and engine [21].

A rule-based fuzzy logic energy management system for a parallel HEV was given in [22]. Efficiency map was used for design of IC engine. Fuzzy based controller takes is the decision for optimum power splitting between the ICE and EM for desired operating condition viz speed, battery SOC and power. A fuzzy logic based optimal power management scheme was given in [23] which minimizes fuel consumption for a vehicle which produces driving torque by and IC engine and Induction motor. Power converters converts the accelerator and break input given by driver to equivalent power command. Fuzzy based controller uses induction motor speed, power command and battery SOC for finding scaling factor and optimized vehicle power. The speed control of ICE was planned by gear scheduling. The ICE efficiency was also optimized by using speed-torque curve at optimal operating point. Simulation was done using ADVISOR. A new strategy for energy management incorporating a novel quantity viz battery working state (BWS) was proposed in [24]. The BWS has the information of battery state of charge and its terminal voltage both and fuzzy logic was used for its definition. The FLC based EMS uses BWS for making power split decision between Energy storage and ICE on the basis of power demand of vehicle ensuring the fuel economy region of ICE. The results of FLC based EMS was verified with HEV simulation having a real battery in loop. Classical fuzzy rule-based system do not have optimality as design is based on the actual state of the vehicle in spite of its driving condition. In [25] a method was proposed to overcome the issue. For increasing the efficiency of controller in each condition, the driving condition information is given as input to the controller.

Genetic algorithm was employed for energy flow management in [26]. The road performance was chosen as design constraint. Non-linear behavior of optimization problem supports the suitability of applying this algorithm. The proposed methodology tunes the energy flow management strategy and minimizes the objective function through its weighing function which considers technical as well as other social, environmental and financial aspects. The energy management optimization problem may address by general rules however it will provide sub-optimal solutions. The optimization is achieved by scheduling the ON-OFF of the engine as per the drive needs and minimizing battery and conversion loss. It will be a simple method of achieving desired result by using basic laws [27]. A heuristic Control Map was formed for analysis of advantage and drawbacks of using on-board power plant with various drive scenario. Control scheme followed the Control Map having logic to respond with batter SOC. An example was demonstrated for the increase in charge sustainability and fuel economy. The implementation of the GA was explained for the optimization of the transmission and control strategy in HEV[28]. The EMS problem was converted as optimal control problem for series HEV in [29]. The fuel consumption was calculated by linear-interpolation over lookup table. The initial co-state was obtained without the use of any root finding methods. Mixed-integer linear programming method was applied for optimizing energy management system in [30]. It minimized the charging cost with the constraint on power balance, remaining battery power limits, SOC limits, charging-discharging rate limits, battery charging-discharging constraint, departure SOC constraint, and transmitted power limits. The analysis of various driving scenario with factors like travel speed, stop and go frequency, energy level was analyzed and better result was obtained.

During analysis of optimization problem the binary controlled state variables as switching the IC engine on-off, use of look-up table with linear interpolation as engine fuel consumption map and associated Hamiltonian function may have multiple minima thus obtained optimal control would not be unique thus infinite number of optimal stage trajectory can be obtained. In [31] a control law was given for constructing few of them. The proposed algorithm was based on Pontryagin's Minimum principle (PMP) and consider optimal solution obtained by switching between the control signals. The proposed algorithm was 17 times faster than conventional methods.

A comparative analysis of Convex optimization and Dynamic-programming method for energy management system was done in [32]. Non-linear relation of ICE fuel rate and battery charging power for various speed level was designed by using convex optimization.

The ICE power requirement was determined by simulated annealing and battery power demand was by convex optimization for obtaining better fuel efficiency. Results were compared with dynamic programming-based method. Results suggested that convex optimization save more fuel with reduced computational stress. A new EMS was developed for series HEV first by using the working characteristics of ICE and battery adjoining logic threshold and FLC. Later a fuzzy-optimization method was planned for better fuel efficiency which was based on improved quantum genetic algorithm (IQGA). The results shows that fuel consumption was decreased by 5.17 % adding IQGA . The optimization effect of IQGA was also compared with conventional genetic algorithm, quantum genetic algorithm and found its supremacy. A new energy management strategy for HEV having fuel cell for supplying main requirements and auxiliary system having battery and super-capacitor was proposed in [34]. The Interconnection and Damping Assignment Passivity Based Control (IDA-PBC) and Hamilton-Jacobi Bellman (HJB) methods were combined for optimal flow of energy between the source. The source limitation was considered in terms of battery state of charge.
The issue of large computation time in using dynamic programing method for optimization was addressed in [35] by introducing rapid DP method. The proposed method modifies the control and state variables and includes a penalty for different speeds of components. The rapid DP was then joined with PSO for testing the vehicle performance. In [36] a projected interior point method was proposed for solution of convex formulation of optimization problem coupled with nonlinear model predictive control of energy management in HEV. The theoretical framework for the proposed strategy was introduced and the global convergence was demonstrated by analyzing the backtracking line search method.

ii. Component Sizing (CS)

Fuel economy may be improved by suggesting the proper size of components like battery, super capacitor etc. Dynamic optimization using state-space model is used in [37] for calculating rating of driveline components of parallel HEV with CVT. As per the PMP, Hamiltonian function of vehicle model was minimized. Dynamic programming method is used for minimizing fuel consumption for known driving schedule. A specific optimization software, named as KOALA, was developed which has short computation time and allows to code new architecture which increases its flexibility. The KOALA may provide the comparison of fuel consumptions for various HEV and may forecast best component sizing for given vehicle architecture [38]. A semi-global optimization problem was formulated for minimizing fuel consumption defined for shorter time horizon. The two stages involved in the techniques include pre-computed static instantaneous optimization for obtaining distribution of basic power and real-time adaptive dynamic compensation optimization for transient loss of diesel APU. The simulation results validate the proposed strategy [39].
Four global optimization algorithms, Namely SA, Direct, GA and PSO was applied in design optimization. Vehicle modeling software, PSAT was used for analysis. The study showed that SA and Direct algorithm are efficient for Design of complex HEV engine. Dynamic programming with reduced model was used for optimization in given drive driving cycle. Method gave fast optimization with better parameterization of controllers [40]. The classical offline optimization technique, Dynamic programming was applied in [41] for getting optimum sizes and powers of element of hybrid power train. A sub-optimal real-time control strategy was based on real time fuel use, battery considered as secondary power source. In [42] a parametric study was presented which was mainly planned for variations of components size in the Powertrain, For considering ICE ability of being turned off, and addressing the issue of energy consumption during start of ICE, a more realistic second state was given for representing the. The reduced model dynamic programming algorithm was used.
Fuel economy may be obtained by sizing the drive train component using PSO algorithm. Fuel optimal control was used for calculating fuel consumption of each particle. The Monte Carlo analysis was done for creating a statistically solid basis for evaluating robustness of PSO. The Pareto analysis was also done for exploring the influence on the solution during change in performance between better fuel economy and lower cost [43]. Hamilton minimization technique is used for optimal design of hybrid vehicle for achieving better fuel economy. The SHM was developed by determining possible modes of optimal control and then developing the components for computation of Hamiltonions in closed form [44]. GA was used for downsizing the power train components in [45] however it was found that downsized vehicle was slow in responding for driver inputs as compared to un-optimized vehicle. New europian driving cycle (NEDC) was used for evaluating the performance.
PMP was used for obtaining best component size EMS design for plugin hybrid electric bus (PHEB). The design was suggested as per the need of China government, The effectiveness of using super-capacitor in PHEB was also verified. The result showed that operation cost decreases with the increase in battery capacity [46]. The author proposed modified design for improving the problems of series hybrid vehicle. Conventional generator was changed by an integrated starter generator which supports traction and vehicle peak torque requirement. It also maintains the battery SOC providing extended drive range. The power train was methodically developed in terms of initial parameters and component sizing, later direct optimization of proposed configuration was done for maximizing fuel economy. The analysis was done using AVL CRUISE and MATLAB software. The result showed an 11 % improvement in operating efficiency and 21 % improvement in fuel economy [47].

iii. Emission Control (EC)

For an ICE, the four regular emissions are HC: Hydro-carbons , CO: Carbon-Monoxide , NOx : Nitrous-Oxides , and PM: Particulate-Matter. In particular, there is a definite relation between these emissions and fuel consumption. The responsibility for the EMS is to maintain a balance between better fuel efficiency and low emission.
In [48]
authors identifies optimal operating point for ICE and motor torque by determining the range of candidate operating points which satisfies the request of driver and for each operating point, a constituent optimization factor was obtained. The result indicates significant
reduction in emission.

A method for the simultaneous optimisation of control strategy parameters and proper HEV component sizing was proposed in [49]. A multi-objective optimisation problem, based on a GA was proposed. Variables were formulated for covering control strategy parameters and HEV component sizes both including motor, battery system and ICE. The objective function was obtained for minimizing the weighted sum of three main emissions and fuel cell.

Most of optimization techniques require a prior information of drive cycle which limits its application in real time. In [50] PSO algorithm is applied for achieving real-time implementation. The algorithm is used for finding the global minima. The result showed the PSO method is 10 times faster than exhaustive optimization techniques and the method may achieve comparable fuel efficiency. A rule-based energy management system was proposed for studying response of control scheme in controller area network (CAN) bus environment. Simulation model for CAN bus was developed in CANoe. Automatic code was generated by importing each model of PHSB from simulink to CAN bus. The simulation result showed that the developed strategy follows the demand power and target velocity. It maintains SOC at 30 % with realization of switching between CD and CS mode at specific interval of travel. The bus load and delay effect was quited good [51]. The optimal control strategy and gear shift schedule was planned in [52] which was based on predicted future time-domain provided vehicle navigation system. The optimal performance was obtained by using dynamic programming based on which the operating point of engine and motor was suggested. The electrical energy consumption and IC engine uses may be minimized by effective switching through embedded microcontroller unit. The system proposed in [53] gives guidance to driver for using the limited resource efficiently at critical energy level .

In [54] an optimization work was presented for HEV power-train using Genetic Algorithm. The main focus was the optimization of powertrain parameters including supercapacitors for obtaining better fuel efficiency. Quasi-Static-Simulation (QSS) backward-facing method was used for Vehicle modeling. The design process uses FTP-75 and HWFET drive cycle in combination [55]. The objective function was designed for minimizing the environmental impact factor (Ecoscore). The performance improvement of HEV was also suggested. GA was used for optimization while Boss Quattro was applied for optimizing iterative process. The approach was exemplified by two numerical examples which dealt with the optimization of a serial hybrid electric bus and a hybrid electric passenger car.

The methods suggested in prior suffered the issue of conflicting design objectives, a large quantity of coupling design parameters and various non-linear constraints, to resolve the issue a detailed methodology was presented based on the non dominated sorting genetic algorithms II (NSGA II) for achieving component size optimization of both control system and powertrain components [56]. The method effectively finds the Pareto-optimal solution set. The results demonstrated that improved fuel efficiency and reduced emissions were obtained without compromising with the efficiency of the HEV. GTPower, An engine simulation software was used for performance and emission analysis of series hybrid vehicle fed by partially premixed gasoline ICE. AVolvo VED D4 Euro-6 4-cylinder CI engine provides the necessary data which was fed to developed series HEV. First battery charging strategy was optimized then Multi-objective (Pareto) optimization was used for obtaining consumption of Nox-fuel for each charging strategy. Results showed superior performance of partially mixed combustion as compared to conventional diesel engine[57].

iv. Other approaches of optimizing fuel efficiency

The EMS design has to deal with non-linear behavior of vehicle components which not only complicates the optimization process, it also put computation burden. A better fuel efficiency strategy may be achieved by forecasting the future velocity and power requirements. In [58] benefits of prediction was compared with heuristic and optimal control scheme using real vehicle date. The EMS for HEV starter generator driven by belt was developed using CRUISE and SIMULINK for modeling and simulation. A BSG HEV was used having a motor with maximum power around 20 kW. The proposed strategy was based on road load recognition. The proposed method was more effective in fuel consumption and launch performance [59]. A novel method of obtaining better fuel efficiency was used in [60] in which vehicle speed was predicted by using vehicle lateral dynamics. The sensor and GPS signal gives vehicle position and instantaneous coefficient for tire and road friction. The maximum cornering speed of the vehicle was evaluated and a controller as designed for forecasting vehicle speed. The system uses more regenerative breaking. An scheme of optimum torque distribution and gear scheduling was also given. A real-time optimization strategy prediction was developed in [61]. The algorithm first took the data of vehicle state viz speed, acceleration, power demand, GPS coordinates then predictions were made for vehicle's future power demand. The algorithm evaluated cost to go objective function using Dynamic programming. The integrated model predictive control (IMPC) method, proposed in [62] combines adaptive velocity control and energy management during vehicle-following conditions. The IMPC could plan the vehicular velocity trajectories and battery SOC for improving the driving safety and fuel efficiency. For the assessment of IMPC performance, comparison was made between DP-based energy management strategies and common charge-depleting and charge-sustaining (CDCS), where an improved full velocity difference model (IFVDM) was incorporated for simulation of vehicle-following behavior. The scheme were tested for the real driving cycle. Results showed fuel economy may be enormously varied by tuning the inter-vehicle distance.

Various techniques of obtaining fuel efficiency of the hybrid electric vehicle are summarized in table 2.

Table 2: Fuel efficiency Techniques

Article	EMS	CS	EC	Optimization Algorithm/ Control Mechanism	Salient feature
Farral etal (1993)	√			Fuzzy logic	The power distribution strategy is planned through FLC

Zoelch etal (1998)		√		Dynamic Programming	Optimal torque for motor and CVT gear ratio was calculated
Johnson etal (2000)			√	Real-time control	Battery SOC is restored to initial state by replacement energy
Kleimaier etal(2000)	√			DIRCOL	i^2-CVT gear makes ICE to operate in best operating points Pollution analysis not done
Piccolo etal (2001)	√			Genetic Algorithm	Operation of power sources at higher operating point
Won etal (2003)	√			Fuzzy Logic	Rule-set for each mode of operation is designed
Langari etal (2003)	√			Fuzzy Logic	Torque distribution as per the need of drive cycle
Sciarretta etal (2004)	√			Dynamic Programming	Sub-optimal control for minimizing cost function in each interval
Won etal (2005)	√			Single objective Linear optimization	Torque distribution and ensuring battery SOC at sufficient level
Scordia etal (2005)		√		KOALA	consumption gain estimation for different HEV and component size forecasting.
He etal (2006)		√		Semi Global Optimization (SGO)	Dynamic compensation for transient loss in Auxiliary power unit
Zhu etal (2006)	√			Dynamic Programming Fuzzy Logic	Optimal fuel efficient operating mode transient
Montazeri etal (2006)		√	√	Genetic-Algorithm	Simultaneous optimization of control strategy and power train size
Moreno etal (2006)	√			Neural Network	Energy management strategy using ultra-capacitor
Bernard etal (2006)	√			Classical optimal control	Optimal Power split between battery and fuel cell
Hannoun etal (2006)	√			Fuzzy Logic	Control over amount of energy flow in various component
Hofman etal (2007)	√			Dynamic Programming Rule Base	Maximum propulsion power of secondary source is chosen as decision variable
Gao etal (2007)		√		Direct, SA GA, PSO	Comparison of four optimization techniques
Rousseau	√	√		Dynamic	Reduced model
etal (2008)				Programming	algorithm
Kermani etal (2008)	√			Optimal Control	Power splitting in real-time with some assumption
Nzisabira etal (2008)		√	√	Response Surface Genetic Algorithm	Minimizing eco-score indicator
Kessels etal (2008)	√			Online power splitting	Physical instruction strategy for energy management
Meintz etal (2008)	√			Supervisory	Comparison of fuel efficiency improvement approaches
Banvait etal (2009)	√			PSO	Simplification of vehicle architecture
Keulen etal (2010)	√			Prediction of power and velocity trajectory	Benefits of prediction
Khoucha etal (2011)	√			Fuzzy Logic	Induction motor sizing for peak power supply and ICE throttle angle control
Fang etal (2011)			√	Multi-objective Genetic Algorithm	Simultaneous optimization of power train and control scheme
Sinoquet (2011)		√		Dynamic Programming	Engine startup cost is determined
Li etal (2011)	√			Fuzzy Logic	Overcame the incorrect SOC estimation issue
Ceraolo etal (2012)	√			On-Off	Energy management through on-off strategy
Ebbesen etal (2012)		√		PSO	Mathematical model of drive train component is scaled
Shaohua etal (2012)	√			Rule Base	ICE operated in optimal efficiency range
Correa etal (2013)	√			Multi-objective Genetic Algorithm	Control strategy and transmission optimization
Denis etal (2013)	√			Fuzzy Logic	Controller input is drive conditions
Delprat etal (2014)	√			Linear interpolation and Singular Control	Specific co-states which generates singular control were utilized
Kaleeswari etal (2015)	√			Mixed Integer Linear Programming	Reduce charging cost
Hu etal (2015)	√			PSO	Real-time optimization with out prior knowledge of driving conditions

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Peng etal (2015)	√			Rule-Base	Switching between CS and CD mode with balanced SOC
Li etal (2015)	√			Dynamic Programming	Vehicle navigation system is used for knowing the future driving conditions
Lin etal (2015)	√			Velocity prediction	Determination of maximum cornering speed
Styler etal (2015)	√			Dynamic Programming	Load prediction for EMS for battery-super capacitor HEV
Zhao etal (2016)		√		Selective Hamiltonian Minimization (SHM)	Selecting the best mode which minimizes Hamiltnonian function
Alsibai etal (2016)	√			Optimal Control	Automatic switching between ICE and Motor by embedded microcontroller
Mangun etal (2016)		√		Genetic Algorithm	Vehicle modeling based on Quasi-static simulation
Delprat etal (2017)	√			Singular Optimal Control	Issue of multiple minima is addressed
Biros etal (2017)		√		Genetic Algorithm	Component sizing for series-parallel architecture
Xiao etal (2017)	√			Convex Optimization Dynamic Programming	Non-linear behavior between engine battery charging power and engine fuel rate is described
Song etal (2017)	√	√		Pontryagin's minimum principle	Determination of optimal sizes for battery and super capacitor
Borthakur etal (2018)		√		DIRECT	Integrated starter generator replaces conventional ICE in series HEV
Li etal (2018)	√			Improved quantum GA Fuzzy Logic	Quantum computing based genetic algorithm is used for EMS
Garcia etal (2018)			√	Multi-objective (Pareto)	Emission analysis of series HEV
Benmouna etal (2018)	√			Interconnection and Damping Assignment Passivity Based Control	Hybridization of battery, super capacitor and fuel cell
Xie etal (2018)				Power management with adaptive velocity control	Combination of power management strategy and velocity control method
Yang etal (2018)	√			Modified DP and PSO	Reduced computation time
East etal (2019)	√			Interior Point	Energy management of HEV with non-linear losses

IV. CONCLUSION

The dynamic programming method is majorly used in optimizing the energy management system and component size determination due to its ability to identify the global minima however it puts a major computational burden which makes it unsuitable for real-time application. Various novel techniques are obtained for real-time implementation of fuel-saving strategy. Fuzzy control is widely used for scheduling the power distribution between ICE and Electrical system however the results of fuzzy control deviate from optimality.The fuel optimization is achieved through designing suitable energy management system, designing proper size of various components of power trains and by minimizing the emission during the operation of drive. The fuel opt Various trade-offs are made to meet the best possible fuel efficiency. The present work will provide an opportunity for readers to identify the research gap and suggest ways to fill it.

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