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Integrating Hybrid Electric Vehicle Components for Optimal Energy Efficiency

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ABSTRACT

Integrating hybrid electric vehicle components for optimal energy efficiency involves sophisticated energy management systems (EMS) that control the distribution of power between the vehicle's energy storage, motor, and other devices using advanced power electronics like DC converters and inverters. As these technologies improve, adding components for hybrid energy systems becomes more viable. The primary goal of EMS in plug-in hybrid electric vehicles (PHEVs) is to meet propulsion power requirements while maintaining optimal vehicle performance, leveraging their extensive electric-only drive capability and external battery charging through electric power sources. This integration enhances both efficiency and functionality of the vehicle.

Keywords: PHEVs, Vehicle's Energy Storage, Fuel Consumption, Energy Management System

1. INTRODUCTION

The energy crisis and environmental problems are becoming crucial issues for the whole world and urgently require humans to take action to save energy and reduce the Greenhouse Gases (GhG) emission (Ambuhl and Guzzella, 2015). The emissions of GhG contribute to atmospheric pollution, climate change, and global warming problems. Internal combustion engines (ICEs) have been a key technology in the development of modern society and the growth of the global economy for over a century (Cao and Emadi, 2012; Chao et al., 2020). Innovations in design and manufacturing have led to lightweight, powerful, and cheap engines that are very popular and found in a huge variety of applications and industries (Ahmed et al., 2014). This success has not been without its drawbacks; however, as ICEs are fueled almost exclusively with oil derivatives, and can be directly linked to important environmental and societal issues including air pollution and climate change (Chen et al., 2014; Ehsani et al, 2015). Increased electrification of vehicles have been identified as a short-term solution to these problems, and improvements in practical and economic viability of electric powertrains have ensured that both hybrid and fully electric vehicles have surged in popularity in the past decade. It is expected that electric vehicles will reach a passenger vehicle market share of 10% by 2024 (Deloitte, 2021). While all-electric vehicles provide regeneration capabilities, zero tailpipe emissions, and greater energy efficiency than internal combustion vehicles, a significant limitation is the driving range available from a full battery charge, due to the low energy density of the current state-of-the-art in battery technology; lithium-ion, 360kJ/kg (Zubi et al, 2018) compared to petrol 45,000kJ/kg; (Heywood, 2018).Typically, electric vehicle (EV) can be categorized into three types according to the electricity used as the vehicle energy source: Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV) (Bunsen et al, 2018).HEVs have both a small-size electric battery and an ICE, which is powered by both electricity and gasoline. Because HEVs have no external socket, the electric battery only can be charged by using the vehicle's (regenerative) braking systems and ICE (Bunsen et al, 2019). PHEVs have both a battery and an ICE. Compared with HEVs, PHEVs have an external socket (plug) and a larger size battery (Barre et al., 2013). The battery is charged both from the external electricity from the plug and the regenerative braking systems. BEVs have an electric battery and no ICE (Bashas and Fathy, 2013). The electric battery is charged only from the external socket. Researchis currently ongoing on energy optimization of HEVs. One of the methods that will be adopted in this research is the use of Model predictive control (MPC) which has the capacity to predict future vehicular behavior with hard constraints on system performance and the use of convex optimization for model predictive energy management in electric vehicles. The aim is to generate convex formulations that permit more general descriptions of system dynamics than linear quadratic MPC, while still ensuring that the resulting optimization problem can be readily solved using limited hardware.

2. TEHRORY OF WORK

Hybrid Electric Vehicles (HEVs)

All-electric vehicles use electric machines and the chemical energy stored in rechargeable battery packs instead of an Internal Combustion Engine (ICE) to provide tractive power. As no fuel is consumed in the operation of the vehicle, zero tailpipe emissions are produced (although emissions may be created in the generation of the electrical energy).

Electric vehicles (EVs) often provide good dynamic performance (acceleration) but the lower specific energy of batteries compared to that of carbon-based fuels means that electric vehicles require battery packs that contribute significantly to the vehicle's mass and still provide a relatively low range.

A HEV combines a conventional ICE with an electric propulsion system. The inclusion of the electrified powertrain is intended to achieve either better fuel economy or better performance than a combustion vehicle. HEVs may use their engine as a generator to produce electrical energy to either recharge their batteries or to power their electric machines. Significantly less emissions are produced by a HEV than a comparable combustion vehicle due to a number of efficiency-improving technologies.

HEVs may also make use of regenerative-braking which converts the vehicle's kinetic energy into electrical energy, instead of it being wasted as heat as is the case with conventional brakes. This recovered energy may, in turn, be used to power the electric propulsion system. Hybrid Electric Vehicles can be classified based on propulsion system, energy storage system, energy source and various other parameters, some of which are discussed below (Ojas, 2017). This is been shown in Figure 1 below;

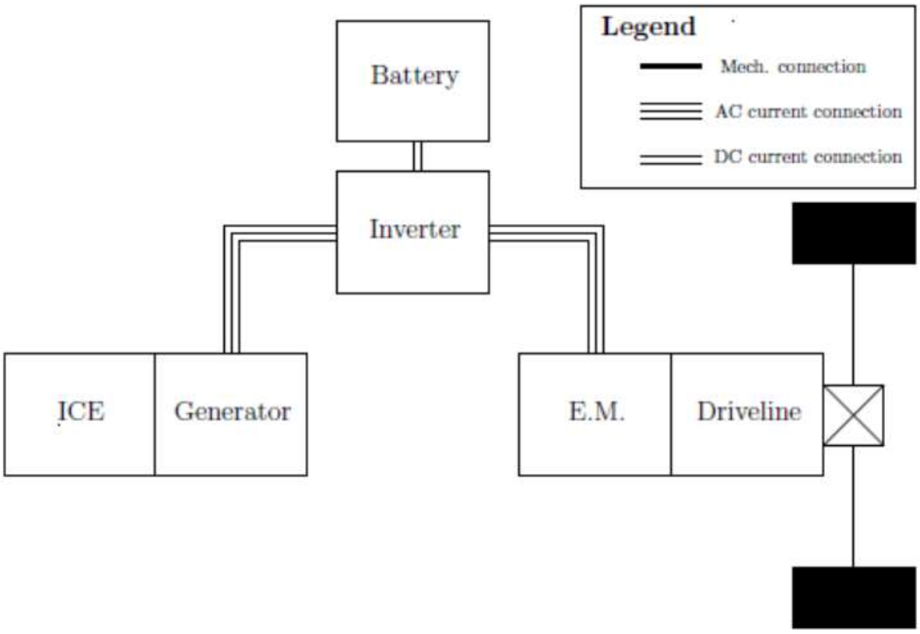

Figure 1: Series hybrid electric vehicle

To convert the mechanical power of the ICE into electrical power a generator with corresponding power electronics (PE) is needed. The combination of ICE and generator is often denoted by an engine-generator unit (EGU) or auxiliary power unit (APU), and can be used for vehicle propulsion or recharging the battery. The mechanical decoupling of the generator unit allows its flexible positioning inside the vehicle.

Since the engine is decoupled from the wheel, it can operate quite close to its maximum efficiency region, and it is possible to strongly simplify the transmission thanks to the shape of the torque curve of the EM. The disadvantage of architecture, represented by Figure 1, is the significant inefficiencies related to multiple conversions of mechanical energy into electrical energy and vice versa.

The hybridization ratio is used to assess the share of power between the battery and the auxiliary power unit. In the case of series configuration, its definition is shown in the Equation 1:

R_hSeries=P_(EL GEN)/P_EM Eq. 1

Where $PELGEN$ is the power of electric generator and PEM is the power of the electric machine. The series hybridization ratio ranges from 0 (pure Battery Electric Vehicle) to 1 (Electric Transmission) as shown in Figure 2:

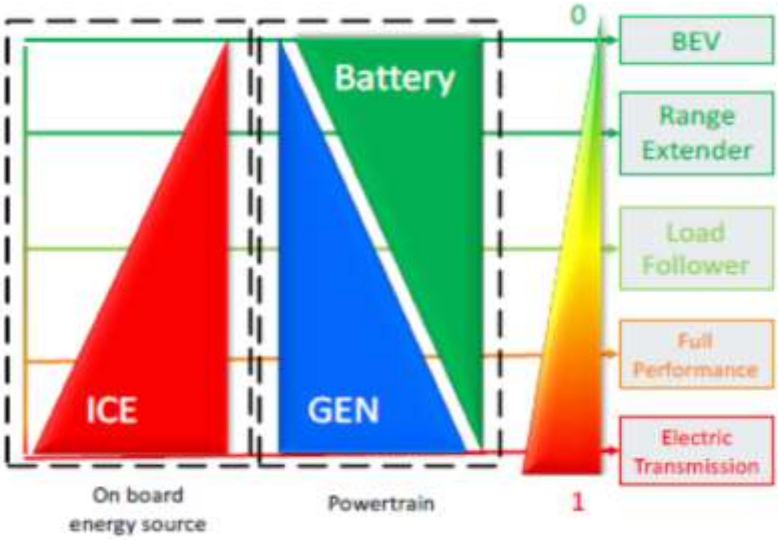

Figure 2: Series Hybridization Level (Mock, 2017)

The value of 0 series hybridization ratio means no generators installed: this is a battery electric vehicle (BEV) with no additional energy sources. As the size of the generator increase, the size of the battery decreases reaching at first the range extender configuration that is characterized by very small ICE (APU) (that works only in the case of high-power request and when the battery is fully discharged in order to enable the last mile distance between the recharge), the battery produces most of the power.

In the load follower and full performance configurations, the propulsion for moving the vehicles could be provided in higher share by the APU instead of the battery. When ($RhSeries$=1) electric transmission is realized, with no battery, and the ICE provides all the power.

Parallel Hybrid Electric vehicle

Parallel HEVs, the vehicle is propelled mechanically. The parallel architecture represents an extension of the topology of conventional vehicles (CVs) and uses an electric motor (EM) as additional energy source as represented in Figure 3.

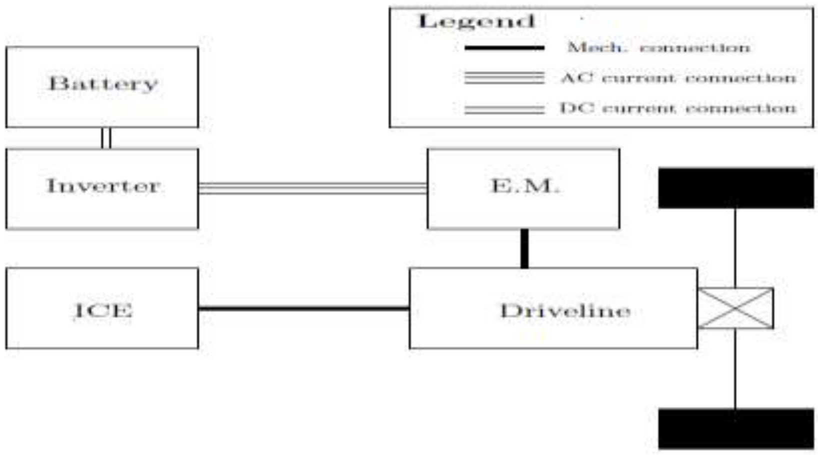

Figure 3: Scheme of a parallel hybrid architecture (Onori et al, 2016)

In contrast to series HEVs, there is a direct mechanical connection between ICE and powertrain which leads to a lower flexibility in terms of component positioning. Furthermore, the integration of components such as clutch and gear box is necessary. Due to the mechanical connection operating points of the ICE depend on vehicle velocity (v). This circumstance does not allow avoiding operating points with poor efficiency. However, the combination of EM and ICE allows shifting load points in regions with better efficiencies.

In parallel HEVs the ICE and EM can supply the propulsion power either alone or in combination. This fact leads to an additional degree of freedom for distributing the power flows in the vehicle. In the recuperation case, the EM acts as generator and charges the battery.

Predominantly, parallel HEVs may have a generally higher efficiency than series HEVs since no energy conversion between ICE and powertrain is needed.

Other characteristics in contrast to series HEVs are the integration of mechanical parts such as clutch and gear box into the powertrain and the omission of the generator. As for series architecture, it is possible to define the Parallel Hybridization Ratio using equation 2:

$$R_{h\,Parallel} = \frac{P_{EM}}{P_{ICE}+P_{EM}} \qquad \text{Eq. 2}$$

In series configuration the ICE is an auxiliary power generator but in parallel configuration it represents one of the two actuators. Figure 4 depicts the possible hybridization levels of a parallel configuration.

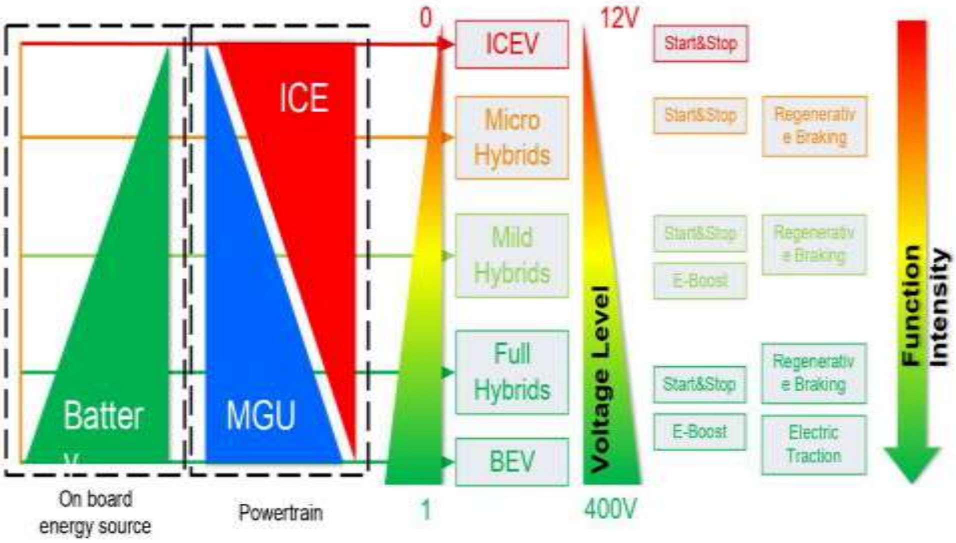

Figure 4: Parallel Hybridization Level (Mock, 2017)

As illustrated in Figure 4, the hybridization ratio lower, the power of ICE when $RhParallel$=1 until only the battery and the electric motor are present in the BEV. Differently from the series configuration, a change of hybridization ratio implies a variation of the functionalities.

3. METHODOLOGY

3.1 The Model Predictive Controller (MPC)

The MPC strategy is implemented using the proposed block structure of MPC controller with the system model of a plug-in hybrid electric vehicle for energy management as shown in Figure 3.

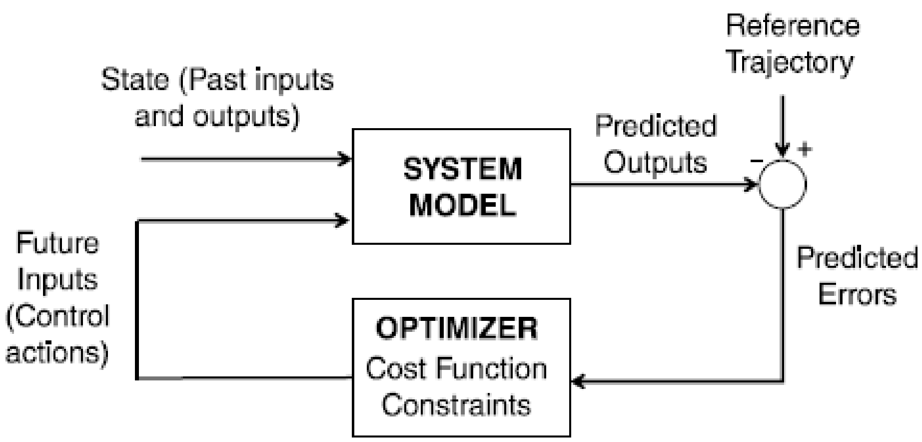

Figure 5: Block description of MPC control strategy for plug in hybrid electric vehicle

In Figure 5, a dynamic control model was employed to forecast the forthcoming system output. This forecast is based on historical and current data, as well as the proposed optimal future control actions. These actions are computed by the optimizer, considering the cost function and adhering to constraints.The model predictive control strategy anticipates the driver's desired reference trajectory over a finite control horizon. It also factors in the vehicle's characteristics to determine the necessary control actions (such as acceleration, braking, and steering) for tracking the intended path. At each moment, only the initial control action is executed, and this process is iteratively applied for subsequent control decisions in a forward-looking manner.

The car's behavior may be influenced by the optimization criteria selected, striving to minimize fuel consumption while optimizing the vehicle's dynamics through the MPC controller.

3.2 Convex Optimization Model

A convex set is one where for any two points in a set, every point between them is also in the set. A line in one dimension (1d) from points a to b, and x and yare points on the line as shown in Figure 6. Then any z between them is also on that line. Thus, a line is a convex set. In the 1d case, a convex function is one where if you draw a line segment between the function evaluated at any two points, the line lies at or above the function everywhere in between

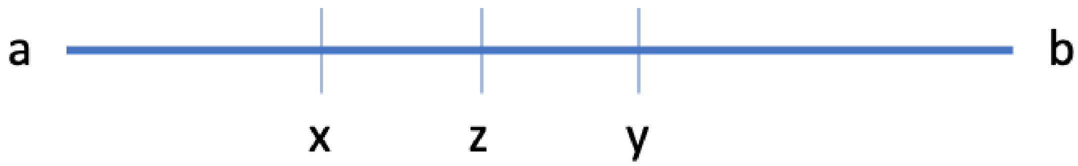

Figure 6: Convex set in one dimension

Geometrically, a function is convex if a line segment drawn from any point (x, f(x)) to another point (y, f(y)) and lies on or above the graph of f as shown in Figure 7:

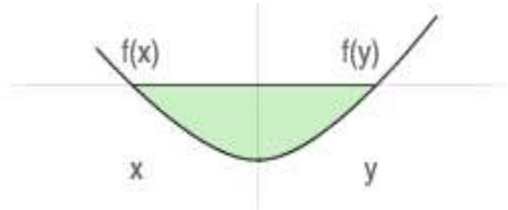

Figure 7: Convex set in two dimensions

Algebraically, f is convex if, for any x and y, and any time (t) between 0 and 1,

$$F(tx + (1-t)y) \leq t\,f(x) + (1-t)f(y)$$

Also, it follows that the energy management problem to minimize the fuel consumed by the PHEV as depicted in equation 3 with the various constraints is a convex function:

$$F(t) = Min\left(\sum_{t=0}^{T} \dot{m}_{feqv}(t)\right) \qquad \text{Eq.3}$$

$$\text{Subject to} \left\{ \begin{array}{ll} e(t), & lb \leq p(t) \leq ub \\ s(t), & lb \leq s(t) \leq ub \\ Q_{lhv}, & Q_{lhv} = \text{constant} \\ T_e(t), & T_e(t) = constant \\ w_e(t), & w_e(t) = constant \\ m(t), & m(t) = constant \\ d(t), & lb \leq d(t) \leq ub \\ P_{batt}. & P_{batt} = constant \end{array} \right\} \qquad \text{Eq.4}$$

3.3 MPC Based Convex Optimization Algorithm

The steps below represent the algorithm for the minimization of fuel consumed by the hybrid electric vehicle using MPC with a gradient descent convex optimization.

Step 1: Initialization

a. initialize $e(t)$, s(t),Q_{lhv} ,$T_e(t)$,$w_e(t)$,$m(t)$, d(t)

b. initialize reference $d(t)_{ref}$

c. Set k = 1,2,3…………n

Step 2: Calculate the power delivered$e(t+k)$,

Step 3: Compute $d(t) = e(t) + m(t) + b(t)$

Step 4: Compute the error signal $(\propto(t)$; Where $(\propto(t) = d(t)_{ref} - d(t)$

Step 5: Optimized the cost function (m_f); $\propto (t)$Is the input value that minimizes

$F\left(\sum_{t=0}^{T} \dot{m}_{feqv}(t)\right)$using convex optimization in equation 15

Step 6: Predict future $e(t+k)$;for(m_f)

Step 7: Optimize control signals T_w, w_e, η_e and input to the system

Else,

Set k= k + 1

Repeat from Step 2 to step 7

Step 8: End.

3. RESULTS AND DISCUSSIONS

The results of the convex optimization-based model predictive controller were presented in this section. The result started with the power drive of the vehicle delivered by the engine as depicted in the figure 6, then the power delivered by the engine clutch, gear box and motor are all reported in the figure 7 showing how the plug-in hybrid electric vehicles is been driven. In addition, the volume and rate of fuel consumed during the process with the new control algorithm developed in the study.

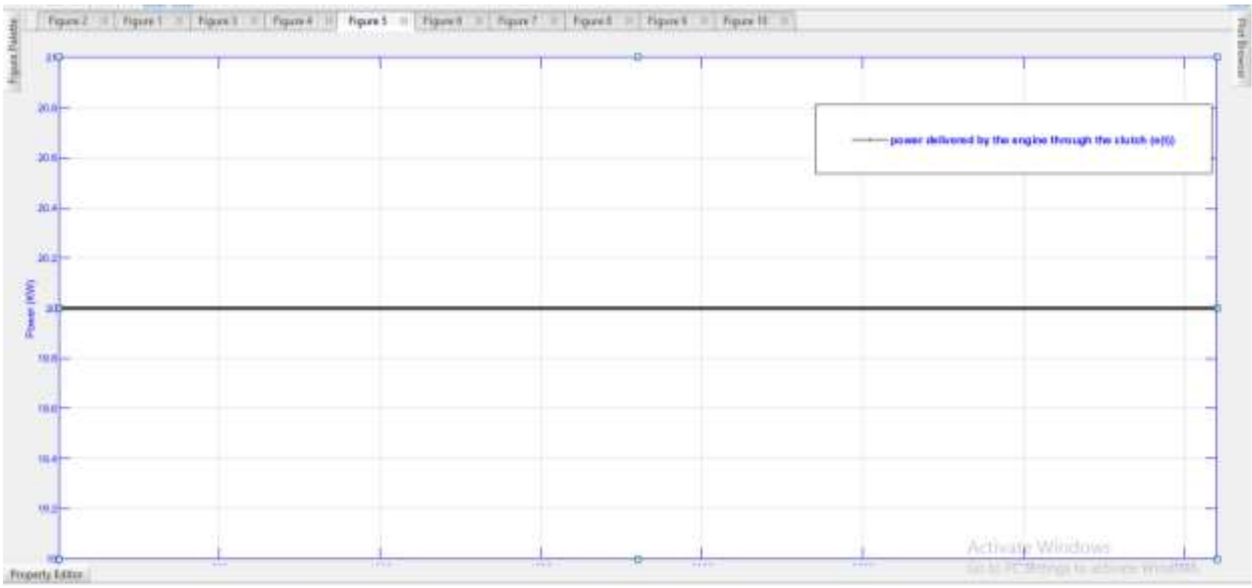

Figure 7: Power delivered by the engine**.**

Figure 7 shows that during the simulation of PHEV model developed, a constant power was delivered by the engine ($e(t)$) which is a product of the wheel torque ($T_w(t)$) and the rotational speed of the engine ($w_e(t)$) at a given time. The simulation was conducted for 3600seconds (1hr), with a constant engine power of 20KW obtained as a result of the PHEV running on the engine mode activated through the clutch.In the parallel architecture for PHEV considered in this thesis, the output of the engine is mechanically coupled with the motor to a common drivetrain.In this condition the fuel mass flow is delivered from a fuel tank to the engine, where it is converted to mechanical power that is delivered through a clutch. Simultaneously, the battery's internal charge is converted to electrical power at its terminals, which is then converted to mechanical power by the motor as show in Figure 8.

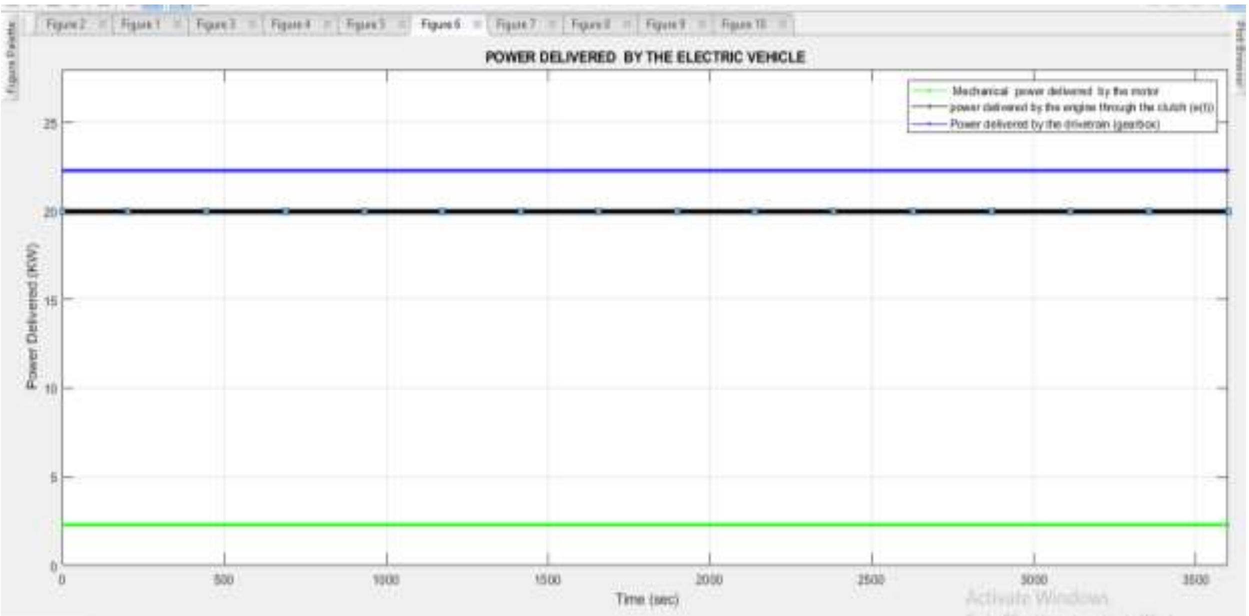

Figure 8: Power delivered to the drive train

Figure 8; show the power delivered by the engine, the power delivered by the motor and the commutative power delivered to the drive train or the wheels. When the clutch is closed, the power from the motor and engine is combined additively to power the drive-train showing an increase in power available at the drive train.When the engine of the electric vehicle is powered by the fuel to produce motion and charging of the battery, the fuel consumed increases as the distance covered and time spent in motion also increases. Figure 9 and 10 depict the rate of fuel consumption and the amount of fuel consumed per time at constant velocity.

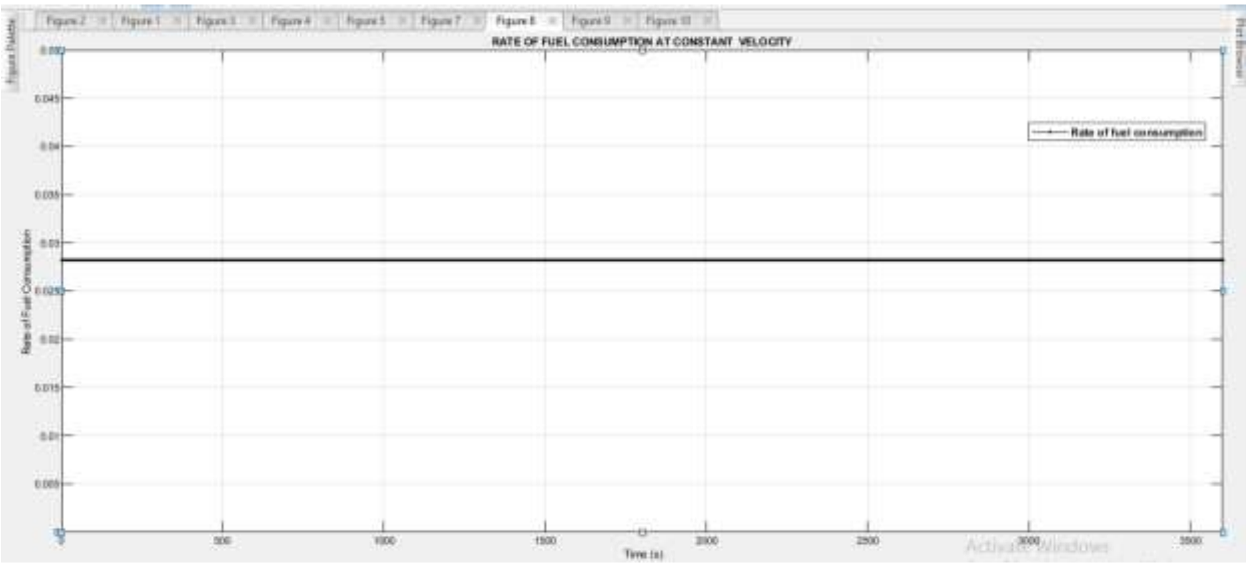

Figure 9: Rate of fuel Consumption in PHEV

Figure 9 indicate a constant fuel consumption at a given speed while Figure 10 also indicate a cumulative increase of the volume of fuel consumed during the duration of the journey that is from the start of the simulation to the end of the simulation at 3600s

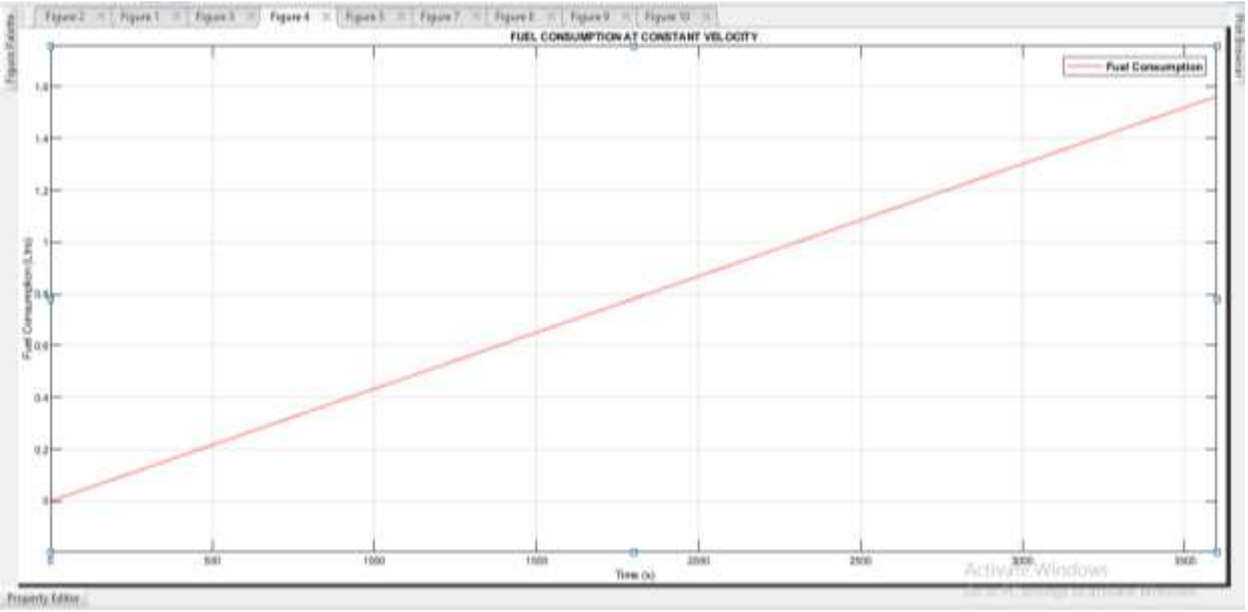

Figure 10: Volume of fuel Consumed in PHEV

In Figure 10, the fuel consumed increase from the start of the journey to the end of the journey at 3600 seconds. About 1.6ltrs was consumed during the journey at 3600s. For figure 9, a constant rate of 0.028 fuel consumption is maintained from the start of the journey to the end of the journey as a result of maintain a constant velocity.Overall the dynamic behavior of the vehicle engine is predicted with the MPC, then the convex optimization is applied to control the volume of fuel consumed by the engine, while maintaining quality of engine behavior. In addition, a comparative analysis of the new convex optimization based MPC was performed with that of genetic algorithm in Dehan et al. (2022), considering the volume of fuel consumed during the dynamic behavior of vehicle and the result was depicted in the figure 11;

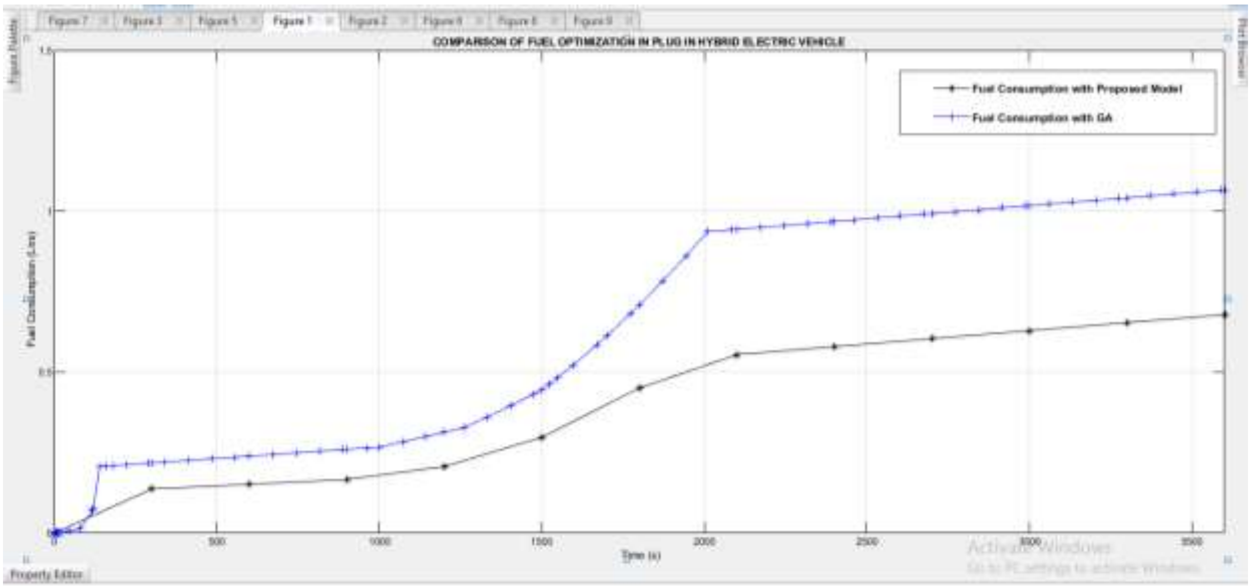

Figure 11: Comparison of fuel consumption

According to the findings in Figure 11, the convex based MPC demonstrates a noteworthy reduction in fuel consumption when compared to the genetic algorithm-based model. The energy management strategies, formulated within the framework of model predictive control, play a pivotal role in enhancing the fuel efficiency of hybrid electric vehicles. This involves intelligently distributing power between two primary sources, namely, the internal combustion engine and the battery, based on output references from the electric vehicle and predictions of future driver demands. The judicious allocation of power between these sources results in improved fuel economy and optimized power flow. From the result the average fuel consumed by the MPC based convex optimization algorithm is 0.4507 as against 0.781 recorded with genetic algorithm, thus giving a percentage reduction of 36.4% reduction in fuel consumed.

4. CONCLUSION

Hybrid Electric Vehicles (HEVs) continue to capture an expanding share of the automotive market. In the evolution of hybrid electric vehicle systems, it has become evident that HEVs represent the most significant transition from conventional gasoline-powered vehicles to hybrid electric alternatives. This transition is attributed to their unique combination of an Internal Combustion Engine (ICE) and an Electric Machine (EM), leveraging electrochemical energy. In the context of Plug-In Hybrid Electric Vehicles (PHEVs), performance is influenced by a multitude of interconnected factors, necessitating advanced control systems to enhance efficiency and reduce costs. The overall performance of PHEVs, particularly in terms of fuel consumption and energy utilization, hinges on the effectiveness of individual power-train components and the seamless coordination of the drive-train.Ultimately, the energy management system in a PHEV plays a pivotal role. The additional levels of flexibility afforded by the vehicle enable the handling of various optimization challenges in distributing power demand between the internal combustion engine and the electric drive-train.

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